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RESEARCH ARTICLE

A Compact Tri-band Slotted Planar Inverted-F Antenna Design for 5G and WLAN Mobile Handsets

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Abstract

This paper presents a compact, tri-band Planar Inverted-F Antenna (PIFA) for 5G sub-6 GHz mobile handsets. The proposed design integrates a slotted G-shaped radiating patch and a defected ground structure (DGS) to achieve multiband operation within a low-profile, four-layer printed structure. The antenna resonates at 2.4 GHz, 3.7 GHz, and 5.7 GHz, effectively covering the 5G NR bands n41 and n78, alongside LTE and WLAN applications. Simulation results demonstrate wide bandwidths of 770 MHz, 400 MHz, and 600 MHz at the respective resonant frequencies, with a peak realized gain of 4.4 dBi. The antenna exhibits high radiation efficiency, a low specific absorption rate (SAR), and an omnidirectional pattern. With its compact dimensions and performance metrics that surpass existing designs, the proposed antenna is a compelling solution for modern 5G-enabled mobile phones.

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Keywords: 5G Antenna; DGS; PIFA; Sub-6 GHz; Tri-band.

1. Introduction

In recent years, there has been an increasing demand for mobile handsets that deliver higher data rates with enhanced reliability. This encompasses superior video calls, streaming high-definition content, and engaging in HD online gaming [1]. Thus, there is a critical need for fifth generation (5G) networks to exceed the capabilities of their predecessors. In contrast, as wireless devices become smaller, there is a need for multiband and compact antennas to reduce the number of antennas required in a limited space, thereby making room for other device components. Consequently, the planar inverted-F antenna (PIFA) is the recommended choice for mobile handsets' radio communications due to its small size, inexpensive manufacturing cost, compact structure, improved radiation features, high gain, and lower specific absorption rate (SAR). This quarter-wavelength patch antenna offers several features related to a half-wavelength patch antenna but is 50% smaller, making it optimal for mobile devices [2, 3]. However, a narrow bandwidth is a common limitation of PIFA. Numerous studies have focused on optimizing antenna configurations, some with multi-band resonance and others capable of wideband operation, often resulting in a trade-off between reduced gain, bandwidth, or design complexity.

A wideband antenna has been developed for LTE and WWAN applications in [4]. The antenna features a low profile and can demonstrate dual-resonant modes. However, it contains specific limitations, including its larger size, reduced gain, and limited bandwidth. A trapezoidal slotted PIFA with a rectangular patch has been developed in [5]. Despite its outstanding results and compact size, this antenna has a restricted bandwidth and requires enhancement to achieve a minimum return loss. As mentioned in [6], the designed wideband antenna includes a rectangular plate at the feeding pin with two cut slots to control high-frequency bands and a shorting pin for low-frequency bands. Although the antenna consists of a broad bandwidth, there is potential to enhance its average efficiency. Moreover, a multi-band antenna selectively covers the required band spectra [7], overcoming interference caused by a wideband antenna that covers unwanted spectra [8]. As mentioned in [9-13], switching diodes have been integrated into antennas to achieve frequency-reconfigurable responses, enhancing connectivity, adaptability to various frequency bands, and improving performance. However, this integration may add complexity to the design, require additional components, and increase manufacturing costs. In [14], researchers designed a dual-band frequency-tunable PIFA for handheld devices by varying the capacitance of the varactor diode. Despite this achievement's success, the design is complex and large, with limitations in bandwidth and gain.

