

# Terahertz Metasurface Antenna For Wireless Body Area Network

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**Abstract-** This paper presents the design and analysis of a meta surface-based antenna system specially created for Wireless Body Area Network (WBAN) applications operating in the terahertz (THz) frequency range. The antenna is designed to meet the growing needs of high-speed, low-power communication in wearable biomedical devices. By integrating a meta surface, the antenna can precisely control electromagnetic waves, improving performance factors such as gain, bandwidth, and efficiency. Using terahertz frequencies allows for better data rates and smaller device sizes. This work introduces an innovative and practical solution for future body-worn technologies.

**Keywords—** Metasurface Antenna, Wireless Body Area Network (WBAN), Terahertz (THz) Communication, Wearable Devices.

## I. INTRODUCTION

In recent years, the rapid advancement of wireless communication systems and high-frequency applications has created a strong demand for compact, efficient, and high-performance antennas [1]. Technologies such as terahertz communication, high-speed data transfer, imaging systems, and sensing applications require antennas that can operate at very high frequencies while maintaining good radiation characteristics [2]. In this context, microstrip antennas have gained significant attention due to their low profile, ease of fabrication, lightweight structure, and compatibility with modern integrated circuits [3].

The proposed antenna design is a microstrip patch antenna array developed and simulated using CST Studio Suite. The design focuses on achieving enhanced performance in terms of gain, bandwidth, and multi-band operation [4]. Unlike a single patch antenna, which typically suffers from low gain and narrow bandwidth, the use of an array configuration significantly improves the overall radiation properties [5]. By arranging multiple radiating elements in a structured manner, the antenna can

produce a more directional radiation pattern and higher efficiency [6].

The antenna consists of a  $3 \times 3$  array of identical radiating elements, each designed with a compact slot-based geometry [7]. These slots are strategically introduced within the patch to modify the current distribution and electromagnetic behavior of the antenna [8]. As a result, the antenna achieves multiple resonant frequencies and improved impedance matching [9]. The slotting technique also helps in reducing the physical size of the antenna while maintaining its operational effectiveness, which is a critical requirement for modern compact devices [10].

The entire antenna structure is built on a dielectric substrate, which separates the radiating patch from the ground plane [11]. The choice of substrate material plays a crucial role in determining the antenna's performance parameters such as bandwidth, efficiency, and resonant frequency [12]. A conductive ground plane is placed at the bottom of the substrate to provide a return path for current and to reduce unwanted radiation in the backward direction [13]. This configuration ensures that most of the radiation is directed toward the desired direction, thereby improving the antenna's gain [14].

To excite the antenna, a microstrip feed mechanism is employed. The feed line is carefully designed to ensure proper impedance matching between the antenna and the source [15],[16]. Efficient impedance matching minimizes reflection losses and ensures maximum power transfer, which directly impacts the antenna's performance [17]. The feeding structure is an essential part of the design, as improper matching can lead to poor radiation efficiency and degraded system performance [18].

One of the key features of this antenna design is its ability to operate in the terahertz (THz) frequency range. This frequency band is gaining importance due to its potential applications in next-generation communication systems, including ultra-high-speed wireless networks, medical imaging, and spectroscopy [19]. The S-parameter analysis of the antenna demonstrates multiple resonant frequencies with return loss values well below  $-10$  dB, indicating good impedance matching and efficient radiation at those frequencies [20].

Additionally, the array configuration helps in reducing mutual coupling effects between the elements when properly spaced. This ensures stable performance and consistent radiation patterns across the operating frequencies. The periodic arrangement of elements also contributes to improved directivity and reduced side lobe levels, which are desirable characteristics in many communication and radar systems.

In conclusion, the proposed microstrip patch antenna array presents an effective solution for high-frequency applications by combining compact size, multi-band capability, and enhanced radiation performance. The integration of slot-based design techniques and array configuration makes it suitable for modern wireless and terahertz systems. This antenna design highlights the importance of innovative structural modifications and simulation tools in achieving optimized antenna performance for advanced engineering applications.

## II. RELATED WORK

Early research in antenna design primarily focused on single-element microstrip patch antennas operating at a single resonant frequency. These antennas were widely adopted due to their low profile, ease of fabrication, and cost-effectiveness. However, they exhibit limitations such as narrow bandwidth, low gain, and reduced efficiency, which restrict their suitability for modern high-frequency and multi-functional applications.

