

Compact Low SAR X-Ku Band Planar Inverted F Antenna for Wearable Application

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Abstract— A compact planar inverted-F antenna (PIFA) operating in the X-band is developed for wireless mobile applications. The antenna is mounted on an extended FR4 substrate mimicking the dimensions of a typical mobile phone and positioned on a realistic head phantom in a talk scenario to replicate actual usage conditions. Initial design optimization is performed in free space to determine the final dimensions, followed by additional tuning for enhanced compactness and performance. The full FR4 ($\epsilon_r=4.3$, $\tan \delta \approx 0.025$, and a thickness of 1.6 mm)-based antenna is then tested on the head phantom to assess potential detuning and performance degradation. Detailed parametric analysis, considering both the phantom and substrate, yields a compact PIFA with dimensions of 36 mm \times 24 mm \times 1.6 mm, offering wide bandwidth coverage across the entire X-band and part of the Ku-band (9.09–12.23 GHz), with $S_{11} < -11.98$ dB, a maximum gain of 6.19 dBi, and radiation efficiency between 50 and 65%. To ensure user safety, the specific absorption rate (SAR) is evaluated at the resonant frequencies and found to be within the limits set by the European Union Council and the Federal Communications Commission (FCC). Simulations are conducted using CST software based on the Finite Integration Technique (FIT).

Keywords— X-band, planar inverted F antenna (PIFA), Specific Absorption Rate (SAR), Wearable Body Area Network (WBAN), and Computer Simulation Technology (CST) software.

I. INTRODUCTION

Planar Inverted-F Antenna (PIFA) is popular for mobile communication due to its good characteristics in terms of low specific absorption rate (SAR), easy integration, lightweight, conformability, low cost, and ease of design [1]. Multiband PIFA has commonly proposed designs for lower-frequency applications such as ISM band, GPS, S-Band WiMAX, LTE, and Wi-Fi [2], [3], [4], [5]. It is also proposed for high-frequency applications such as radar and satellite communication systems the X-band (9–12 GHz) [6], [7], [8], [9] and Ku-band (12 – 18 GHz). To obtain the required performance for PIFA in certain applications, innovative techniques have been proposed in the literature to enhance bandwidth (BW), isolation (Multiple Input Multiple Output (MIMO)), reduce size, reduce SAR, and maintain good radiation performance.

A simple and low-cost X-band (10.5 GHz) inverted-F antenna (IFA) optimized in [10] for active RFID tags using a driven monopole and metal casing. Ojaroudi et al. (2014) proposed a compact quad-band PIFA that operates at WiMAX (3.5 GHz), WLAN (5.2 GHz), X-band (7.25–7.75 GHz), and ITU (8.02–8.4 GHz) frequencies. This design incorporates a hook-shaped slot and uniquely shaped slots in the ground plane, enabling multiband operation that covers satellite frequencies [2].

MIMO configurations are the best solution to improve data throughput, spectral efficiency, and link reliability without requiring additional spectrum or increased transmit power [11]. A 4 \times 1 MIMO X-band (10.16 GHz) PIFA array is proposed in [12] with high gain (12.87 dBi), excellent impedance matching, and high efficiency (91.9%), making it ideal for satellite and radar systems. In [13], a genetic algorithm-based approach is used to design a dual-band (2.52–3.71 GHz and 5.2–5.95 GHz) MIMO PIFA with high isolation and excellent MIMO metrics, making it suitable for a high-performance wireless system.

Numerous studies have addressed the challenge of achieving wide and multiple frequency bands. An octa-band (DCS 1800, UMTS, PCS, Wi-Bro, WiMAX, Wi-Fi (5 GHz), and WLAN (5.39–5.47 GHz and 7.03–7.93 GHz) PIFA is proposed in [4] using meandered lines and ground slots suitable for various wireless handsets. Similarly, Iyampalam and Ganesan (2019) proposed a triple-band (0.795 GHz, 2.050 GHz, and 3.405 GHz) IFA tailored for LTE handheld devices, demonstrating compactness and effective impedance matching across bands from 795 to 3405 MHz [3]. The work was extended in [5] to a penta-band IFA incorporating spiral-shaped resonators, offering independent tunability and strong miniaturization for targeting GPS, S-Band, Wi-MAX, 5G, and WLAN applications.

