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Design and Analysis of a Multi band Array Antenna on HR- Silicon for 6G and Beyond Wireless Communication

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Abstract
This paper presents the design and simulation of a silicon substrate-based patch antenna array for operation at the THz frequency band for future 6G wireless communication systems. A coaxial feed network is utilized for equal power division and phase alignment of the four radiating elements, which is extremely crucial for better directional performance. The Structure is simulated with ANSYS HFSS, a full-wave electromagnetic simulator for terahertz-frequency structures. Silicon substrate is utilized due to its integration with integrated circuit technology and capability to facilitate high-frequency miniaturization. Simulation studies indicate the antenna hold a maximum gain of 12.68 dB, along with suitable impedance matching and stable broadside radiation pattern. These characteristics make the suggested antenna array highly appropriate for short-range, ultra-high-speed wireless communications within 6G networks. The paper demonstrates the performance of microstrip-based THz antennas and gives an insight into feed structure optimization and material selection for high-frequency systems.

Keywords: *Microstrip patch antenna; High-Speed Data Transmission; 6G; far field; Coaxial Feed.*

1. Introduction

A Microstrip patch antennas have been under focus in the last two decades due to their numerous advantages such as low profile, light weight, ease of fabrication, planarity, and integrability with printed circuit board (PCB) technology and integrated circuits. All these attributes make them highly versatile for low-cost, compact, and interactable antenna applications [1], [2]. The need for high-frequency antennas, especially in the terahertz (THz) band, has increased dramatically with the emergence of sixth-generation (6G) wireless technology, which promises ultra-high data rates (up to 1 Tbps), ultra-low latency, and great reliability [3]. The THz frequency range, spanning from 0.1 THz to 10 THz, offers immense spectrum availability that remains largely untapped compared to microwave and millimetre-wave bands [4]. Specifically operating around 2 THz presents several advantages, including wide bandwidth, high resolution for imaging, and suitability for compact on-chip communication. However, challenges such as high path loss, material dispersion, and signal attenuation due to atmospheric absorption have limited the commercial deployment of 2 THz systems [5], [6]. Despite these challenges, 2 THz has emerged as a promising spectrum for applications such as ultra-fast intra/inter-chip wireless communications, terabit-per-second device-to-device communication, terahertz nano-networks, secure high-speed backhaul, biomedical sensing, spectroscopy, and high-resolution imaging [7], [8], [9]. Researchers are actively exploring high-performance antennas that can operate efficiently at this frequency. However, achieving high gain, low loss, and compactness simultaneously is still a research challenge, especially when targeting compatibility with integrated circuits.

The development of efficient microstrip antennas at THz frequencies demands careful selection of substrate materials and feed mechanisms. High-resistivity silicon (HR-Si) is particularly favorable due to its low dielectric loss, high thermal conductivity, and compatibility with CMOS processes [10], [11]. Coaxial feed networks are equally significant in THz antenna arrays, offering equal power distribution and low reflection loss across multiple radiating elements [12]. Recent works in THz microstrip antennas include the tri-band design, which uses a photonic bandgap (PBG) substrate to enhance isolation and bandwidth [13]. The authors [14] developed a graphene-integrated patch antenna tunable in the 1–1.8 THz band. The authors [15] fabricated a 2×2 THz patch antenna array on a CMOS-compatible silicon wafer, demonstrating on-chip integration potential. The authors [16] utilized a polyimide substrate to maintain compactness and efficiency, while authors [17] implemented a quartz-based patch antenna for biomedical sensing. Despite these advancements, there remains a research gap in achieving simultaneously high gain, high efficiency, and CMOS-compatible fabrication at exactly 2 THz frequencies. Moreover, the literature on coaxial feed networks tailored specifically for THz silicon-based antenna arrays remains sparse. This paper addresses these gaps by proposing a 2 × 2 microstrip patch antenna array using high-resistivity silicon as the substrate and a coaxial feeding network designed and simulated in ANSYS HFSS at 2 THz. The antenna achieves a peak gain of 12.68 dB, directivity of 12.63 dB, and total efficiency above 71%, demonstrating suitability for future 6G ultra-high-speed wireless communication systems. The proposed design combines high gain and efficiency while maintaining manufacturability and integration potential for on-chip wireless communication. A comprehensive comparative analysis is presented in Table 1, showing the trade-offs in substrate choice, gain, and feeding techniques across recent literature. Table 1 shows Comparative Analysis of THz Antennas