This paper presents a low-profile tri-band PIFA designed for 5G mobile handsets within the sub-6 GHz communications spectrum. The radiating patch uses a G-shaped slot, mounted over two substrates to produce lower-frequency bands. Furthermore, the ground plane is carefully designed to facilitate operation in the higher-frequency band. The optimized PIFA resonates in the 2.4 GHz band (2.25–3.02 GHz), 3.7 GHz band (3.6–4 GHz), and 5.7 GHz band (5.5–6.1 GHz) to cover 5G NR (n41, n78), LTE, and WLAN bands. The suggested PIFA has been designed and simulated using CST simulation software. To validate the antenna results, the HFSS simulation software has been employed in the suggested design, and the results have been compared. The results indicate that the proposed PIFA is suitable for handheld devices in 5G due to its small size and features of operating on three sub-6 GHz bands, which is considered an important characteristic to minimize the number of antennas used in wireless devices.

2. Design Method of Proposed PIFA

The proposed design, illustrated in Figure 1, consists of four distinct layers. Figure 1(a) shows the initial layer as a slotted, flipped G-shaped rectangular patch measuring 22 × 20 mm². The second layer comprises a low-cost FR4 substrate, characterized by a relative permittivity of 4.3 and a thickness of 0.8 mm. Figure 1(b) illustrates the subsequent layer, a vacuum layer consisting of an air gap with a dielectric constant of 1 and a height of 3 mm, which enhances bandwidth in the suggested design. The fourth and final layer is a ground plane shown in Figure 1(c) with dimensions of 39 × 20 mm². The feeding technique employed is coaxial feeding, which contributes to bandwidth optimization. Experiments have shown that the location of feeding significantly impacts overall antenna performance. Consequently, the feeding location has been optimized, as illustrated in Figure 1(c), to achieve the best results. Additionally, the multiple openings in the design enhance the vibration state, greatly increasing the amplitude of the electromagnetic waves. The overall dimensions of the proposed design are 39 × 20 × 3.8 mm³. Table 1 shows the dimensions of the proposed design.

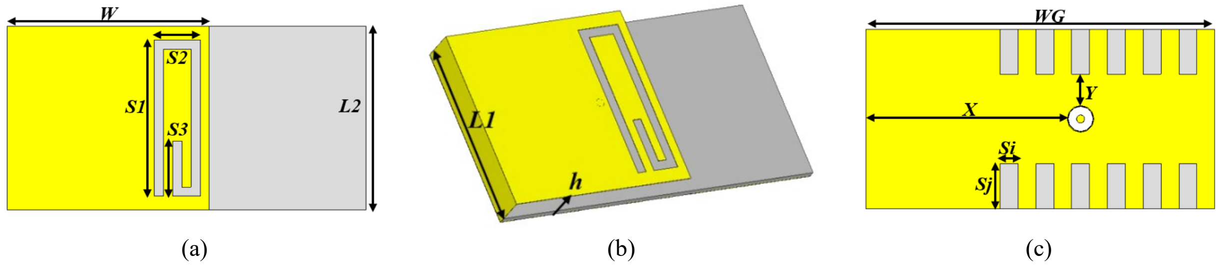


Fig. 1. Geometric shape of the proposed PIFA. (a) Front View, (b) Back View, (c) 3D View.

TABLE 1. Dimensions of the proposed PIFA design.

Parameters	Value (mm)
W	22
WG	39
L1	20
L2	20
X	22
Y	4
S1	17
S2	5
S3	6
Si	2
Sj	5
h	3.8

The following formula is applied in the suggested PIFA design, with resonating frequencies improved through the use of a slotted radiating patch and defected ground structure (DGS). Figure 1 exhibits the dimensions used in the formula [16]:

$$f_0 = \frac{c}{4(L2+W-L1-h)\sqrt{\varepsilon_r}} \tag{1}$$

Where c is the free-space speed of light, and εr is the dielectric constant of the substrate.

