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Design of a Meandered Monopole Antenna for Dual-Band Applications

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ABSTRACT: This paper describes the design and analysis of a compact folded monopole antenna based on a Y-shaped meandered configuration, to operate within the 5 GHz to 6.5 GHz frequency range. The antenna has a compact size of $40 \times 30\,\mathrm{mm}^2$, and is fabricated on a low-cost FR4 epoxy substrate, making it suitable for easy integration into wireless systems. The main radiating configuration consists of a central vertical feedline connected symmetrically to meandered arms, forming a Y-shaped layout that enables a compact size without affecting radiation efficiency. The antenna is fed through a microstrip line, with the input signal equally distributed to both arms, each functioning as a quarter-wavelength monopole. The antenna demonstrates omnidirectional radiation patterns in both the E and H-planes and achieves a gain of 3 dB. To ensure human safety, we also performed a specific absorption rate (SAR) analysis using a human baby phantom model. The maximum SAR is 0.128 W/Kg at both frequencies, well below the acceptable 1.6 W/kg limit set by the ICNIRP guidelines. The fabricated prototype was tested, and the measured results closely match simulations, validating the antenna's suitability for modern compact wireless applications.

1. INTRODUCTION

The advancement of wireless communication technologies such as Wireless local area networks (WLAN), 5G communication systems, and the Internet of Things (IoT) has driven an increasing demand for antennas that are compact, cost-effective, and capable of functioning across multiple bands. To support these applications, antennas must exhibit dual-band performance, omnidirectional radiation characteristics, and the ability to be embedded in small devices without compromising performance among various antenna types. Monopole antennas have gained wide acceptance due to their simple configuration, broad bandwidth, easy fabrication, and easy incorporation into printed circuit boards (PCBs). Despite these advantages, achieving multiband functionality in a compact monopole design remains challenging to enhance bandwidth and introduce multiple resonant frequencies. Multiple design methodologies have been used, including meandered and folded structures, slot integration, and partial ground planes. Numerous compact printed monopole antennas have been documented in the literature for use in wireless applications. A Y-shaped monopole antenna integrated with a metasurface was proposed in [1] to support improved gain and polarization but introduced structural complexity due to additional parasitic elements. A circular metasurface compact dual-band monopole for sub-6 GHz and IoT applications was developed in [2], using an inverted C-shaped feed and partial ground. However, the feeding structure was sensitive to variations in manufacturing. Similarly, [3] presented a dual-square monopole antenna developed for radar satellite communication systems, using ground slots to enhance performance, at the expense of increased geometric complexity. In another study [4], a rose-shaped slot structure was employed to enable dual-band functionality, but it resulted in a relatively large and intricate structure. Although these methods have been proven effective in achieving multiband performance, they often involve increased structural complexity and require accurate fabrication and optimization. A low-cost meander-line antenna operating at 450 MHz is shown in [5]. A fully planar and ultra-compact dual-band implantable antenna was proposed for biomedical applications [6, 7]. A sea pimp-shaped dual-band monopole antenna was developed using reflector and slot modification techniques [9]. A dual-band planar monopole antenna has been developed for off-body communications, using via-free metasurfaces [10]. Interdigitated capacitor-loaded metasurfaces demonstrated significant miniaturization and impedance bandwidth enhancement for modern wireless systems [11]. A meandered radiating structure, an inverted G-shape component, and a defected ground plane to operate in three different bands are discussed in [12]. Many comparable structures face challenges related to complex design processes and increased size, or multilayer fabrication requirements, limiting their applicability in compact and low-cost wireless systems.

This paper presents a compact folded meandered Y-shaped monopole antenna designed to support dual-band operation at approximately 5 GHz and 6.5 GHz. The antenna is realized on a single-layer FR4 substrate. It demonstrates return loss below -10 dB in both frequency bands, an omnidirectional radiation pattern, and a gain of approximately 3 dB, confirmed through simulation and experimental measurements. This design is fabrication-friendly, cost-effective, and well-suited for incorporation into space-constrained wireless systems.

