Multiband Slotted Planar Inverted-F Antenna using Reactive Impedance Surface for Wireless Applications

Tejaswi Mahaling J Jadhav (✉ tejaswi.jadhav@walchandsangli.ac.in)

Walchand College of Engineering <https://orcid.org/0000-0003-2614-4873>

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Abstract This research work presents a low profile slotted planar inverted-F antenna (PIFA) on a reactive impedance surface (RIS) for multiband. The quad-band frequency antenna for 2.4 GHz (WLAN), 4.2 GHz (C-band satellite downlink), 7.1 GHz (C-band satellite uplink), and 9 GHz (X-band) for wireless applications. The structure of the proposed PIFA has a compacted patch size of $23.33 \text{ mm} \times 2.66 \text{ mm} \times 1 \text{ mm}$ placed on a dielectric substrate flame retardant 4(FR4) material, along with tangent loss = 0.02. The proposed antenna used two dielectric substrates whose heights are $h_1 = 1.59 \text{ mm}$ and $h_2 = 1 \text{ mm}$. The rectangular slot is added in a radiating patch of the PIFA for multiband operations. The proposed antenna improves the parameters such as reduction scale, efficiency, narrow bandwidth, and gain enhancement. The slotted PIFA shows a quad-band with an $S_{11} < -10 \text{ dB}$ bandwidth of approximately 15.83% (2.24-2.62 GHz), 11.19% (3.93-4.4GHz), 12.67% (6.90-7.80GHz) and 10.55% (8.29-9.24GHz) under measurement. The proposed antenna design is excited by 50 Ω microstrip line feed. The antenna exhibits radiation pattern, gain, and impedance matching across their operating bandwidths to demonstrate the benefits of multiple PIFA.

Keywords Planar inverted-F antenna · Reactive impedance surface · Gain · Multiband · Slots

1 Introduction

Recently, in our everyday life, the growth of wireless devices, the demand for smartphones to change, miniature, low-cost, better mobility, and lightweight antenna. The handheld wireless device always suffers narrow impedance, less bandwidth, multiband, and less gain. The PIFA structure is a simple, low

profile, and flat that allows an omnidirectional pattern, a stable, and rational benefit in manufacturing, in discussed [1]. Due to its tactlessness property of the antenna, the PIFA gives more resistance elasticity for multiband mobile devices[2]. PIFA is usually suitable to use of multiband for industrial scientific and medical (ISM), long-term evolution (LTE), the global framework for handheld phones, Wi-max, WLAN, and other wireless technologies are discussed in [3]. The L-loaded PIFA has added the open end of capacitive load for additional antenna miniaturization. The electrically unconnected compact, novel, and multiband PIFA using multi-strip ground[4]. The combination of the thickness and feed position of antenna substantially providing at low frequency, increase the bandwidth, change and enhance at the desired frequencies, the gain, and the radiation effectiveness for the resonant frequency bands and the small ultra-thin PIFA with independent power[5]. A planar microstrip-fed triple-band PIFA is reported for the GSM835, DCS1940, and Wi-Fi 2340 bands[6]. The new design multiband PIFA has simulated cellular phones at different frequency bands is explained in [7]. Tri-band PIFA for ISM, GSM and DCS applications [8] and fractal PIFA with three separate iterations for mobile phones [9]. For wireless communication systems, a triple-band PIFA with a parasitic element and the compact triple-band internal mobile antenna for IEEE 802.11[10]. The four slots joined into a radiating patch, and the ground surface of PIFA with a maximum gain [11] and slot dimension had carried out to obtain a robust antenna design using the Taguchi quality method against changes in uncontrollable factors[12]. The antenna efficiency predicted by electromagnetic software to validate the design and compared to fabricated results[13], [14]. Rectangular complementary split-ring resonator (CSRR) for PIFA using branch-line has explained in [15]. The PIFA antenna was designed and developed by adding two parasitic elements with rectangular slots placed under the radiating patch to obtain a triple-band operation. In [16] the three resonant modes using an F-T shaped radiating structure by a trapezoidal feeding plate has produced and enhancing the antenna's impedance bandwidth. The microstrip antenna composed of a fork-shaped strip etched on the rectangular patch [17] and a rectangular-defected ground plane [18], [19]. On the bottom side, a partial ground plane that acts as a defective ground structure is added, and it is built to provide appropriate bandwidths for multi-frequency bands [20],[21].