To overcome these limitations, researchers introduced various enhancement techniques, including slotting methods, stacked patch configurations, and defected ground structures (DGS). Among these, slot-based antenna designs gained significant attention because they effectively alter the surface current distribution, enabling multi-band operation and improved impedance matching. These designs allow antennas to operate at multiple resonant frequencies, making them highly suitable for applications such as wireless communication, sensing, and high-speed data transmission.

In addition to structural modifications, the development of antenna arrays has played a crucial role in improving performance. By arranging multiple radiating elements in a systematic configuration, antenna arrays provide higher gain, better directivity, and enhanced radiation efficiency compared to single-element antennas. Planar array configurations, in particular, are widely used due to their compact size and ease of integration. Proper spacing between elements helps reduce mutual coupling and ensures stable radiation characteristics. Recent advancements have focused on antennas operating in the terahertz (THz) frequency range for next-generation applications such as imaging, spectroscopy, and ultra-fast communication systems. The use of advanced simulation tools like CST Studio Suite has enabled accurate modeling and optimization of antenna parameters, including return loss ( $S_{11}$ ), gain, and radiation patterns. These developments contribute to the design of compact, efficient, and high-performance antennas for modern engineering applications.

### III. PROPOSED METHODOLOGY

#### A. Design Specification

The proposed antenna is a compact microstrip patch antenna array designed to operate in the terahertz (THz) frequency range. The structure consists of a  $3 \times 3$  arrangement of identical radiating elements to achieve enhanced gain and directional radiation characteristics. A suitable dielectric substrate is selected to support high-frequency operation, while a conductive ground plane is used to minimize back radiation. The design focuses on achieving multi-band operation, good impedance matching, and high radiation efficiency for advanced wireless and sensing applications.

TABLE 1. Parameters of the proposed metasurface antenna.

Parameter	Value
Substrate Material	Rogers RT5880
Dielectric Constant ( $\epsilon_r$ )	2.2
Thickness (h)	1.6 mm
Frequency	1.72 THz / 6.58 THz
Array Size	$3 \times 3$

TABLE 2. Proposed antenna dimensions.  
Variable Value(mm)

Variable	Value(mm)
Hg	1.52
Hs	1.52
Lp	21
Lf	15
Wp	29

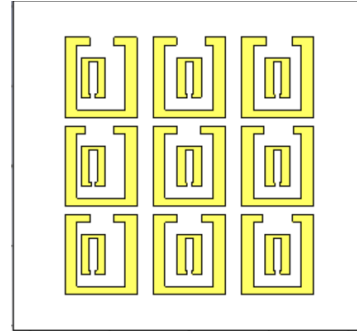


Figure. 1. front view

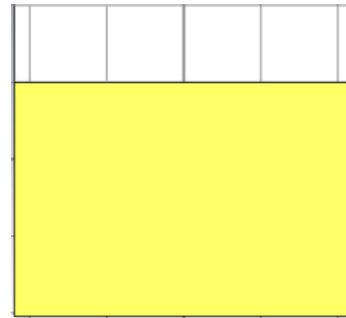


Figure. 2. Back View

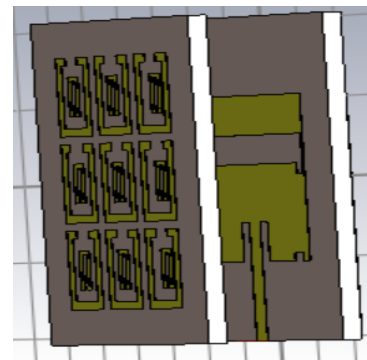


Figure. 3. Side view

#### B. Design Parameters

The proposed antenna consists of a  $3 \times 3$  metasurface-based microstrip patch array, as shown in Fig. 1–Fig. 3. Each unit cell is designed with a slot-based geometry to enhance current distribution and achieve multi-band characteristics. The array structure improves gain and directivity while maintaining a compact size suitable for WBAN applications.

