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A Multi-band Microstrip Planar Inverted-F Antenna for Wireless Applications

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***Abstract*- A new multi-band planar inverted-F antenna (PIFA) is presented for wireless applications. PIFA is designed in two stages. First, the antenna consists of a radiating plate injected with a slot and it is shorted to ground plane with two shorting walls. The structure covers three bands. A small and narrow slot on the ground plane is embedded to afford increasing the bandwidths of the antenna at the resonance frequencies and improve radiation patterns at the second resonance frequency, thereby giving a more omnidirectional pattern. Second, a parasitic element is used at the antenna to design a quad-band PIFA antenna. Moreover, an L-shaped slot is embedded on the radiating plate to improve the reflection coefficient at the third resonance frequency. The antenna is optimized to operate at 1.1 GHz, 2.4 GHz, 3.6 GHz and 5.3 GHz bands. It can be used both indoor and outdoor wireless video, wireless cameras and wireless security applications at the 1.1 GHz band, Bluetooth, Wi-Fi and Wireless Local Area Network (WLAN) at the 2.42 GHz band, Microwave Access (m-WiMAX) at the 3.6 GHz band, and WLAN at the 5.3 GHz . The antenna is simulated and fed through a coaxial cable connected to the feeding strip; then it is fabricated and measured. The total antenna volume of the proposed design is 90 × 42 × 7.5 mm^2.**

Index Terms- Multiband PIFA antenna, bandwidth enhancement, wireless applications, U-shaped slots, L-shaped slots.

I. INTRODUCTION

With the rapid development of wireless technology and the use of it in wireless devices and transmitters, an important requirement for the design of antennas with small dimensions and low volume has emerged. In addition, wireless communication technology needs small elements for wireless subsystems [1]. PIFA, due to its small size, is used widely in portable wireless devices such as mobile handsets. New wireless devices work at several frequency bands; they also are able to operate at multiple frequency bands and PIFA can play the role of multi-band frequency antenna for these devices[2-5]. In fact, the PIFA is a kind of monopole antenna wherein the main radiating arm has been folded to become

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parallel with the ground plane and a shorting pin is added to obtain the desirable input impedance [2]. The impedance matching of PIFA can be obtained by the correct positioning of feeding and grounding pins. Thickness of the antenna and permittivity of the substrate can affect the impedance of the feeding point [3]. To reduce the size of PIFA, various techniques can be used, such as inserting the slots on the radiating plate [6-8]. Inserting U-shaped slots on the radiating plate of the PIFA can reduce the resonance frequency; this is such that the size of the antenna can be reduced by about 30%, as compared to the the conventional PIFA. In [6], three U-shaped slots were added to the radiating surface to create three different resonance frequencies; then the length and width of the U-shaped slots formed the size of the obstacle, such that the surface current on the patch was forced to propagate around to create new resonance frequencies. On the other hand, the embedded slots on the radiating plate of the PIFA antenna can affect the input impedance, bandwidth, and resonant frequencies of the antenna [9]. As investigated in [9], L-shaped slots can reduce or increase the lower resonance frequency; also, U-shaped slots influence both low and high resonance frequencies independently. In some works, these techniques have been used for controlling the resonance frequencies of PIFA independently [10-12]; for example, in [10], PIFA with independent controls of the resonant bands was designed for UMTS, m-WiMAX and 5 GHz WLAN by changing the length and width of the arm and other sections of the radiating pattern; this work is possible by the study of surface currents and independent major current paths on the radiation pattern. In [12], by using L-shaped slot, a second frequancy resonance with high beamwidth has been proposed.

The insertion of slots on the ground plane of a PIFA can be enhance the bandwidth of the resonance frequencies and reduce the antenna size [13-16]. In [13], the slotted ground plane was used for two main purposes: first, it tuned the PCB to resonate at low frequency (GSM900); second, it improved the bandwidth at high frequencies (DCS1900); this was since the slot had a length of $\lambda/4$ at the high frequency and acted as a parasitic element resulting in bandwidth improvement. Furthermore, sometimes several slots are used on the ground plane to further enhance the bandwidth at high frequencies [14] or to achieve a dual-band antenna [15]. But using a ground plane full of slots may interface with the electrical elements of the device; therefore, at a PIFA antenna, the ground plane full of slots can be highly sensitive. In [17], to increase the bandwidth of the antenna, an air gap was created between the substrate and the ground plane; also, a U-shaped slot was added on the radiating plate to improve the bandwidth at the resonance frequency. Using U-shaped slot is a very effective method to increase bandwidth [7, 18]. The antenna bandwidth can be widened by employing two shorting walls [19]. In this way, antenna bandwidth can be widened and a multiband antenna can be obtained [10], [19] and [20].