Additionally, the compactness techniques were studied to overcome physical constraints in portable devices. Minkowski pre-fractal geometry and defected ground plane are used in [14] to reduce (2.19–2.52 GHz) ISM band antenna size without compromising performance, achieving a stable radiation pattern and boresight gain. While in [6] a short-circuit wall at the electric field null improved the compactness and BW by 50% and 18.9%, respectively, of an X-band (8.34–10.09 GHz) microstrip patch PIFA

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antenna with an L-shaped feedline. The integration of a reactive impedance surface (RIS) into a quad PIFA enhances compactness, gain, and impedance matching in [15]. Frequency bands are achieved by incorporating rectangular slots in the radiating patch, supporting wireless applications at 2.4 GHz (WLAN), 4.2 GHz (C-band satellite downlink), 7.1 GHz (C-band satellite uplink), and 9 GHz (X-band). The PIFAs also offer reconfigurability, as demonstrated by a multi-state tunable X-band PIFA that has been developed using meandered lines and a metallic back cavity, enabling flexible control over resonant frequencies—an essential feature for dynamic environments [9].

The growing interest in wearable and conformal electronics has also led to the development of flexible PIFAs. A flexible multiband PIFA operating at 2.45 GHz, 5.8 GHz, and 8 GHz is proposed, featuring low SAR performance. The design employs a Kapton polyimide substrate and is intended for ISM, WLAN, and X-band applications. A slotted artificial magnetic conductor (AMC) structure is added to the proposed wearable PIFA to reduce the SAR by 43.3% at the wideband-code-division-multiple-access (WCDMA) band [16]. For 5 GHz wireless body area network (WBAN) applications, a compact PIFA is proposed based on a metasurface (MS) metamaterial [17]. To save time by avoiding the trial-and-error method, the design of experiment (DOE) method is used to optimize the design of a compact, 2.4 GHz PIFA with a conformal shape suitable for a prosthetic arm [18]. Suitable for smart garments, the size of the ISM PIFA antenna is reduced by modifying the patch geometry, using a felt substrate, and lateral feeding [19]. A compact 5G PIFA with dual-mode operation is designed by loading a pair of horizontal slots and using a high dielectric substrate [20].

This paper presents a compact wide-BW wearable PIFA designed for radar and satellite communication applications covering all the X-band and partially in the Ku-band. The antenna is positioned on a realistic head phantom in the talk position to simulate typical usage scenarios, and SAR analysis is conducted to ensure user safety.

II. DESIGN AND ANALYSIS OF COMPACT X-KU BAND PIFA

The conventional layout of the X-band PIFA antenna (Ant. 1) with width ($W = 29$ mm) and length ($L = 36$ mm) is shown in Fig. 1(a). To get a 50% size reduction, the patch is shortened to the ground via a shorting pin or sheet (width, W_s) at the position, S , with a distance, P , from the feeding point, F , and this allows a quarter wavelength resonance [21]. Ant. 1 achieves $S_{11} < -10.94$ dB at (9–10.46 GHz). As illustrated in Fig. 1(b), in Ant. 2, a stub with width (W_{st}), upper length (L_{stu}), and lower length (L_{stl}) improved the BW by 1.06 GHz ($S_{11} < -10.64$ dB at (9.03–11.55 GHz)). For the practical scenario, Ant.2 is mounted on a full FR4 ($\epsilon_r = 4.3$, $\tan \delta \approx 0.025$, and a thickness of 1.6 mm) substrate positioned on the head phantom as shown in Fig. 1(c) to evaluate potential detuning, performance degradation, and to determine the optimized dimensions. As illustrated in Fig.1(d), Ant. 3 ($S_{11} < -11.98$ dB at 9.09–12.23 GHz) improves the BW by 1.46 GHz and 0.62 GHz compared to Ant. 1 and Ant. 2, respectively. This continuous bandwidth covers the full X-band and extends into the lower Ku-band, providing wide frequency coverage suitable for radar and

satellite applications. It should be mentioned here that the simulated S_{11} (–11.98 dB) of Ant. 3 is slightly below the typical –10 dB threshold; however, this reduction is attributed to the presence of the head phantom, where the expected human tissue loading effect causes minor impedance matching degradation under realistic on-body conditions. The equivalent circuit of the proposed antenna is shown in Fig. 1(e).