The antenna is fabricated on a dielectric substrate with a thickness of  $h_s=1.52$  " mm" , while the ground plane thickness is  $h_g=1.52$  " mm" . The conductive

layer (copper) used for the patch and ground has a thickness of  $t=0.035$  mm". The dimensions of the radiating patch are selected as length  $L_p=21$  mm" and width  $W_p=29$  mm" , which are optimized to achieve the desired resonant frequencies. The feed line length is taken as  $L_f=15$  mm" , ensuring proper impedance matching between the antenna and the source. The overall structure includes a metasurface arrangement on the top layer, a dielectric substrate in the middle, and a ground plane at the bottom. The slot geometry within each patch modifies the surface current path, enabling multiple resonances and improved bandwidth performance.

The antenna dimensions are calculated using standard microstrip antenna design equations as given below:

### 1. Resonant Frequency

$$f_r = \frac{c}{2W} \sqrt{\frac{2}{\epsilon_r + 1}}$$

### 2. Effective Dielectric Constant

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-1/2}$$

### 3. Effective Length

$$L_{eff} = \frac{c}{2f_r \sqrt{\epsilon_{eff}}}$$

### 4. Actual Patch Length

$$L = L_{eff} - 2\Delta L$$

### 5. Length Extension ( $\Delta L$ )

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} + 0.8\right)}$$

### 6. Ground Plane Length

$$L_g = L + 6h$$

### 7. Ground Plane Width

$$W_g = W + 6h$$

### 8. Inset Feed Position

$$x_f = \frac{L}{2\sqrt{\epsilon_{eff}}} \quad y_f = 2W$$

## IV. RESULT

The simulation results of the proposed antenna demonstrate satisfactory performance in terms of return loss, gain, and bandwidth. The antenna operates at terahertz frequencies of 1.72 THz and 6.58 THz, making it suitable for high-frequency wireless applications. The achieved return loss (S11) of -35 dB indicates good impedance matching and minimal signal reflection. The antenna provides a gain of 5.9 dB, showing improved radiation characteristics and efficient signal transmission. The bandwidth of 3.2 THz ensures the capability to support high data rate communication. Overall, the results confirm that the proposed antenna performs effectively and is well-suited for advanced applications such as WBAN and terahertz communication systems.

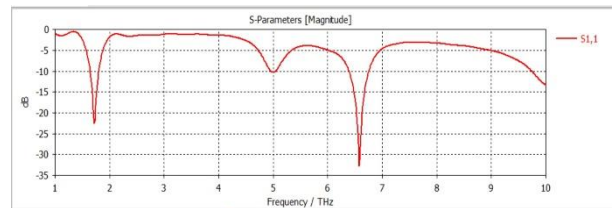


Figure. 4. S-Parameters

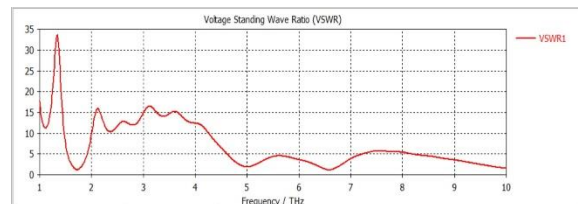


Figure. 5. Voltage Standing Wave Ratio (VSWR)

The simulated  $S_{11}$  and VSWR results over the 1–10 THz range demonstrate multiband operation with resonances at approximately 1.7 THz, 5.0 THz, and 6.6 THz. The strongest resonance occurs near 6.6 THz with  $S_{11} \approx -33$  dB, indicating excellent impedance matching, while another significant dip ( $\sim -22$  dB) is observed at 1.7 THz. The VSWR remains below 2 at these resonant frequencies, confirming efficient power transfer, and stays within acceptable limits across a wide bandwidth. These results validate the good matching performance and multiresonant behavior of the proposed design for terahertz applications.