Many different designs for this type of antennas have been proposed. Many researchers are trying to reduce the size of these antennas, however, there many of them suffer low gain [4],[5], or they can operate in one or two frequency bands. In [13], the antenna operates in three frequency bands with good efficiency, but it has a big profile that make it unsuitable for small antenna applications.

In this paper, the design of a new multiband PIFA that can support four frequency bands at 1.1 GHz, 2.4 GHz, 3.6 GHz and 5.3 GHz is presented. The proposed antenna satisfies the return loss, bandwidth and gain requirements for wireless applications. Results are obtained based on the available finite element package HFSS software. The remaining sections of this paper are organized as follows: Section II describes the design and structure of the new multiband PIFA, and addition of a slot on the ground plane for increasing bandwidth at 3.6 GHz band and improving radiation pattern at 2.4 GHz band. Section III is related to adding the fourth resonance frequency by using a parasitic element; to improve the radiation pattern at the third resonance frequency, an L-shaped slot is added on the radiating plate. Section IV presents the results of simulation and measurement of the antenna and compares the reflection coefficient, bandwidth and radiation patterns. Finally, the conclusions are detailed in Section V.

II. DESIGN OF TRI-BAND PIFA ANTENNA

A. Antenna Design

A conventional PIFA has a simple structure such as in Fig. 1(a). All the parameters of PIFA are optimized by the EM software, High Frequency Structure Simulator (HFSS), in order to get the maximum bandwidth at resonance frequencies, as represented in Table I. The antenna is composed of a ground plane with the size of $W_g \times L_g$, and an FR-4 dielectric substrate with the thickness of 1.5 mm and the permittivity of 4.4 is placed on ground plane. A rectangular radiating plate with the dimensions $W_r \times L_r$ is parallel to the ground plane (X-Y plane) and is printed on a dielectric Duroid 5880 substrate with the thickness of *h* and the permittivity of 3. Because Duroid 5880 with a thickness of 125 mil is available, two layers of it is used under the patch of PIFA. Eventually, the radiating plate is shorted to the ground plane using a shorting wall with the width of W_{p1}. The antenna is fed by a coaxial probe that feeds the radiating plate through a feeding strip. In this case, the PIFA antenna operates at a resonance frequency achieved by the equation (1) [19]

$$f = \frac{c}{4(L_r + W_r - W_{p1})\sqrt{\varepsilon_r}}, \tag{1}$$

where c is the velocity of light, W_r and L_r are, respectively, the width and length of radiating plate, W_{p1} is the width of shorting wall, and ε_r is the dielectric constant. Therefore, there is a resonance frequency at 1.15 GHz band, as shown in Fig. 2. As seen in Fig. 1(b), a rectangular slot is added on the radiating plate to give a Bi-band PIFA operating at higher frequencies, as compared to the first resonance frequency, at 3.6 GHz. In this antenna, the resonance frequency can be decreased by increasing the width of slot.

Table I. Dimensions of the proposed Tri-band PIFA antenna (in millimeter).

Parameter	Dimension (mm)
W_g	42
L_g	90
W_r	22
L_r	40
w_s	7
L_s	37
W_{p1}	4.5
W_{p2}	2
W_1	13
h	6.35