The shorting pin or plate plays a crucial role in reducing the size of the PIFA and can be calculated using the following formulas [2, 17]:

Case 1

If $L1=L2\,;\ W=\lambda/4$

Case 2

If $L1\approx 0\,;\ W+L2=\lambda/4$

The proposed antenna design is specifically intended for a frequency of 3.7 GHz. Considering this antenna is designed for mobile handsets, reducing the number of antennas is crucial to make room for other electronic components. Therefore, the design has been modified to enable tri-band resonance. To allow the antenna to resonate in dual-band mode, the radiating patch has been slotted with a flipped G-shape. This causes the antenna to resonate at 2.4 and 3.7 GHz, as shown in Figure 2. The ground structure has been divided into six small symmetrical rectangles, enabling the antenna to resonate in a tri-band mode and providing an omnidirectional radiation pattern. In addition, using a rectangular DGS optimizes the antenna bandwidth [18]. The shorting plate has been incorporated instead of the shorting pin between the radiating patch and ground plane to achieve maximum radiation efficiency while maintaining the desired resonant frequency.

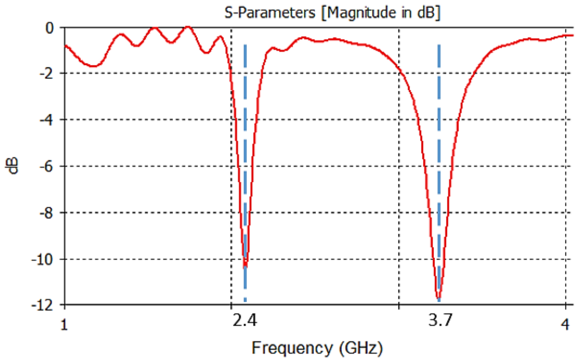


Fig. 2. Dual-band mode with slotted radiator.

3. Simulation Results and Analysis

This section presents and discusses the results of the suggested design, including return loss, VSWR, radiation pattern, SAR, and efficiency. The antenna under consideration exhibits resonance at frequencies of 2.4 GHz, 3.7 GHz, and 5.7 GHz, with corresponding impedance bandwidths of 779 MHz, 400 MHz, and 600 MHz. This configuration effectively covers the 5G NR bands n41 (2496–2690 MHz), n78 (3300–3800 MHz), and WLAN applications. Figure 3 compares the simulated antenna in CST and HFSS. The impedance bandwidth threshold is lower than -10 dB.

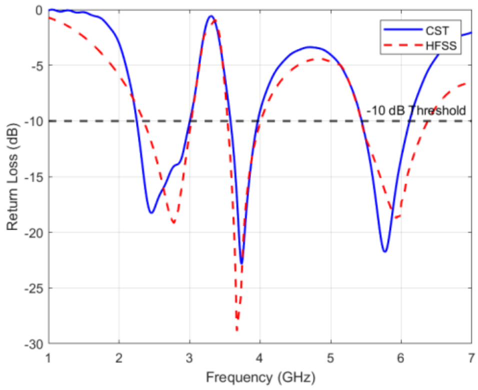


Fig. 3. The proposed tri-band PIFA return loss behavior versus frequency.

Figure 4 illustrates the impedance matching of the suggested antenna, as indicated by the VSWR at the resonance frequencies. In general, the antenna VSWR is 2:1, indicating that the transmitter directs the energy towards the antenna. The comparison ratio reveals an optimal match of less than two, while the frequency of 5.7 GHz yields approximate results.