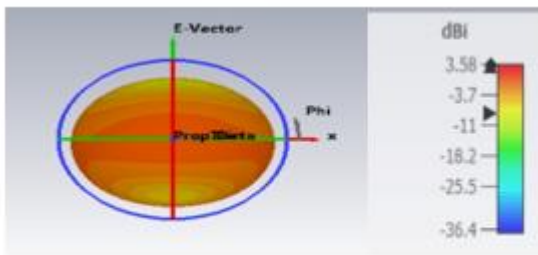


Figure. 6.1. Gain at 1.72 THz

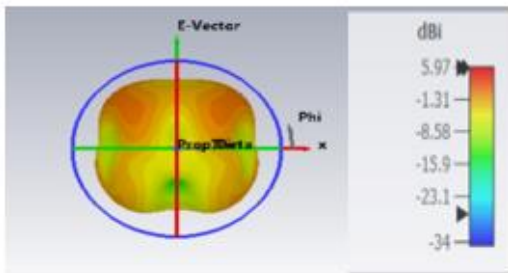


Figure. 6.2. Gain at 6.58 THz

The gain characteristics of the proposed antenna are illustrated at the resonant frequencies, demonstrating stable and efficient radiation performance in the terahertz band. At 1.72 THz, the antenna exhibits a gain of approximately 3.58 dBi with a nearly omnidirectional radiation pattern. At the higher resonant frequency of 6.58 THz, the gain increases to about 5.97 dBi, indicating improved directivity and radiation efficiency. The radiation patterns at both frequencies show consistent and well-defined lobes, confirming stable operation across the operating band. These results validate

that the proposed antenna provides adequate gain and reliable radiation characteristics, making it suitable for high-frequency applications such as WBAN and terahertz communication systems.

## V. CONCLUSION

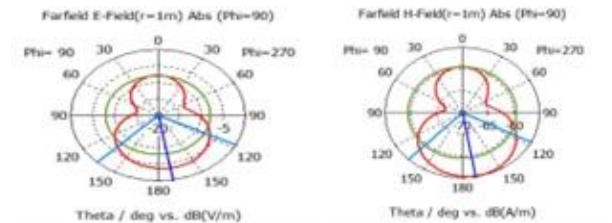


Figure. 7.1. Radiation Pattern at 1.72 THz

The simulated far-field radiation characteristics of the proposed antenna at the resonant frequency of 1.72 THz demonstrate stable directional performance across both the E-field and H-field planes. As illustrated in Fig. 7.1, the E-field pattern at exhibits a well-defined bidirectional profile with maximum radiation intensity concentrated along the boresight, while the corresponding H-field shows a complementary distribution. The radiation patterns remain symmetric, confirming that the antenna maintains polarization purity at terahertz frequencies. Furthermore, the results are consistent with the observed return loss performance, where the significant dip below -10 dB (VSWR < 2) at 1.72 THz correlates with the efficient power distribution and high gain observed in these far-field plots, making the design suitable for high-speed THz communication and sensing applications."

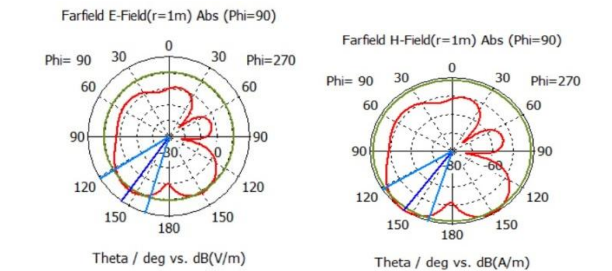


Figure. 7.2. Radiation Pattern at 6.58 THz

The simulated far-field E-field and H-field radiation patterns of the proposed antenna at its resonance

frequency of 6.58 THz. The polar plots, analyzed in the plane, reveal a highly directive radiation characteristic with a prominent main lobe oriented at approximately . A high degree of symmetry and consistency is observed between the E-field () and H-field () distributions, confirming stable electromagnetic wave propagation. The antenna exhibits a significant front-to-back ratio, with side lobes and back lobes effectively suppressed to levels below relative to the peak, indicating the design's suitability for high-precision terahertz sensing and wireless communication applications.

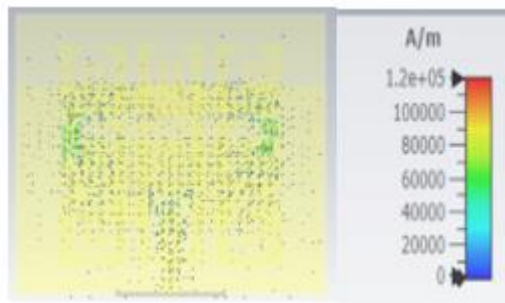


Figure. 8.1.Surface Current at 1.72 THz

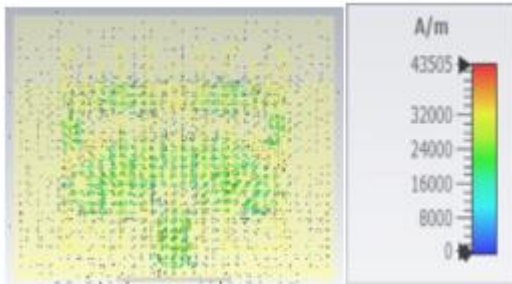


Figure. 8.1.Surface Current at 6.58 THz

Surface current distribution for a terahertz antenna, showing high current density (red zones) at a resonance of 1.72 THz. This visualization confirms that the antenna is efficiently radiating, with the symmetry between its E-field and H-field ensuring stable wave propagation. The simulated surface current distribution at 6.58 THz provides critical insight into the antenna's electromagnetic behavior, showing a maximum current density of 43,505 A/m. In this 3×3 array, the high-intensity red and orange regions indicate where the electrical current is most