The wireless handheld device system is compact, needs size reduction, and multiband. Miniaturization and bandwidth enhancement of the antenna becoming deliberations for wireless handheld devices [22], [23]. The low profile PIFA is an internal mobile antenna and easy to implement, which are applicable in several areas like space, military, wireless and commercial applications [24]. Therefore, the PIFA is an internal mobile antenna that compensates problems associated with polarisation, narrow bandwidth, lesser gain, and a smaller power handling capability. The metamaterial periodic structure of the RIS has demonstrated the ability to decrease the size of antennas and the cutting slot used for multiband operation. In this research, reduce the disadvantages of PIFA with an optimal technique and introduced a new, innovative, low profile

effective design of a slotted PIFA with RIS is designed, simulated, analyzed, and developed for multiband operations.

2 ANTENNA DESIGN

The conceptual framework of the slotted PIFA with RIS has shown in Fig. 1. The workflow of the proposed antenna simulated, analyzed, optimized, fabricated, and compare results. The conventional PIFA has a radiating patch, a ground plane, a shorting pin, a dielectric substrate (FR4), and a microstrip feed presented in [25]. RIS is a periodic metamaterial above the ground plane of slotted PIFA, as shown in Fig. 2(a). A simple structure of the PIFA is known as a “Conventional antenna”. The geometric parameters of the radiating patch have $23.33 \times 2.66 \times 1$ mm, and the ground plane is $56.4 \text{ mm} \times 41.68 \text{ mm}$. It's made up of a monopole antenna that's grounded at one end and runs parallel to the ground plane. The antenna is fed from a distance from the grounded end, at an intermediate position. Because of its space-saving features, it is most commonly used in mobile wireless devices as a PIFA. An antenna slot has made up of metal. The rectangular slots to cut a flat plate or holes on the surface of the radiating patch. If the metallic plate of the PIFA drives an operating frequency, then radiates electromagnetic waves in the antenna. Fig. 2(b) shows a modified PIFA with a rectangular slot of an antenna. Fig. 3(a) illustrates the optimized geometrical dimensions of the slotted PIFA, which is designed by the transmission line model. Fig. 3(b) shows the periodic structure of metallic square unit cells. The RIS consists of periodic structures 5×6 array of square unit cells. The adjacent dimension is set to have $g_1 = 0.342$ mm, $g_2 = 0.28$ mm, $a_1 = 0.8$ mm and $a_2 = 0.9$ mm for the periodic metal unit cells. RIS has been using for size reduction, impedance matching, and improvement of impedance bandwidth. The overall dimensions, as shown in table 1, of the adjusted slotted PIFA with RIS. Fig. 4 shows the front view (cross-section) of the modified slotted PIFA with RIS. There are two h_1 and h_2 dielectric substrates in the improved proposed antenna, which height is $h_2 = 1$ mm and $h_1 = 1.59$ mm. The surface of the RIS is among h_1 and h_2 dielectric substrates. The feed from the slotted PIFA and the antenna ground plane directly joined using the surface mount sub-miniature (SMA) connector. The SMA feeding probe connector does not explicitly contact the RIS structure, so the feed point mount on one corner of the radiating patch. The slotted PIFA has a frequency band of 2.4 GHz and impedance bandwidth of -10 dB, ranging from 2.16 to 2.56 GHz. Alternatively, the antenna limit to a single choice band and low matching impedance has shown in Fig. 5(a).