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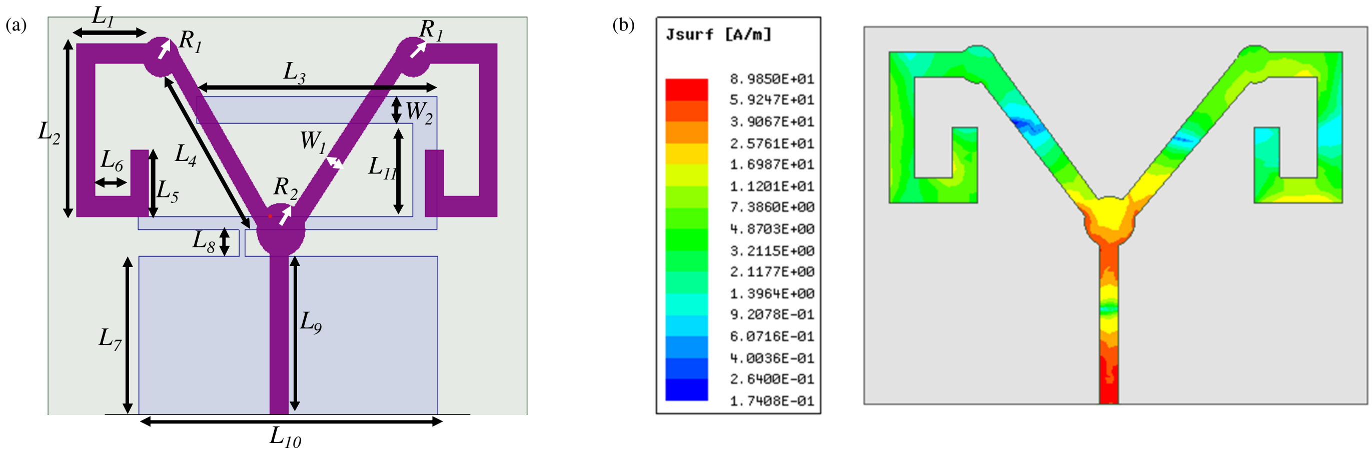

FIGURE 1. (a) Geometry of the proposed Y-shaped monopole antenna and (b) geometry of the proposed Y-shaped monopole antenna.

2. ANTENNA DESIGN

2.1. Geometry and Configuration

Figure 1 shows the configuration of the proposed compact meandered monopole antenna based on a Y-shaped configuration, inspired by [1], operating in dual frequency bands of 5 GHz and 6.5 GHz. The antenna is printed on a low-cost FR4 epoxy substrate with dimensions $40 \times 30\,\text{mm}^2$. FR4 epoxy was selected because it is low cost, easily available, and suitable for practical antenna fabrication. The antenna comprises a feedline to the center vertical arm and is symmetrically connected with the meandered arm, forming a Y-shaped meandered design pattern. The proposed geometry allows for achieving desired operating bands with a simple planar structure, without additional parasitic elements, slots, or multilayer configurations, in contrast with conventional meandered monopoles, thus reducing fabrication complexity while providing good impedance matching and radiation performance.

2.2. Feed Mechanism and Current Distribution

The microstrip line excites the antenna, which is connected at the bottom of the Y-shaped radiating structure. The two symmetrical arms get equal power from this line. Because of the symmetrical structure and balanced current, a stable radiation pattern and reliable performance are obtained across the proposed frequency band.

2.3. Meandered Structure

The radiating elements comprise a single loop meander line, which increases the effective electrical path, allowing the antenna to operate at lower frequencies while keeping a smaller physical size. A slot introduced at the junction divides the current into two distinct paths: a longer path supporting lower-frequency resonance and a shorter one enabling higher-frequency operation. This dual-path current distribution enhances impedance bandwidth, supporting broadband performance. Dimensions of the proposed antenna are listed in Table 1.