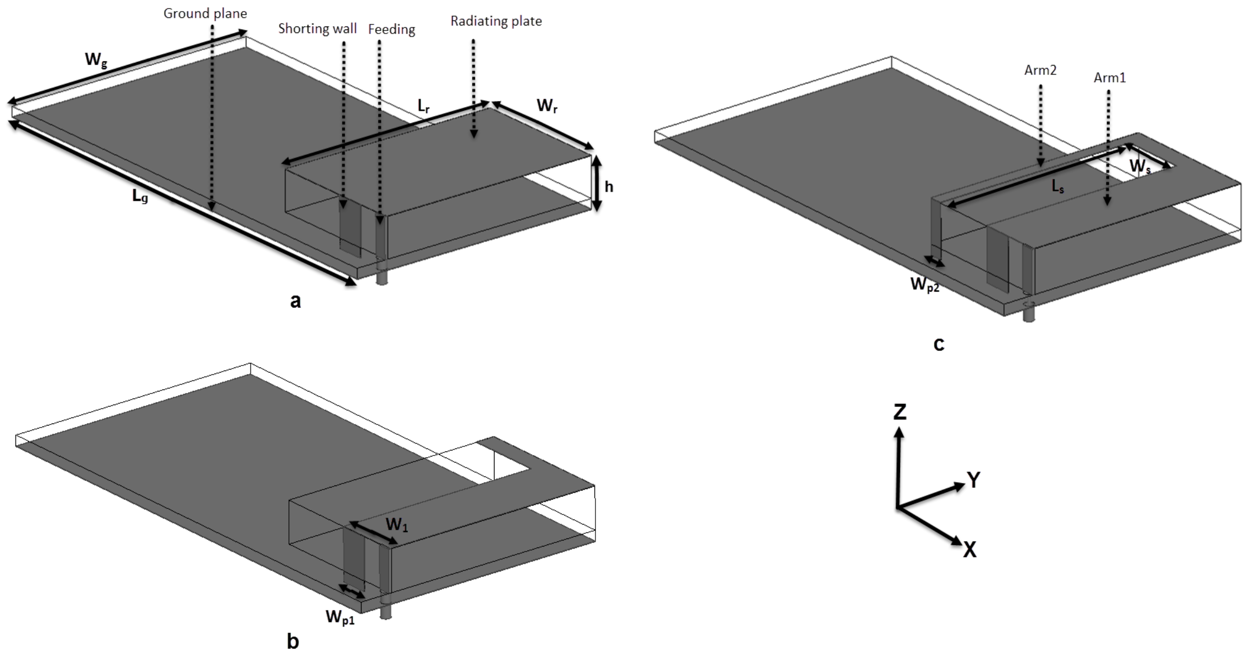


Fig. 1. Antenna design (a) conventional PIFA antenna (b) Bi-band antenna (c) Tri-band antenna.

If the slot moves in the positive X direction while keeping width the shorting wall, we have a Tri-band PIFA, as seen in Fig. 1(c). But to increase the bandwidth and improve the reflection coefficient (S11), another shorting wall is used to short Arm2 to the ground plane [6]; therefore we have a resonance frequency at 2.42 GHz band. In this case, by increasing the length of the slot, the resonance frequency can be shifted to the lower bands.

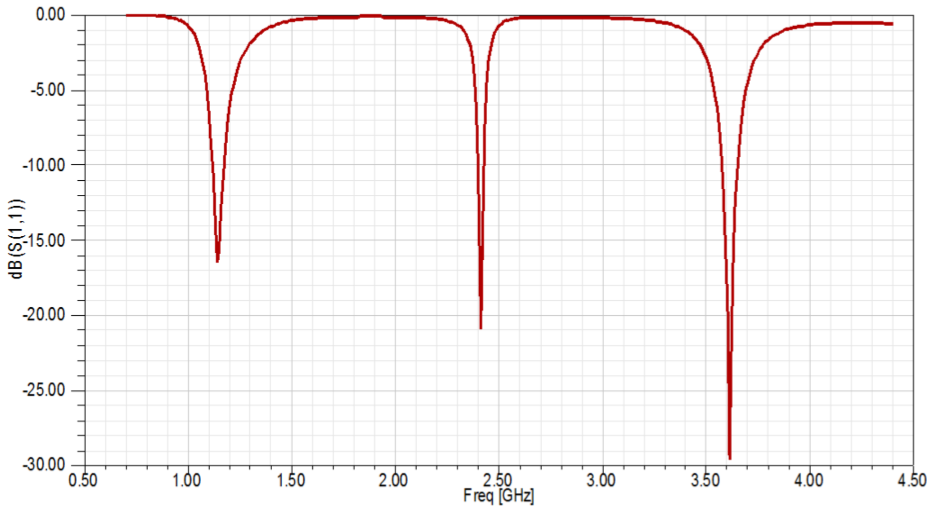


Fig. 2. Reflection coefficient magnitude of the proposed Tri-band PIFA antenna for the full-wave simulation.