The slotted method improves the performance parameter of the antenna. The slot of the antenna is useful for compact size, easy to integrate for mobile devices. It also provides a wideband and a good option for design a multi-band antenna. Therefore, a rectangular slot with PIFA is introduced in the “proposed antenna” to enrich its operational capabilities. The antenna slots change the surface current distribution as a consequence, enabling the pro-

Fig. 1: Overall performance of slotted PIFA with RIS

Fig. 2: Evaluation stage of PIFA

Fig. 3: Structure of proposed antenna

posed design to operate at frequency bands of 2.4, 4.2, 7.1, and 9 GHz and rise the total current length direction. The simulated impedance bandwidth has shown in Fig. 5(a), and the voltage standing wave ratio (VSWR) have illustrated in Fig. 5(b) of the proposed antenna. It noted that the VSWR value is almost 1.60 at 2.4 GHz frequency, which is precisely competent in the manufacturing phase. VSWR varies between 1 and 2, then the antenna gives better performance and acts as a better radiator. The rectangular slot ($S_1 \times W_1$) is affected on the radiating patch to change the resonance at 2.4GHz. The ($S_2 \times W_2$) and ($S_3 \times W_3$) able to change the frequency band and also to improve the impedance matching. The ($S_2 \times W_2$) slot changes the 4.2 and 7.1 GHz resonance frequency of the proposed antenna. The rectangular antenna slot ($S_3 \times W_3$) is included in the slotted PIFA design to generate a resonance frequency at 9 GHz. The antenna slot ($S_1 \times W_1$) provides impedance balancing of multiband operating frequencies using the $\lambda/4$. The proposed antenna provides impedances 50Ω using the lumping port excitation mechanism fed into the radiating patch. The RIS discusses in the next subsection.

Table 1: Geometric parameters of Slotted PIFA

Parameters	Value(mm)	Parameters	Value(mm)
Lg	56.4	Wg	41.68
Lp	23.33	Wp	2.66
A ₁	7.26	A ₂	2.6
A ₃	4.6	A ₄	5.8
S ₁	3.7	W ₁	1.8
S ₂	3.7	W ₂	1.8
S ₃	22.5	W ₃	1.8
h ₁	1.59	ϵ_r	4.4

Fig. 4: Cross sectional view of slotted PIFA with RIS

Fig. 5: Simulated return loss and VSWR of slotted PIFA

2.1 RIS for slotted PIFA

The RIS is a metamaterial, relaxed construction of two-dimensional arrangement, periodically metallic square unit cells, below the radiating patch, and dielectric substrate backed on the ground. RIS has enhanced miniaturization, impedance bandwidth, and multiband performance[26]. Perfect magnetic conductor (PMC) and electric conductor (PEC) boundaries around the RIS and exciting with a transverse electromagnetic (TEM) mode of an antenna to obtain broad bandwidth and miniaturization. Robust electromagnetic coupling between PEC (PMC) boundaries, the radiating patch, and the ground surface is the miniaturization of the antenna hence the near-field of slotted PIFA containing electromagnetic energy expansion with the dielectric substrate.

The PIFA miniaturization improved features such as less matching impedance, low gain, and narrow bandwidth for corporate costs. The reactive impedance surface reduces the reciprocal coupling between the radiating patch and the ground plane, the output substantially recovered from the PEC and PMC surfaces, size reduction, narrow bandwidth, and back radiation are improved. The RIS is a periodic structure that operates parallel inductive and capacitive