TABLE 1. Dimensions of the proposed antenna.

Parameter	Value (mm)	Parameter	Value (mm)
L_1	5.8	$L_1$0	24.9
L2	12	$L_1$1	9
L_3	10	$L_1$2	30
L_2	14	$L_1$3	40
L_5	6	W_1	2
L_6	3	W_2	2
L_7	1_2	R_1	1.5
L_8	2	R_1	1.5
L_9	12.6	R_2	3

The resonant frequency of the proposed antenna is mainly determined by the effective electrical length of the feed line and Y-shaped radiating arms. The surface current distribution shown in Fig. 1(b) displays that the current is concentrated near the feed and lower portions of the slanted arms, while the outer meandered sections mainly contribute to capacitive loading and impedance matching. Thus, it is inferred that increasing the lengths of the main radiating arms shifts the resonant frequency to lower bands, whereas decreasing these lengths shifts it to higher bands.

2.4. Parametric Analysis

The electromagnetic (EM) simulation tool ANSYS HFSS is used to study the influence of various geometric parameters on the dual-band behaviour of the proposed folded meandered Y-shaped monopole antenna. The study aimed to optimize three key parameters, namely, the width of the ground plane strip (W_2), the radius of the centre circle (R_2), and the length of the two radiating arms (L_2). The antenna's performance was evaluated based on its return loss characteristics. The strip width (W_2) played a crucial role in determining impedance matching at both resonant frequencies. Increasing W_2 led to better impedance matching and thus better return loss in the lower-frequency range. The optimal value for strip width was identified as 2 mm, which ensured proper matching at both 5 GHz and

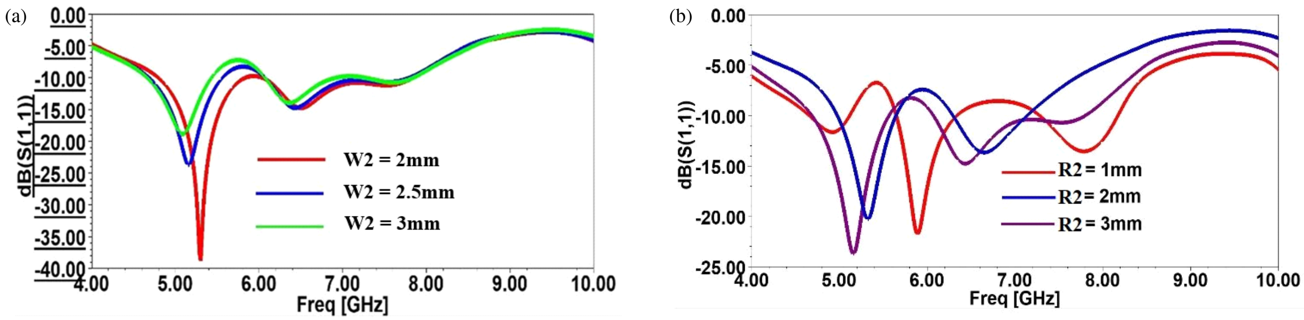

FIGURE 2. Parametric analysis results for dimension. (a) W_2, (b) R_2, and (c) L_2.

6.5 GHz. Modifying the circular junction radius (R_2) helped optimize current distribution. Increasing the radius shifted the resonance to lower frequency ranges, and decreasing it shifted the frequency to higher ranges. Thus, a value of 3 mm provides the required results. The folded arm length (L_2) influenced the antenna's effective electrical length and primarily affected the lower resonance. As L_2 increased, the lower resonance shifted to a lower frequency. A length of 14 mm gave the most favourable result, producing well-separated resonant bands with strong return loss characteristics. These results are presented in Fig. 2. The final design was chosen by balancing physical compactness, bandwidth performance, and impedance matching.

