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Design and Analysis of a Compact Wideband Antenna for Modern Wireless Communication System

Dheeraj Pandey(1), Banoth Kavitha(2), and Surajit Kundu(2)
(1) Department of ECE, NIT Sikkim, Ravangla, India
(2) Department of ECE, NIT Jamshedpur, Adityapur, Jamshedpur, India

Abstract

This paper presents the design and analysis of a wideband antenna suitable for operation in the 3.23-6.5 GHz frequency range. The antenna is constructed on a low-cost FR4 substrate with dimensions of 30 mm×40 mm×0.8 mm, making it economical and compact. The antenna employs a coplanar waveguide feeding mechanism, simplifying the design and enhancing impedance matching. A maximum gain of 4.48dBi and a high radiation efficiency of 96.8% are achieved. The omnidirectional radiation pattern and flat group delay make it ideal for applications requiring uniform signal distribution in all directions, such as wireless communication systems, Wi-Fi, and IoT devices.

1. Introduction

Wideband antennas are essential in modern wireless communication for their ability to support multiple frequencies, enhance data rates, ensure future compatibility, enable compact designs and reduce costs, thereby driving the evolution of seamless and efficient connectivity solutions across diverse applications [1].
Numerous studies have been conducted in recent years to develop wideband or ultra-wideband antennas (UWB). A leaf-shaped UWB patch antenna designed for ground penetrating radar (GPR) applications was introduced in [2] and subsequently tested in sandy soil conditions. Another UWB antenna designed with a circular patch configuration, featuring a tapered ground and CPW feeding, was introduced in reference [3]. Ghouz et al. proposed both monopole and array antennas to achieve high-gain broadband characteristics suitable for Wi-Fi, LTE, and WiMAX applications [4]. Kumar proposed a cavity-cavity-backed substrate integrated waveguide (SIW) antenna incorporating an octa-star slot to achieve a frequency band spanning from 9.26 GHz to 11.02 GHz [5]. Biswas et al. proposed a wideband capsule antenna for wireless endoscopy, designed on a silicon substrate. The antenna utilizes a slot line and chamfered edges to achieve impedance matching [6]. In [7], a biconical broadband antenna featuring reactance loading with shorting pins and comprising three copper-clad substrates was introduced. This antenna is designed for indoor base station applications and operates within a frequency range of 1.66 GHz to 3.95 GHz. In [8], a wideband antenna utilizing three rectangular patches on a single substrate with coaxial feeding was proposed. Kapoor et al. employed the concept of a slotted partial ground plane to achieve a wide frequency band [9]. Wen et al. proposed a circularly polarized wideband antenna designed for transportation systems, operating within the 1.07 GHz to 1.85 GHz frequency band [10]. In [11], a quasi-microstrip antenna was utilized as the driven element, while parasitic patches were employed to enhance the antenna's bandwidth. Hall et al. utilized a Vivaldi antenna to achieve enhanced gain across the frequency range of 1-9 GHz [12]. Pandey et al. proposed a heart-shaped patch antenna for the UWB range by combining circular and elliptical rings [13].
Drawing upon a comprehensive review of diverse design methodologies and the imperative for an economical, space-efficient, and broad-spectrum antenna, this study introduces a CPW-fed compact wideband antenna. Section 2 delineates the iterative design process culminating in the optimized dimensions. Section 3 presents findings from simulations and fabricated prototypes, encompassing reflection coefficients, simulated gain, radiation efficiency, radiation patterns, group delay, and transfer function. Section 4 summarizes the conclusions drawn from the performance evaluation of the proposed antenna.

2. Antenna Design

To design an antenna covering specific frequency bands with optimal reflection coefficients, CST microwave studio is used for simulations and FR4 epoxy as the substrate material, with dimensions of 30mm×40mm×0.8mm. The first design stage aims to cover the 2.5-5GHz frequency band for which parameters r_1 and r_2 have been chosen according to equations 1 and 2 where λ_1 is the wavelength corresponding to 2.5GHz and f_2 is kept 5GHz, relative permittivity (εr) and substrate height (h in cm) are kept 4.4 and 0.08 for FR4 substrate. After setting up the simulation in CST with the specified material properties, the patch dimensions are optimized and the ground plane size is reduced to achieve the desired frequency band as shown in Figures 1(a) and (b). The first design resonates in the band of 2.56- 5.6GHz with a reflection coefficient (S_{11}) of -13dB.

$$r_1 \approx \frac{\lambda_1}{20} \tag{1}$$

$$r_2 \approx \frac{8.791}{f_2\sqrt{\varepsilon_r}} - \frac{h}{\sqrt{\varepsilon_r}} \tag{2}$$