Figure 2 presents the detailed parametric in terms of S_{11} and maximum gain (MG), where the optimized value is shown with a solid red line. The optimized design parameters that enable the proposed antenna to achieve an $S_{11} < -11.98$ dB within the 9.09–12.23 GHz range and a MG of 6.19 dBi are as follows: $W = 24$ mm, $L = 36$ mm, $L_1 = 15$ mm, $L_2 = 29$ mm, $W_{st} = 2.9$ mm, $L_{stl} = 6$ mm, $L_{stu} = 10.43$ mm, $W_1 = 3$ mm, $W_2 = W_3 = 7$ mm, $W_4 = 5.4$ mm, $P = 2.5$ mm, $F = 2.8$ mm and $W_s = 20$ mm.

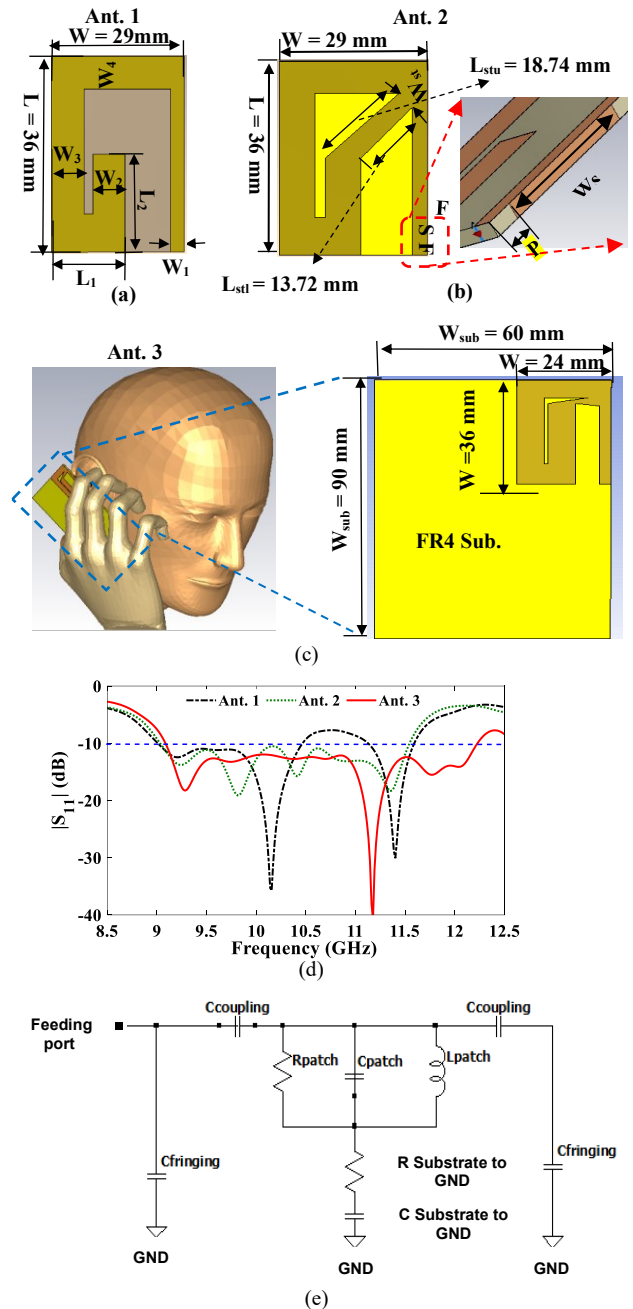


Fig.1. Design modification: (a) Ant. 1, (b) Ant. 2, (c) Ant. 3, (d) the simulated S_{11} , and (e) the equivalent circuit of the proposed X-band PIFA