Table 1 Comparative Analysis of THz Antennas

Ref.	Freq (THz)	Substrate	Gain (dB)	Feed Type
[13]	1.5	Si+PBG	11.2	Coaxial
[14]	1.8	Graphene	9.8	M- Strip
[15]	1.9	Si	8.9	M- Strip
[16]	1.5	Polyimide	10.1	M- Strip
[17]	2.2	Quartz	9.2	Coplanar
Paper	2.0	HR-Si	12.68	Coaxial

2. Design Methodology

The design methodology for the proposed 2 × 2 silicon-based microstrip patch antenna array operating at 2 THz involves substrate selection, patch design, feed network layout, and full-wave simulation in ANSYS HFSS. The methodology is divided into the following steps:

2.1. Substrate and Material Selection

The choice of high-resistivity silicon ($\varepsilon r \approx 11.9$) as the substrate material offers low loss and high permittivity, making it suitable for miniaturized terahertz applications [1], [20]. Perfect Electric Conductor (PEC) is assumed for the patch and ground to minimize conductor loss, while vacuum and air are used for surrounding radiation boundaries and dielectric layers.

2.2. Patch Design

The patch dimensions are calculated to resonate at 2 THz using the transmission line model [1], [2]. The resonant frequency of a rectangular patch is given by (1) & (2).

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \tag{1}$$

Where:
h = Thickness
w = Width

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}} \tag{2}$$

Where:
f_r = Resonant frequency (2 THz)
C = Speed of light (≈ 3×10^8 m/s)
L = Patch length (43um)ε_r
ε_{eff} = Effective dielectric constant

2.3. Coaxial Feed Network

The coaxial feed network is structured using a T-junction layout to equally distribute power to all patches [21]. This feed network ensures minimal reflection and phase errors across the array elements. Impedance transformation using quarter- wave transformers is employed using (3).

$$z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(\frac{8h}{w}+\frac{w}{4h}\right) \tag{3}$$

Where:
ε_{eff} = Effective dielectric constant
z_0 = Impedance
w = width
h = Height

2.4. Simulation Setup in HFSS

The simulation is performed using the finite element

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method in ANSYS HFSS [21]. Key configurations are:

- Excitation: Wave Port
- Boundaries: Radiation box with Air
- Meshing: Adaptive with λ/10 step size
- Solver: Driven Modal for frequency-domain analysis

3. Procedure

To design a 2THz Array antenna using HFSS, the following steps are involved:

- **Step 1:** Selecting the correct geometry, here the geometry used are Cuboid, Rectangle, Cylinder & Circle.
- **Step 2:** The choice of substrate material and its thickness significantly impacts the antenna's performance. In this design, High Resonating Silicon substrate with a dielectric constant of 11.9 and a thickness of 1.6 um was employed.
- **Step 3:** The dimensions of the patch play a crucial role in determining the resonant frequency. In this specific design, the patch sheet of dimensions 185um*162um are set and later 4 different Patches of dimension 43um*54um is cut from the patch sheet.
- **Step 4:** To ensure optimal performance and minimize unwanted radiation, the ground plane with Dimensions 220*203*45um chosen for this Design.
- **Step 5:** Using Ansys HFSS software, creating model of the antenna array in fig 1. & by defining the substrate material and its thickness, patch dimensions, and ground plane dimensions.
- **Step 6:** **Once** the model is constructed, A wave port is Defined having Coaxial Feed as Feed line, shown in Fig.2 The Variables used in Design are in Table2. Figure 1 shows 2 ×2 Array Antenna Structure Figure 2 shows Coaxial Port for Feeding Point