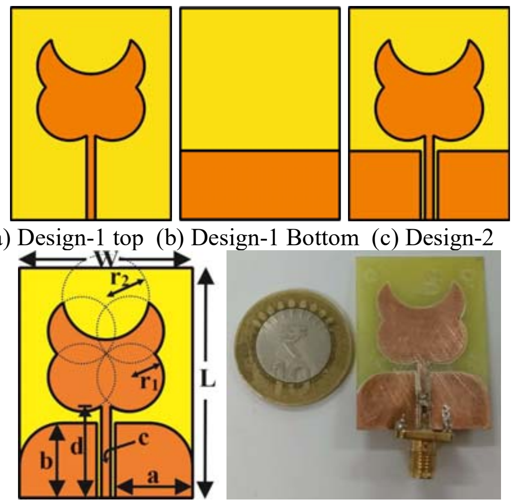
For the second stage, a Coplanar Waveguide (CPW) feed structure is used, which offers better impedance matching and enhanced bandwidth as shown in Figure 1(c). Retaining the patch dimensions from the first stage, the traditional feed was replaced with the CPW feed, ensuring the width and gap dimensions matched 50Ω. For the second design, the antenna resonates 3.3-6.36GHz with an S11 value of -25dB. Based on the approach used in [3] and [14] design equations 3-5 are formed to calculate the values of parameters a, b, c and d, where λ_3 is the wavelength corresponding to the frequency of 3GHz.

$$\frac{\lambda_3}{8} \leq a, b \leq \frac{\lambda_3}{7} \tag{3}$$

$$\frac{\lambda_3}{7} \leq d \leq \frac{\lambda_3}{6} \tag{4}$$

$$d + \frac{c}{2} \approx \frac{\lambda_3}{6} \tag{5}$$

In the final stage, by Maintaining the CPW feeding and patch dimensions of the same patch, ground plane edges are tapered at an angle of 7.5^0 as mentioned in Figure 1(d). This tapering helped in gradually transitioning the impedance, improving matching, and reducing reflections. That gives the frequency band of 3.23-6.6GHz with an S11 value of -37dB. Figure 2 represents the variation in the reflection coefficient in each design step.
After simulations, the antenna was fabricated using a precise CNC machine on a 0.8mm FR4 substrate as shown in Figure 1(e). A 50Ω SMA connector was attached, and reflection coefficients were measured using a Vector Network Analyzer (VNA) to validate the design. This systematic approach ensured the antenna met the desired performance criteria at each design stage. Table 1 represents the corresponding values of parameters used in Figure 1(d).



(a) Design-1 top (b) Design-1 Bottom (c) Design-2

(d) Final Design (e) Final Fabricated Antenna

Figure 1. Various design steps and final proposed antenna.

Table 1. Optimized Values of the Final Proposed Antenna

Parameter	Value (mm)	Parameter	Value (mm)
a	13.4	r_1	6
b	13	r_2	8
c	1.6	L	40
d	15.92	W	30

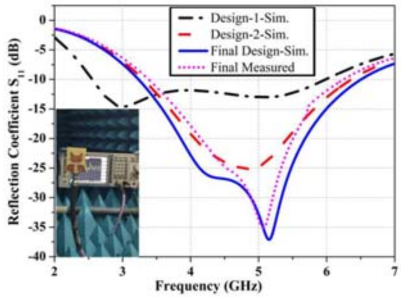
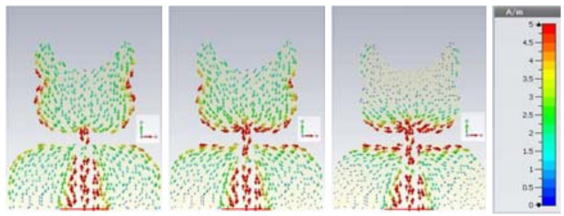


Figure 2. Reflection coefficient variation of the proposed antenna with each design step.

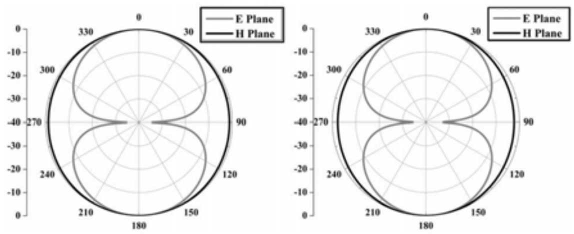
3. Results and Discussion

The reflection coefficient, as depicted in Figure 2, demonstrates excellent matching, with a simulated impedance bandwidth of 3.37 GHz (3.23-6.6 GHz) and a measured impedance bandwidth of 3.2 GHz (3.3-6.5 GHz). Figure 3 illustrates the surface current distribution of the proposed antenna. The current exhibits symmetric behaviour around the axis for all frequencies, with concentrations near the feed line and ground plane. Specifically, it is concentrated at the patch edges for 4 GHz and 5.15 GHz, while at 6 GHz, it is primarily concentrated at the lower part of the patch. Correspondingly, Figure 4 presents the radiation patterns, demonstrating omnidirectional characteristics across all frequency bands.