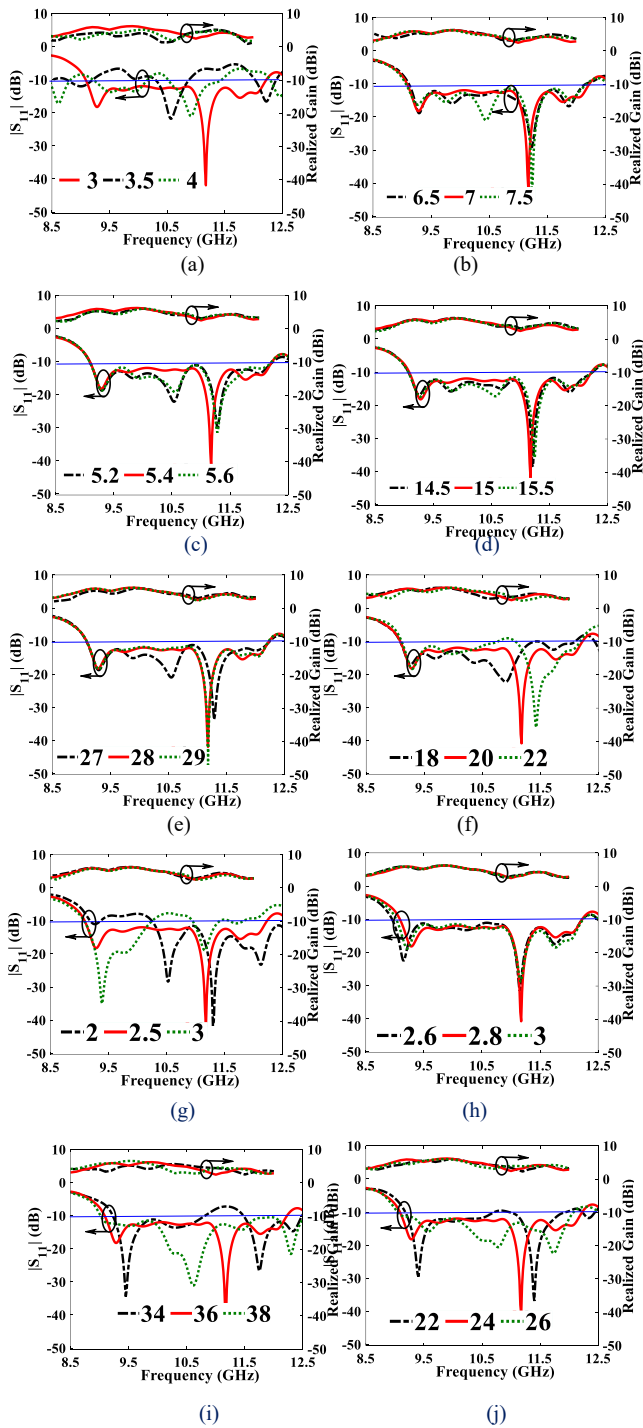


Fig. 2. Parametric study on (a) W_1 , (b) $W_2 = W_3$, (c) W_4 , (d) L_1 , (e) L_2 , (f) W_s , (g) P , (h) F , (i) L , and (j) W (Dimension in mm)

III. RESULTS AND DISCUSSION

Based on the optimum design values obtained in Section II, the antenna provides a good level of impedance matching through (9.09–12.23 GHz), with $S_{11} < -11.98$ dB, and matched input impedance, Z_{in} ($Z_{in}(\text{real}(\text{Re.})) \approx 50 \Omega$ and $Z_{in}(\text{imaginary}(\text{Img.})) \approx 0 \Omega$) as illustrated in Fig. 3(a) and (b) respectively. As can be shown in Figure 3(c), it also demonstrates a radiation efficiency that is satisfactory (between 50 and 65 %) and an MG of 6.19 dBi. This is mostly attributable to the high dielectric characteristics of the head phantom, which is the primary cause of the decreased efficiency.