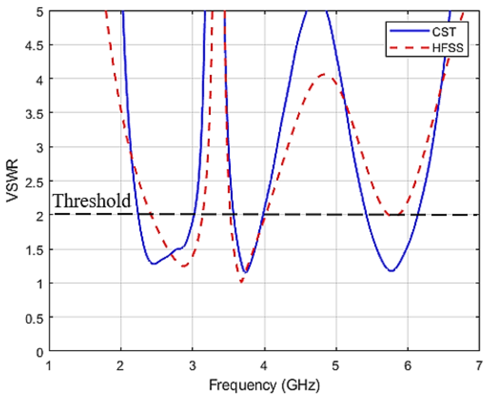
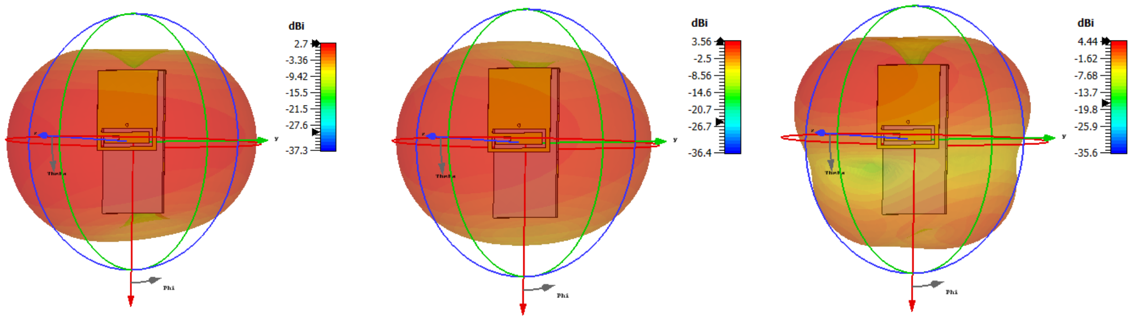


Fig. 4. VSWR as a function of frequency.

The proposed antenna radiates omnidirectionally at its resonant frequencies. Figure 5 presents a 3D radiation pattern exhibiting realized gains of 2.7 dB, 3.5 dB, and 4.4 dB, respectively. The gain increases with frequency. The reduced antenna size and the use of FR4 material decrease the antenna's gain. However, using different semiconductor materials can further affect the outputs [19].



(a) (b) (c)

Fig. 5. Realized gain in the 3D radiation pattern of the suggested tri-band PIFA.

As illustrated in Figure 6, the proposed antenna highlights the key parameters and their relationship, with the antenna efficiency measured by the following formula:

$$\eta = \frac{G}{D} \tag{2}$$

The suggested PIFA demonstrates a high efficiency of 98% at frequencies 2.4 GHz and 3.7 GHz, while at 5.7 GHz, the efficiency reaches 96%.

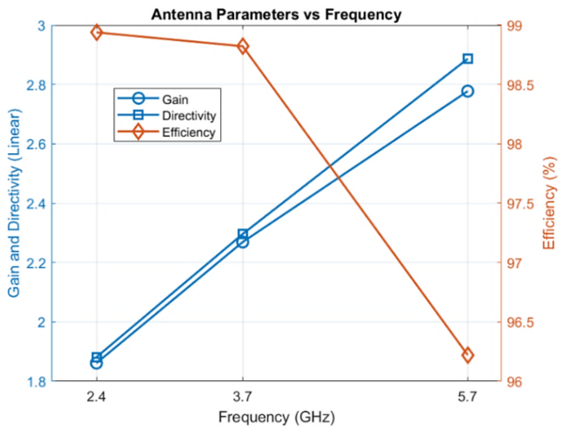
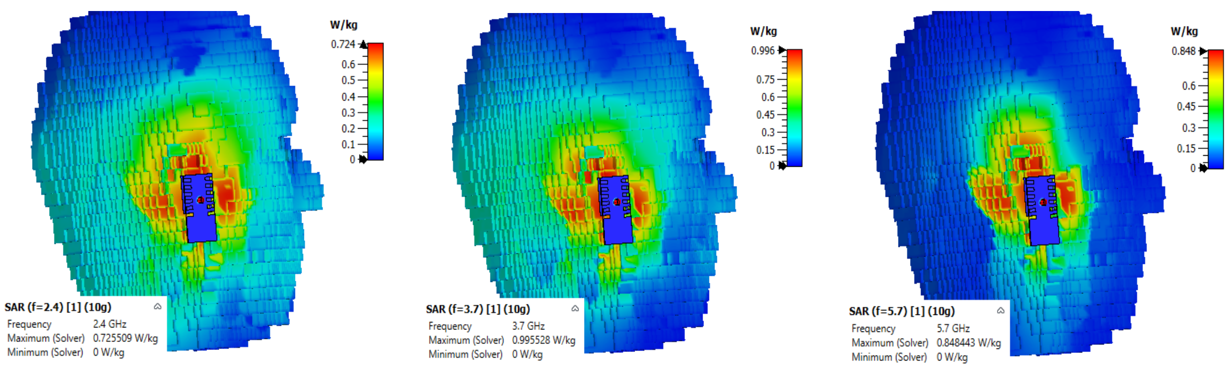