Table 2 Variables used in Design

Variables	**Values**
$\boldsymbol{\varepsilon_0}$	8.85418781761e-12
feed	$\lambda/2$
f_{max}	4.5e12
f_{min}	0.5e12
$freq$	2e12
hsub	1.6e-6
ε_{eff}	11.9
Lp	43um
Wp	54um
Lsub	190um
Wsub	180um
Rport	1.62um

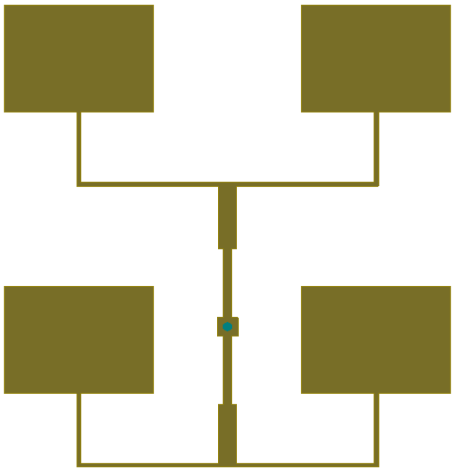

Figure 1 2 ×2 Array Antenna Structure

Table 3 Probe Dimensions

Parameter	**Radius Dimension(um)**
Inner	0.7
Outer	1.6

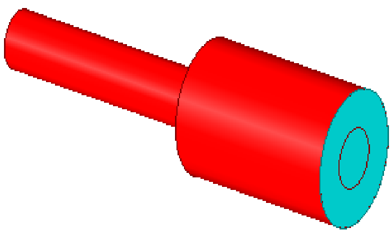

Figure 2 Coaxial Port for Feeding Point

4. Simulation Result

4.1. Gain

The gain obtained for 2x2 array antenna is 12.68dB as shown in Figure 3.

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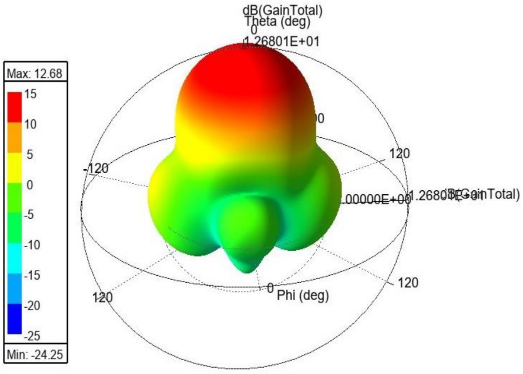

Figure 3 Total Gain Plot of Antenna

4.2. Realized Gain

The Realized gain obtained for 2x2 array antenna is 11.10 dB as shown in Figure 4.

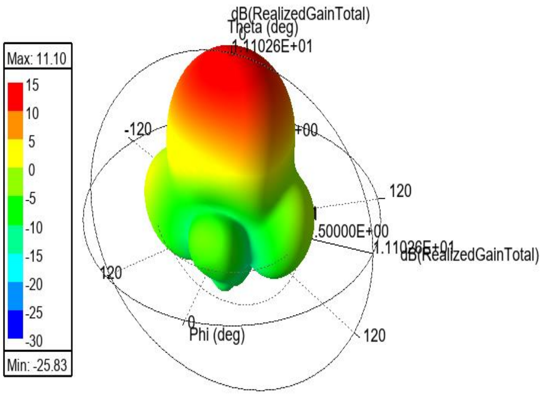

Figure 4 Realized Gain Plot of Antenna

4.3. Radiated Electric Field

The magnitude of the far-field electric field, radiated by the antenna in the observation direction (θ, φ), at 2THz frequency is shown in Figure 5.