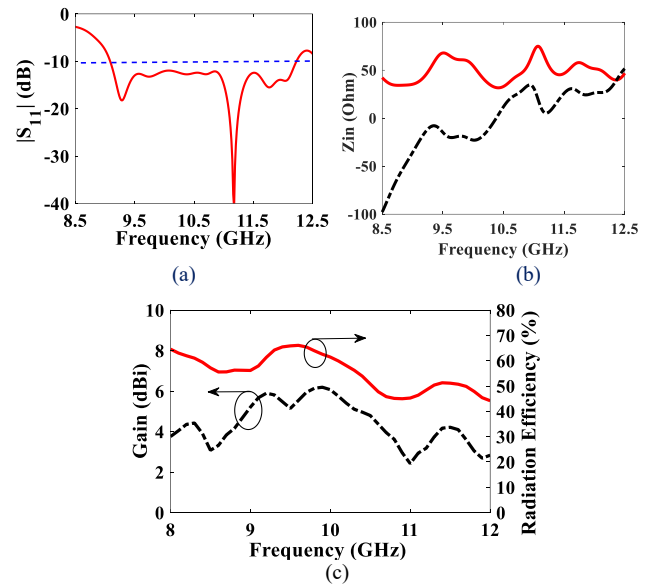
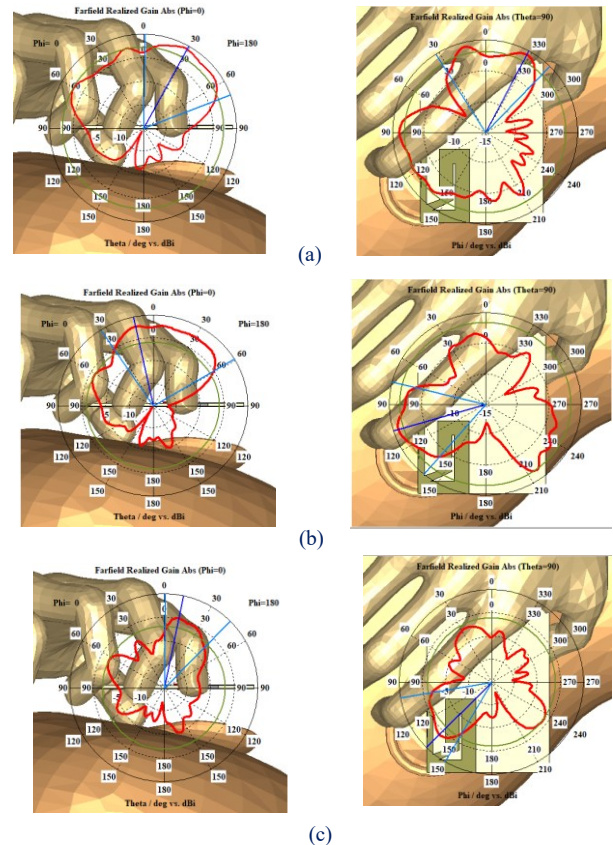


Fig. 3. (a) S_{11} , (b) Z_{in} , and (c) peak realized gain with radiation efficiency of the proposed antenna.

Figures 4(a)–(d) and 5(a)–(d) illustrate the 2D and 3D radiation patterns of the proposed PIFA at 9.5 GHz, 10 GHz, 10.5 GHz, and 11 GHz. The antenna maintains stable radiation characteristics across the entire extended X-band (9–12 GHz) and into the lower Ku-band. This radiation stability ensures reliable signal transmission and reception, which is essential for body-centric and wearable applications. Consistent performance across these frequencies enhances signal integrity in dynamic environments, making the PIFA antenna particularly suitable for transmitting data from wearable devices to mobile networks for continuous monitoring and analysis.



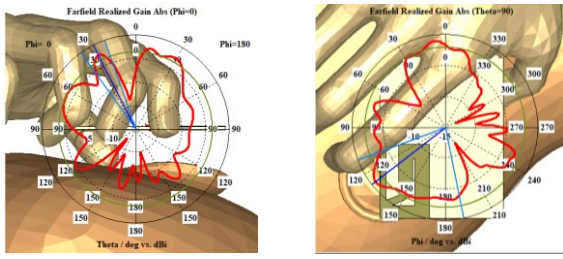


Fig. 4. 2D radiation patterns of the proposed antenna at (a) 9.5 GHz, (b) 10 GHz, (c) 10.5 GHz, and (d) 11 GHz.