3. SIMULATION RESULTS

3.1. Return Loss Characteristics

Figure 3 shows the simulated return loss characteristics of the designed antenna, emphasizing its dual-band performance. Analysis shows two distinct resonance modes at 5 GHz with a return loss of -20.95 dB and at 6.5 GHz with a return loss of -14 dB. These results confirm that the antenna offers a broad impedance bandwidth, making it a strong choice for sub-6 GHz applications, including WLAN, 5G, and Industrial, Scientific, and Medical (ISM) bands. The lower-frequency resonance is due to the extended current path formed by folded meandered Y-arms. The higher-frequency resonance results from a shorter current path introduced by the slot near the feed point. Both frequency bands demonstrate good impedance matching, with return losses below -10 dB, indicating efficient performance.

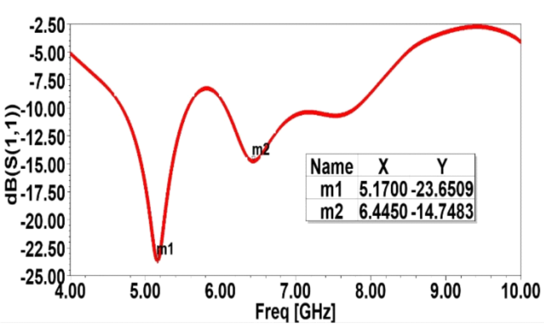

FIGURE 3. Simulated return loss chracteristics of the proposed antenna.

4. FABRICATION AND MEASUREMENT

To verify simulated performance, the proposed folded, meandered Y-shaped monopole antenna was fabricated on an FR4 substrate using conventional single-layer printed circuit board (PCB) etching. The substrate possesses a dielectric constant of 4.4, a loss tangent of 0.02, and a thickness of 1.6 mm. A 50 Ω SMA connector was soldered at the feed point to allow radio frequency (RF) signal input during measurements. Fig. 4 shows the fabricated antenna prototype. The top view shows the folded Y-shaped radiating element along with the feedline, while the bottom view shows the partial ground plane. The fabricated antenna closely follows the optimized dimensions provided in Table 1, ensuring accuracy between the design and fabrication.

The antenna's reflection coefficient was measured with a Vector Network Analyzer (VNA), as shown in Fig. 5. Before testing, standard SOLT (Short-Open-Load-Through) calibration was performed, and the measurements were conducted over the frequency range 3 to 10 GHz.

As shown in Fig. 6, the measured return loss response shows two distinct resonant frequencie, 5.1 GHz with a return loss of -22.7 dB and 6.5 GHz with a return loss of -17.2 dB. These measurements confirm that the fabricated antenna operates in dual bands and show good agreement with simulated results at 5 GHz and 6.5 GHz. Both frequency bands demonstrate return losses well below -10 dB, confirming effective impedance matching and reliability of the antenna design.

5. DISCUSSION

The designed folded meandered Y-shaped monopole antenna exhibits reliable dual-band functionality, as verified through both simulated and measured results. The return loss remained below -10 dB, confirming good impedance matching and efficient radiation characteristics. The antennas' dual-band performance is primarily attributed to its folded meandered arms and the inclusion of a slot at the feed-arm junction. The meandered design extends the electrical path, making it resonant at the lower frequency without increasing the antennas' physical size. Meanwhile, the slot modifies the current flow, introducing an additional resonant mode at a higher frequency. The measured co-polarization and cross-polarization radiation characteristics are shown in Fig. 7(a). The radiation patterns exhibit an approximately omnidirectional behavior in the H-plane at both