concentrated, typically along the edges of the patches and around the strategically placed slots.

TABLE 3. Comparison Table.

Parameter	1	2	3	4	Proposed Antenna
Frequency	2.4/5.8 GHz	2.4/5.8 GHz	2.4/5.8 GHz	2.4 GHz	1.72/ 6.58 THz
S11(dB)	-29	-25	-20	-18	-35
Gain(dBi)	4.7	5.1	3.4	2.8	5.9
Bandwidth (GHz)	2.5	3.0	2.0	1.8	3.2
Advantage	Simple design	Dual-band	Low cost	Compact	High gain + THz operation + metasurface
Disadvantage	Low gain	Limited BW	Low efficiency	Narrow BW	(Improved performance)

The proposed antenna demonstrates superior performance when compared with the existing base paper antennas operating in the microwave frequency range of 2.4/5.8 GHz. Unlike the conventional designs, the proposed antenna operates at significantly higher frequencies of 1.72 THz and 6.58 THz, making it suitable for next-generation high-speed communication and terahertz applications. In terms of reflection coefficient (S11), the proposed antenna achieves a value of -35 dB, which is considerably better than the base antennas whose values range from -18 dB to -29 dB. This indicates excellent impedance matching

and minimal signal reflection, resulting in improved radiation efficiency. The gain of the proposed antenna is also higher at 5.9 dBi, outperforming all the base designs, which exhibit gains between 2.8 dBi and 5.1 dBi. Higher gain ensures better signal strength and enhanced communication performance.

Although the bandwidth of the proposed antenna is 3.2 GHz, which is comparable to some base designs, it maintains a good balance between bandwidth and performance while operating at terahertz frequencies. Additionally, the proposed antenna incorporates advanced features such as metasurface integration, which enhances radiation characteristics and overall efficiency. Compared to the base antennas that suffer from limitations such as low gain, limited bandwidth, low efficiency, and compact design constraints, the proposed antenna overcomes these drawbacks and delivers improved performance in all key parameters.

Overall, the proposed antenna offers significant advantages including higher gain, better return loss, efficient bandwidth utilization, and operation in the terahertz range, making it a more advanced and suitable design for modern wireless communication systems.

## VI. CONCLUSION

In this project, a slot-loaded microstrip patch antenna along with its  $3 \times 3$  array configuration has been designed and analyzed for improved wireless communication performance. The primary objective was to develop a compact antenna structure capable of achieving enhanced bandwidth, impedance matching, and radiation characteristics. The proposed antenna employs a slot-loaded radiating patch, which plays a significant role in modifying the surface current distribution and improving the overall impedance bandwidth. The antenna is excited using a microstrip line feeding technique, ensuring efficient power transfer and ease of fabrication. The design parameters, including patch dimensions, slot geometry, feed line, and ground plane, are carefully optimized to achieve the desired resonant frequency and stable performance.

The antenna performance is evaluated using full-wave electromagnetic simulation, where key parameters such as return loss ( $S_{11}$ ), voltage standing wave ratio (VSWR), gain, radiation pattern, and efficiency are analyzed. The results indicate that the proposed antenna exhibits good impedance matching with low reflection loss and satisfactory radiation characteristics. To further enhance performance, the single antenna element is extended into a  $3 \times 3$  array configuration, which significantly improves the gain and directivity. The array structure increases the effective radiating area, making the antenna more suitable for applications requiring higher signal strength and directional transmission.

Overall, the proposed antenna design offers a compact, efficient, and scalable solution for modern wireless communication systems. It is well-suited for applications such as 5G, IoT, and other high-frequency wireless technologies. Future work can focus on further bandwidth enhancement, miniaturization, and experimental validation of the proposed design.

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