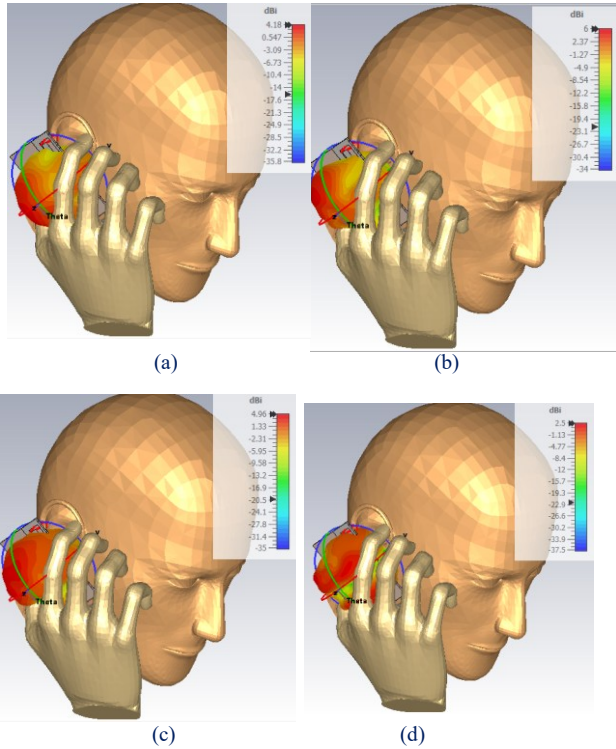


Fig. 5. 3D radiation patterns of the proposed antenna at (a) 9.5 GHz, (b) 10 GHz, (c) 10.5 GHz, and (d) 11 GHz.

The 3D specific absorption rate (SAR) distribution at 9 GHz, 9.5 GHz, and 10.5 GHz is calculated for an input power of 100 mW to guarantee no harmful effect on the human body (head with hand phantom) as shown in Fig. 6 and Table I. The values achieved are lower than the limits recommended by the Federal Communications Commission (FCC) and the Council of the European Union (EU). The FCC limit is 1.6 W/kg averaged over 1 g of tissue, while the EU limit is 2.0 W/kg averaged over 10 g [22].

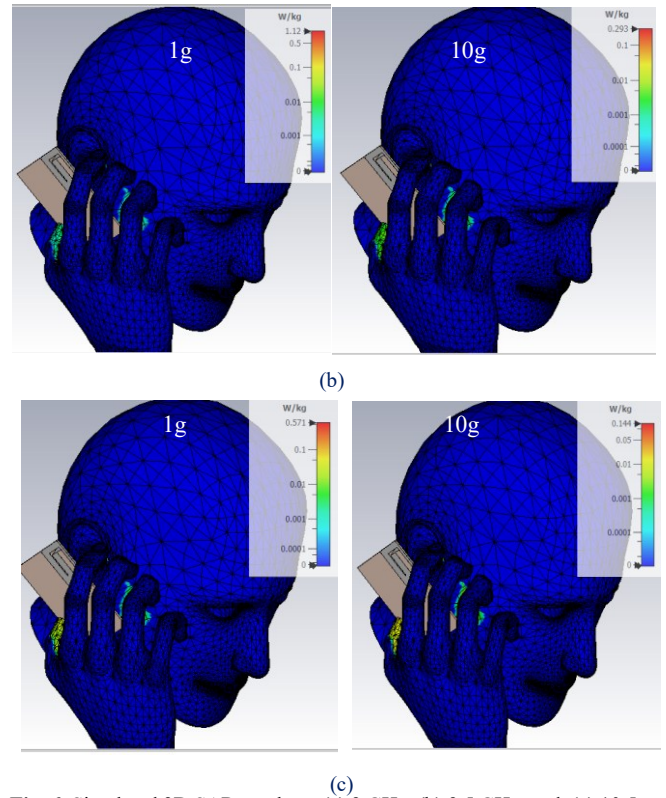
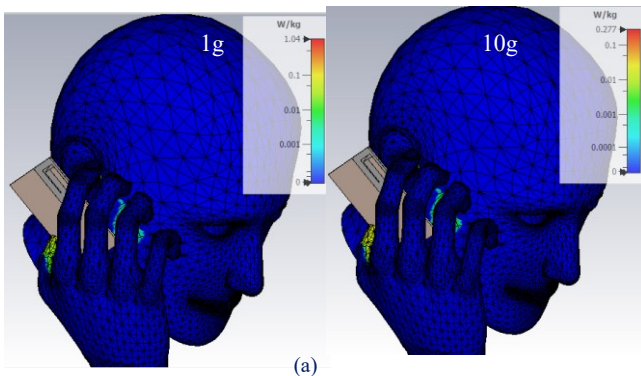