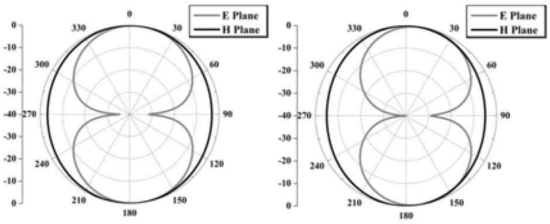


(a) 4GHz (b) 5.15GHz (c) 6GHz

Figure 3. Simulated Surface current distribution



(a) 3.5GHz (b) 4.5GHz



(c) 5.15GHz (d) 6.5GHz

Figure 4. E and H plane radiation pattern.

Figure 5 illustrates the gain and radiation efficiency versus frequency. The gain shows a steady increase from 2dBi to 4.48dBi as the frequency rises. Simultaneously, the radiation efficiency remains relatively stable, fluctuating slightly within the range of 94% to 96.8%. This consistent efficiency, coupled with the increasing gain, highlights the antenna's effective performance across the specified frequency range.

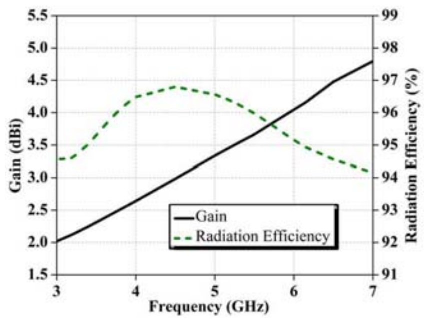


Figure 5. Gain and radiation efficiency v/s frequency.

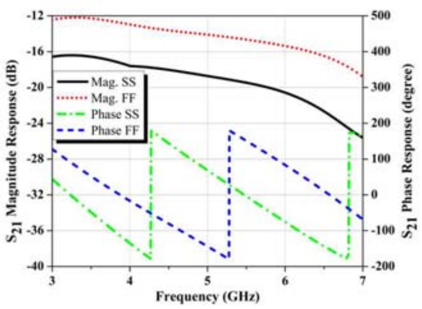


Figure 6. Magnitude and Phase response of antenna transfer function.

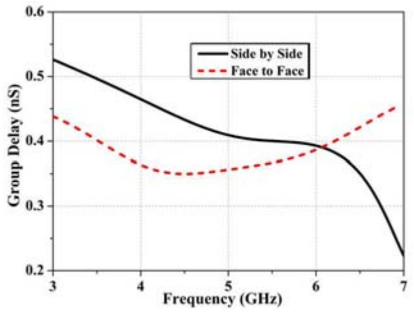


Figure 7. Group Delay of the proposed antenna.

Antennas are positioned side by side and in a face-to-face orientation to calculate the magnitude response and phase response of the transmission coefficient (S_{21}) and the group delay. The variation in the S_{21} magnitude is less than 10 dB, and a linear phase response is observed across the entire range, as illustrated in Figure 6. Furthermore, Figure 7 shows that the variation in group delay is less than 0.3 ns, indicating an approximately flat group delay. This minimal variation in both S_{21} magnitude and group delay signifies the stable and consistent performance of the antenna system, which is crucial for maintaining signal integrity and minimizing distortion across the frequency spectrum. These characteristics are essential for applications requiring precise phase alignment and consistent signal transmission, highlighting the effectiveness of the antenna design in maintaining high-performance standards.

4. Conclusion

This paper presents a wideband antenna design, built on a low-cost FR4 substrate with dimensions of 30 mm x 40 mm x 0.8 mm. Utilizing a CPW feeding mechanism, the antenna achieves a maximum gain of 4.48 dBi and a high radiation efficiency of 96.8%. The omnidirectional radiation pattern ensures uniform signal distribution, ideal for wireless communication systems, Wi-Fi, and IoT applications. Detailed simulations and measurements of group delay and transmission coefficient confirm the antenna's performance. The design strikes a balance between cost and performance, with its compact size facilitating easy integration into portable devices. This antenna offers a practical, cost-effective solution for modern communication needs.

6. Acknowledgements

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7. References

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