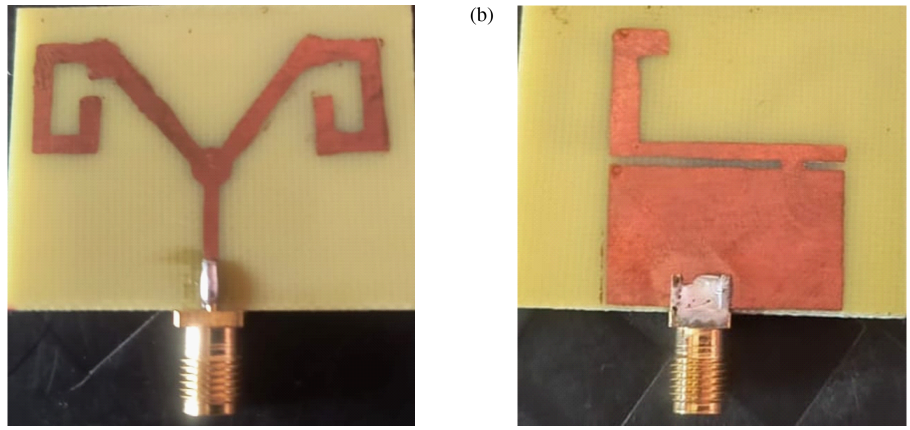

FIGURE 4. Fabricated antenna prototype: Top view with Y-shaped meandered radiator. Bottom view with partial ground.

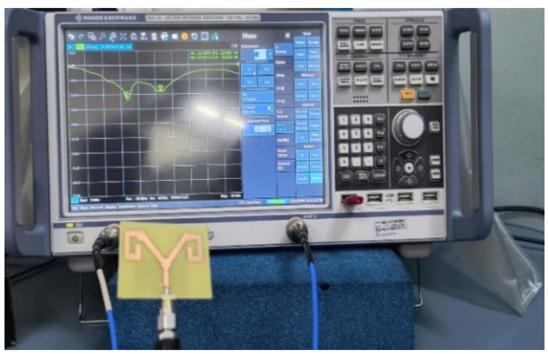

FIGURE 5. Measurement setup with VNA and fabricated antenna under test.

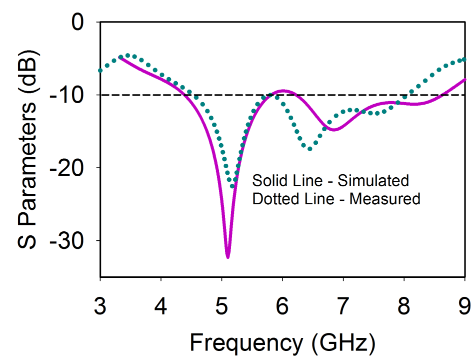

FIGURE 6. Simulated and measured return loss characteristics of the proposed antenna.