Fig. 6. Simulated 3D SAR results at (a) 9 GHz, (b) 9.5 GHz, and (c) 10.5 GHz.

TABLE I. 3D SAR RESULTS FOR THE PROPOSED ANTENNA ON THE HEAD PHANTOM

Frequency	1 g	10 g
9 GHz	1.04 W/kg	0.277 W/kg
9.5 GHz	1.12 W/kg	0.293 W/kg
10.5 GHz	0.571 W/kg	0.144 W/kg

These simulation results provide strong evidence of the antenna's suitability for realistic on-body mobile applications. However, experimental verification remains essential to confirm the simulated performance. Future work will therefore focus on fabricating the proposed PIFA prototype, carrying out measurements in both free-space and on-body scenarios, and integrating it with a complete mobile phone assembly for real-world performance evaluation. Such measurements will also enable further investigation into user-hand and device-housing effects, as well as extended SAR compliance testing under practical operating conditions.

Finally, compared to previous PIFA designs, our proposed antenna achieves a compact size ($36 \times 24 \times 1.6$ mm³) while operating across a wide X-band frequency range (9.09–12.23 GHz) with a peak gain of 6.19 dB. As illustrated in Table II, unlike earlier studies that either offer limited gain [2], [6], [15], narrow bands [6], [12], or bulky structures [8], [9], [12], our design delivers an optimized trade-off between miniaturization, bandwidth, and gain. The use of a single-layer FR4 substrate also ensures cost-effectiveness and ease of fabrication, setting it apart as a strong candidate for compact X-band wireless and radar systems.

TABLE II. COMPARISON TO X-BAND ANTENNAS IN THE LITERATURE

Ref.	Substrate	Size (mm ³)	Freq. Band (GHz)	MG(dBi)	Improvement Methods
[2]	FR4	24 × 3 × 1.6	3.5, 5.2, 7.25–7.75, 8.02–8.4	~2–3	hook-shaped slots in the ground
[12]	silicon	40 × 30 × 2.8 (single)	10.16	12.87	4×1 MIMO array
[6]	N/A	N/A	8.34–10.09	4.8	L-feed & short-circuit wall
[15]	FR4 dual layer	23.33 × 2.66 × 1	2.4, 4.2, 7.1, 9	~2.5	RIS with slots
[8]	Kapton polyimide	52 × 40 × 3	2.45, 5.8, 8	~3	CST based optimization
[9]	F4B220	50 × 50 × 3.35	7.86 - 12	6.5	meandered line & metallic back cavity
This work	FR4	36 × 24 × 1.6	9.09–12.23	6.19	CST based Optimization

I. CONCLUSION

A compact planar antenna (PIFA) designed for X-band wireless mobile applications has been successfully developed and validated through realistic simulations. Optimized initially in free space and later fine-tuned for on-body conditions, the antenna demonstrates stable performance when mounted on an extended FR4 substrate placed on a head phantom. With compact dimensions of 36 × 24 × 1.6 mm, it offers a wide impedance bandwidth from 9.09 GHz to 12.23 GHz, covering the full X-band and the lower part of the Ku-band. The antenna achieves a peak gain of 6.19 dBi and maintains acceptable radiation efficiency (50–65%). Importantly, SAR analysis confirms compliance with international safety standards, ensuring suitability for wearable and body-centric mobile applications. As a next step, fabrication and real-world measurements on the human body, including integration with a fully assembled mobile phone, will be undertaken to validate performance, assess practical usage scenarios, and guide any necessary design refinements.

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