Fig. 6. Antenna parameters at operating frequencies.

This type of antenna is known for its low SAR on human tissues, lower head loss [20], and compact size. In Europe, the SAR limit for the head is 2 W/kg, averaged over a volume of 10 grams of tissues [21]. Figure 7 shows that the SAR calculations indicate that the proposed antenna has an acceptable and low effect on human head tissues. The simulated results are 0.77, 0.99, and 0.84 W/kg at resonance frequencies, when a distance of 2 mm from the head is considered.



(a) (b) (c)

Fig. 7. Proposed PIFA SAR on human head tissues.

The CST simulation software has been utilized to design and showcase the proposed antenna's results, while the HFSS simulation software has been employed to validate these outcomes. The proposed antenna is promising in 5G networks for mobile handsets due to its compact design and the results obtained in comparison to earlier research. Table 2 presents a comparison of the proposed design's results with results from prior studies. The proposed antenna demonstrates high efficiency, functions at three resonance frequencies, offers a broad bandwidth, and maintains a compact design.

TABLE 2. Proposed PIFA evaluation with earlier investigations.

Ref.	Dimensions (mm)	Operating Bands (GHz)	Bandwidth (GHz)	Gain (dBi)	Efficiency (%)
[7]	20 × 16 × 1.6	2.45	2.38–2.51	2	86
		3.5	3.44–3.84	2.1	86
		5.8	5.53–7.23	2.5	86
[22]	110 × 110 × 23	2.59	2.51–2.68	7.6	82
		3.5	2.51–2.68	8.5	81
		4.9	4.73–5	12.1	89
[23]	38 × 40 × 1.9	1.32	1.28-1.38	2.5	96
		3.12	3.05-3.17	4.5	90
		5.2	4.93-5.44	6	95
[24]	15 × 20	2.45	2.35–2.5	1.84	75
		3.5	3.3–3.55	2.13	75
		5.8	5.18–7.63	2.72	75
[25]	60 × 50 × 1.6	1.8	1.4-2	2.34	73
		3.5	3.4-3.8	5.2	68
		5.4	5.2-5.6	1.42	59
This Work	39 × 20 × 3.8	2.4	2.25 - 3.02	2.7	98
		3.7	3.6 - 4	3.56	98
		5.7	5.5 – 6.1	4.44	96

4. Conclusion

This study presents a compact tri-band PIFA suitable for sub-6 GHz 5G mobile handsets. The proposed design achieves a small form factor through the use of a shorting plate while maintaining high radiation efficiency. Furthermore, the incorporation of a DGS enables an omnidirectional radiation pattern and tri-resonant operation. The antenna effectively covers the essential 5G NR, LTE, and WLAN bands. When measured by the bandwidth of the impedance, it operates at different frequencies for the given ranges, with different gains as well. Simulations performed with both CST and HFSS show good agreement in performance, with only minor discrepancies in the VSWR at the 5.7 GHz band. The antenna also demonstrates compliance with safety standards for portable devices through its low SAR values. In comparison to existing designs, this antenna offers a compelling combination of enhanced bandwidth, high efficiency, and a compact footprint. These attributes position it as a highly suitable candidate for integration into future 5G mobile handsets. The future work will address the use of FR-4 and Rogers materials for their cost and efficiency benefits in the proposed antenna, including model fabrication and comparison of measurement results with simulations.

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