circuits. It also increases the bandwidth and provides better impedance characteristics over RIS with the same dielectric substrate and radiating patch. The periodic arrangement of PIFA is mounting at one end of the dielectric substrate. The ground surface moved away from the radiating element because the micro-strip ground has under its substrate. The fringing field created a small area, so the ground plane moves away from the radiating to have better radiation emission and the complete ground and partial ground around the radiating element. Here the proposed model ground and the feed are also connected by the coaxial probe feed. The connector of the feed points a little bit away from the radiating portion to avoid interaction between the feed and metasurface. It is connected by a small stripline so that its resonant frequency is not determined by conventional equation but by simulation. Instead of the ground plane insert metamaterial, to enhance its radiation with the tuning, change the dimensions and different frequencies. It initially to design, to mitigate the surface waves the way how these high impedance structures work. If the ground plane has placed below the PIFA, it generates image currents of its reflection. The radiation energy has confined to a small place so, the ground reflection can be out of phase resulting from the disturbance in the radiation pattern. The better performance of the antenna RIS shifts the additional energy incident on it. So the energy is added in a constructive interference way instead of canceling it. For better matching to the PIFA, the metasurface had designed by the analysis described. The variation in L and C metasurfaces is based on the gap between the metal sheets and the metal pin height. The PIFA work at the different resonant frequencies with enhanced BW and good radiation pattern.

3 Analysis of slotted PIFA

3.1 Antenna Equation

The design of slotted PIFA is using the Transmission line model, which essential three parameters like a resonance frequency (f_0), selection of a dielectric substrate (ϵ_r), and substrate height (h). The geometric radiating patch length (L_P), patch width (W_P), and different slots in the patch had calculated by using the mathematical model [27]. Calculated dimensions have been optimizing with their respective frequency bands. The impedance bandwidth is directly proportional to the thickness of the substrate and inversely proportional to the square root of the dielectric constant of the substrate (ϵ_r). The width of the patch is calculated by using equ(1) as follows:

$$W_P = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r \epsilon_{eff} + 1}{2}}} \quad (1)$$

$$\frac{\Delta L}{h} = 0.412 \frac{\begin{matrix} \subseteq \epsilon_{eff} + 0.3 \\ \supseteq \epsilon_{eff} - 0.258 \end{matrix}}{\begin{matrix} \subseteq \frac{w}{h} + 0.264 \\ \supseteq \frac{w}{h} + 0.8 \end{matrix}} \quad (2)$$

Fig. 6: (a) Variation in slot S_1 (b) Variation in slot S_2 (c) Variation in slot S_3 (d) Return Loss with slot S_1 , slot S_2 and slot S_3 of slotted PIFA

For a resonance frequency f_0 , the effective length by using equ(3) is

$$L_{eff} = \frac{c}{2f_0\sqrt{\epsilon_{reff}}} \quad (3)$$

The length of the patch using equ(4) is

$$L_p = \lambda_g/4 \quad (4)$$

Resonance frequency of PIFA antenna for TM_{mn} mode is given as: Where m and n modes are alongside L and W respectively. Where, A is a fixed and, h is the substrate height = 1.6 mm, dielectric constant

Fig. 7: Surface current distribution of slotted PIFA at (a) 2.4, (b) 4.2, (c) 7.1 and (d) 9 GHz

= 4.4, The effective dielectric constant is measured by using equ(5) and (6) as the width of the strip line (W_3) and the length of the strip (S_3)

$$\frac{W_3}{h} = \frac{8 \exp(A)}{\exp(2A) - 2} \quad (5)$$

and

$$A = \frac{ZL}{60} \left(\frac{\epsilon_r + 1}{2} \right)^{\frac{1}{2}} + \left(\frac{\epsilon_r - 1}{\epsilon_r + 1} \right) \left(0.23 + \frac{0.11}{\epsilon_r} \right) \quad (6)$$