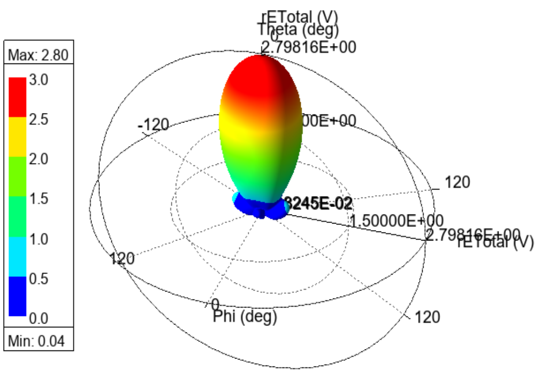

Figure 5 Radiated Electric Field Plot of Antenna

4.4. Directivity

The Directivity obtained for 2x2 array antenna is 12.63dB as shown in fig. 6.

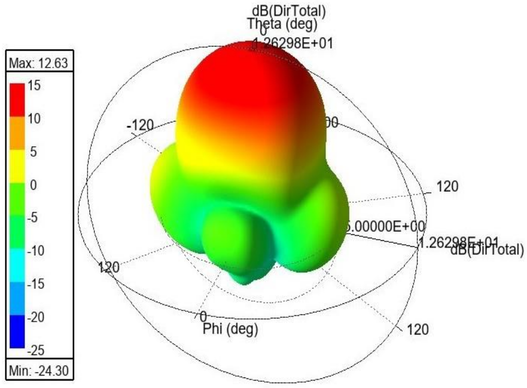

FIGURE 6. Directivity

4.5. Return Loss and Bandwidth Analysis

The proposed antenna design demonstrates strong multi-resonant behavior across the terahertz frequency range. These all are shown in Figure 7.

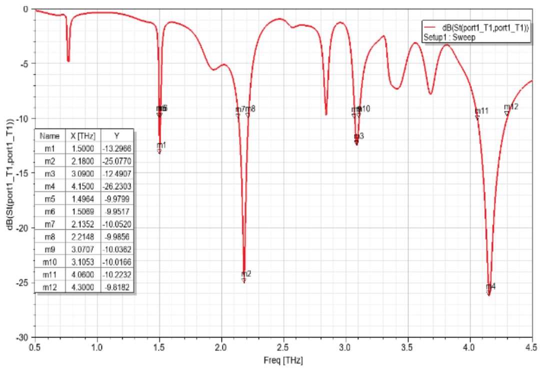

Figure 7 Terminal S Parameter Plot

5. Discussion

After carefully performing a parametric study of the S_{11} plot, it is observed that the designed antenna exhibits Four distinct resonances. At 1.50 THz, the antenna exhibits a return loss of –13.29 dB with a bandwidth of 10.2 GHz, indicating effective impedance matching. A deeper resonance occurs at 2.18 THz, where the return loss reaches –25.07 dB, accompanied by a wide bandwidth of 79.7 GHz. Another notable resonance is seen at 3.09 THz, where the return loss is –12.49 dB, and the bandwidth is

35.4 GHz. Lastly, at 4.15 THz, the return loss drops to –26.23 dB, with an exceptionally wide bandwidth of 230 GHz, which shows excellent power transfer, minimal reflection, and ultra-wideband behavior.

Conclusion

A 2×2 microstrip patch antenna array based on high-resistivity silicon substrate was designed and simulated for terahertz (THz) frequency applications, covering a wide frequency sweep from 0.5 THz to 4.5 THz with a central frequency of 2 THz. The antenna achieved a peak gain of 12.68 dB, directivity of 12.63 dB, and a realized gain of 11.10 dB, with four distinct bandwidths observed at 10.2 GHz, 79.7 GHz, 35.4 GHz, and 230 GHz, confirming strong multiband behaviour. The compact size and high-performance characteristics make the proposed design well-suited for advanced wireless applications such as 6G communication systems, satellite and inter-satellite links, terahertz imaging, high-speed short-range chip-to-chip data transmission, non-invasive medical diagnostics, security scanning, and IoT-based smart environments. Future work will focus on extending the design to larger MIMO configurations, integrating reconfigurable materials such as graphene and meta surfaces for dynamic beam control, and developing full-system integration with THz photonic or electronic front-ends for practical implementation in next-generation communication and sensing platforms.

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