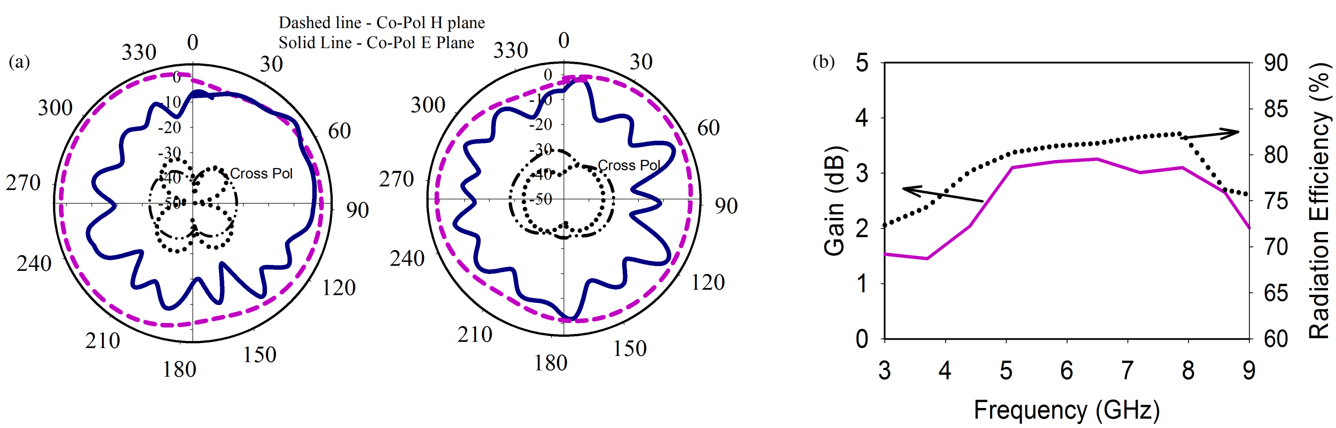

FIGURE 7. (a) Measured E plane and H plane (co-pol and cross-pol) pattern, at (i) 5 GHz and (ii) 6.5 GHz. (b) Simulated gain and radiation efficiency Vs frequency of the proposed antenna.

resonant frequencies, which is a characteristic of monopole antennas. The results also show that the co-polarized radiation is dominant, while the cross-polarization level remains significantly lower, confirming good radiation performance of the proposed antenna. Fig. 7(b) shows simulated gain and radiation efficiency plots with respect to frequency. The maximum gain is 3 dB, and the efficiency is 83% in the desired frequency range, making it suitable for sub-6 GHz applications such as WLAN and 5G. The strong correlation between simulation and measurement outcomes confirms the antennas' practical effectiveness.

5.1. Specific Absorption Rate Model

When designing antennas to operate near the human body, evaluating Specific Absorption Rate (SAR) is essential. Fig. 8

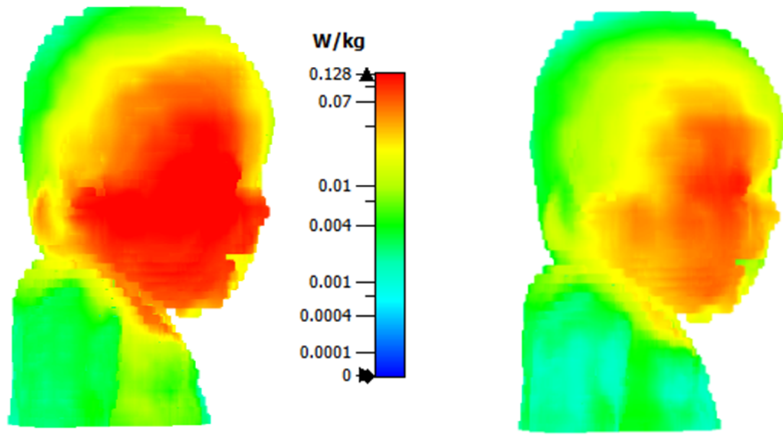

FIGURE 8. SAR distribution of antenna near human baby model at (a) 5 GHz and (b) 6.5 GHz.

presents the SAR distribution obtained using a human baby model. The antenna is placed at a distance of 10 mm from the phantom's ear, and the analysis was carried out by exciting the antenna with an input power of 1 W. A full-wave simulation was conducted to assess both the safety and exposure to electromagnetic fields generated by the antenna. The maximum SAR obtained is 0.128 W/Kg, which is much less than the standard 1.6 W/Kg as stated by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) guidelines.

6. CONCLUSION

This paper presents the design, optimization, fabrication, and testing of a compact, folded, meandered Y-shaped monopole antenna for dual-band operation in sub-6 GHz wireless systems. The antenna was implemented on an FR4 substrate. The prototype size is $40 \times 30\,\text{mm}^2$ and features a symmetrical Y-shaped radiator with meandered arms and a slot at the junction of the feed and radiating arms, enabling it to support two distinct resonant frequencies. Resonances at 5.1 GHz and 6.5 GHz are confirmed by simulated and experimental results. The proposed antennas show a nearly omnidirectional radiation pattern in the H plane, demonstrating their effectiveness for applications such as WLAN and sub-6 GHz.

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