3.2 Parametric Study

The parametric study of the slotted PIFA with RIS had performed, and its simulation results have illustrated in Fig. 6. The analysis is achieved by varying antenna rectangular slots such as S_1 , S_2 , and S_3 while maintaining constant other measurements. Fig. 6(a) shows the variance of slot S_1 from 3 mm to 4 mm at phase 0.5 mm is observed, thus influencing the operating frequency of 2.4 GHz. Fig. 6 (b) indicates the variance of slot S_2 , demonstrating that the resonance frequency of 4.2 GHz is not disrupting but the change in the operating frequency observed at 7.1 and 9 GHz, respectively. Fig. 6(c) illustrates a change in impedance bandwidth and operating bands of the antenna. When the patch length varies from 23 mm to 24 mm at phase 0.5 mm, for $L_P = 23.33$ mm, then improved impedance bandwidth. The frequency bands

at 2.4, 4.2, 7.1, and 9 GHz have moved either right and left of the resonance with the variance of radiation patch slots S_3 illustrated in Fig. 6(c). Antenna deviation slots S_1 , S_2 , and S_3 are shown in Fig. 6(d) that resonance at 7.1 GHz is not disruptive, but the shifting of the operating frequency band observed in 2.4, 4.2, and 9 GHz, respectively. Fig. 7 shows the current distribution of the slotted PIFA. The current density is equivalent to the rectangular slot $S_3 \times W_3$ as illustrated in Fig. 7(a) and (b), which are resonant at 2.4, and 4.2 GHz, respectively. The front radiating patch current had used to change the resonant frequency at 2.4 and 4.2 GHz. A larger current density had observed near the rectangular slot that is accountable at 7.1 GHz, as shown in Fig. 7(c). The resonance at 9 GHz is indicated by the additional current path nearby S_1 and S_2 slots, as shown in Fig. 7(d).

Table 2: Comparison of simulated and measured results of slotted PIFA

Simulated Results			
Frq (GHz)	Return loss (dB)	-10 dB impedance bandwidth (GHz)	% Band width
2.4	-20.7	2.161-2.589	17.83
4.2	-18.47	4.082-4.300	5.19
7.1	-14.9	6.755-7.522	10.89
9	-16.38	8.448-9.538	12.10
Measured Results			
Frq (GHz)	Return loss (dB)	-10 dB impedance Bandwidth (GHz)	% Band width
2.4	-17.12	2.24-2.62	15.83
4.2	-15.97	3.93-4.4	11.19
7.1	-14.73	6.90-7.80	12.67
9	-13.70	8.29-9.24	10.55

4 Results and discussion

The simulated and measured performance parameters of slotted PIFA with RIS such as VSWR, return loss, gain, and radiation pattern discussed in this section.

4.1 Return Loss

As shown in Fig. 5(a), the reflection coefficient (S_{11}) is obtained using the simulation tool. Slotted PIFA showing a quad-band with an $S_{11} < -10$ dB

Fig. 8: (a) Measured and simulated Return Loss of slotted PIFA (b) Measured and simulated VSWR of slotted PIFA

bandwidth of approximately 17.83%, 5.19%, 10.89% and 12.10% under simulation and approximately 15.83% (2.24-2.62 GHz), 11.19% (3.93-4.4GHz), 12.67% (6.90-7.80GHz) and 10.55% (8.29-9.24GHz) under measurement respectively. The proposed slotted PIFA is manufactured, tested, and concluded that the RIS surface increases the broad bandwidth and gain. In the vector network analyzer (VNA), the VSWR and return loss of slotted PIFA with RIS has calculated. Table 2 shows the simulated and measured results of slotted PIFA with RIS. Fig. 8(a) displays the simulated and fabricated results obtained from output parameters such as return loss. The comparison between

Fig. 9: Gain of slotted PIFA

Table 3: Comparison of proposed slotted PIFA with the previous literature

Ref.	Size	No of band	Oprating Freq(GHz)	Gain (dBi)
[5]	25.6 × 26 × 3.57	3	2.09/ 3.74/ 5	2.05/2.32/3.47
[8]	34 × 17 × 8	3	0.9/ 1.7/ 2.4	0.4/ 1.7/ 1.1
[10]	16.5 × 11.5 × 5	3	2.4/ 5.2/ 5.8	4.44/4.91/ 4.94
[14]	90 × 42 × 7.5	4	1.1/ 2.4/ 3.6/ 5.3	1.45/ 1.6/ 3.56/ 4
[16]	25 × 11 × 8	3	2.4/5.2/5.75	1.6/2.3/4.4
[17]	26 × 20 × 1.6	3	2.4/3.5/5.8	2.24/2.8/2.6
[18]	100 × 65 × 1.6	3	0.9/1.8/2.6	0.25/0.6/3.28
Prop Work	23.33 × 2.66 × 2.59	4	2.4/ 4.2/7.1/9	5.75/ 6.10/ 1.25/7.14

simulated results and calculated results of the return loss (S_{11}), and VSWR increased marginally due to the wide air distance between the radiating patch and the ground plane prepared during the manufacturing process. For a mobile application, the designed antenna is helpful to demonstrate the strong matching impedance. The photograph of the manufactured slotted PIFA with RIS has shown in Fig. 10. Table 3 illustrates the details of the comparison between proposed slotted PIFA in terms of all geometric dimensions, miniaturization, frequency range, gain, and bandwidth with previous work.

4.2 VSWR

Fig. 8(b) shows the measured VSWR of the slotted PIFA with RIS. It noted that the VSWR value is almost 1.60 at the 2.4 GHz frequency that is effective in the manufacturing phase. The slotted PIFA VSWR is 1.60, 2.07, 2.55, and 2.79 dB observed for operating bands 2.4, 4.2, 7.1, and 9 GHz, respectively. The lower the VSWR, it more suits the power transmitted to the antenna the transmission line it means that better matching of impedance and the antenna's input power to the patch.

4.3 Gain

The gain of the slotted PIFA for a handheld device, as shown in Fig. 9, is acceptable for the better multiband antenna. The slotted PIFA gain is 5.75, 6.10, 1.25, and 7.14 dBi observed for operating bands 2.4, 4.2, 7.1, and 9 GHz, respectively. The averagely gain of an antenna for a quad-band is 5.06 dBi across their operating bandwidth.

4.4 Radiation pattern

The radiation pattern of slotted PIFA simulated in HFSS for the E-plane and H-plane. The radiation pattern depends on the magnetic field and electric field of the slotted PIFA. For multiband, the slotted PIFA radiates when the wave path alongside the Z-axis (-Z path and + Z path) then an antenna's port 1, is excited in the simulation. In this Fig. 11, the slotted PIFA radiation path deviates from the Z-axis towards the X-Z right plane to the Y-Z left the plane. The radiation pattern of the antenna (co-plane and cross-plane) illustrate in Fig.11 (a), (b), (c), (d), (e), (f), (g), and (h) of the X-Z plane, and Y-Z plane for the $\phi = 0^\circ$ and $\phi = 90^\circ$ at 2.4, 4.2, 7.1 and 9 GHz in measurement respectively.

5 CONCLUSION

A compact, multiband slotted PIFA with RIS presented for WiMax, C-band satellite downlink, C-band satellite uplink, and X-band applications. The slotted PIFA exhibit multiband with $S_{11} < -10$ dB bandwidth of about 15.83 % , 11.19 % , 12.67 % and 10.55 % at 2.4, 4.2, 7.1 and 9 GHz in measurement respectively. Parametric analysis reveals that the small change in the rectangular slots significantly impacts the antenna impedance matching. It also increases the bandwidth and provides better gain with the same dielectric substrate and radiating patch. The advantage multiple bands illustrate on the slotted PIFA exhibits radiation pattern, wideband, impedance matching, and gain across their operating bandwidths.

Fig. 10: Radiation pattern X-Z and Y-Z planes of slotted PIFA at 2.4, 4.2, 7.1 and 9 GHz

Fig. 11: photograph of slotted PIFA with RIS

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