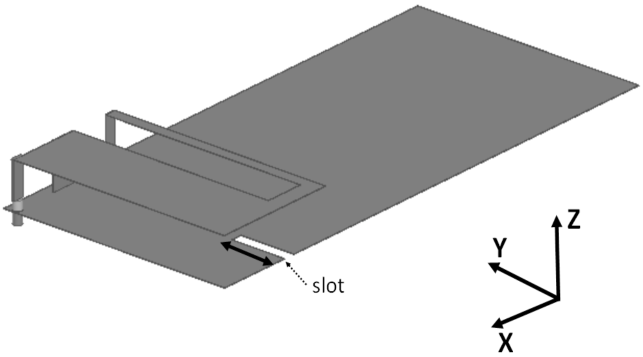


Fig. 3. Addition of a slot on the ground plane.

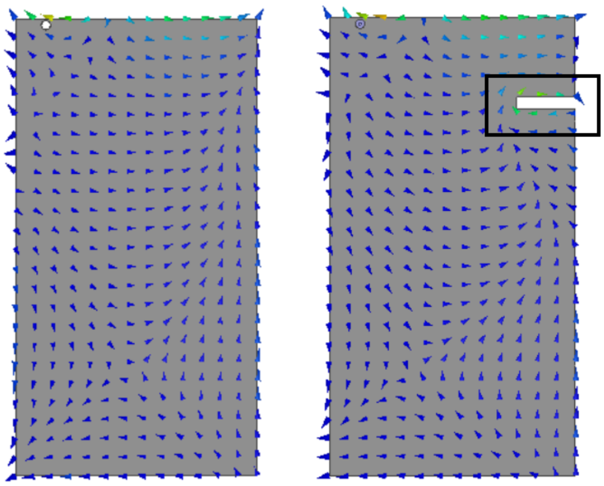


Fig. 4. Simulated current distribution on the ground plane at 3.6 GHz band

B. Addition of a Slot to the Ground Plane

When proper slots are embedded in the ground plane of a PIFA antenna, increasing bandwidth at the resonance frequencies can be achieved [13]. Also, the electrical size is extended by the slots in the ground plane while the physical size is not increased [15]. For this antenna, a narrow slot is embedded in the ground plane, and the length of 9.5 mm and the width of 2 mm using an optimization process. The slot is placed under the radiating plate with Y direction, as can be seen in Fig. 3.

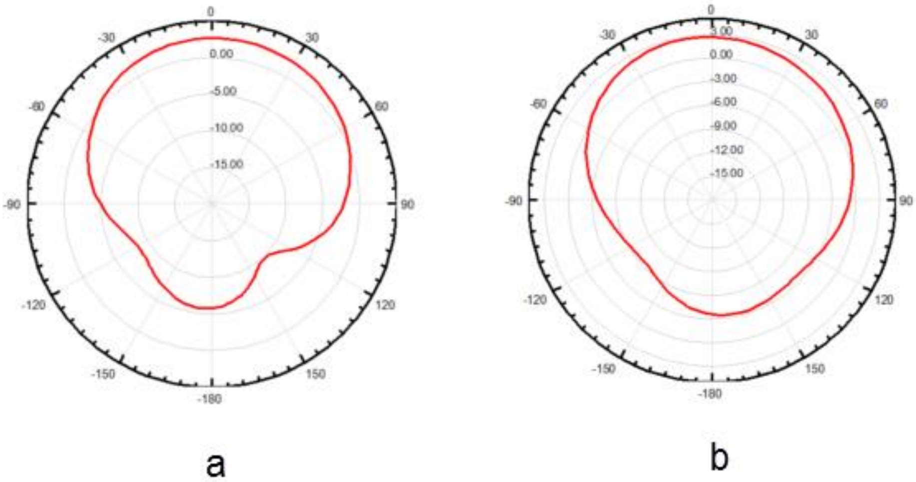


Fig. 5. Radiation patterns at 2.42 GHz band: (a) without the slot on the ground plane (b) with the slot on the ground plane

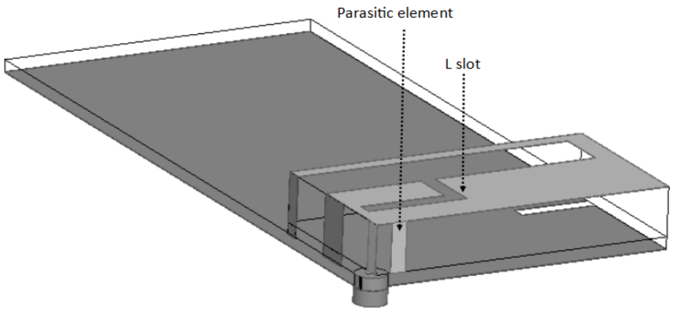


Fig. 6. Quad-band PIFA antenna with a parasitic element.

In this case, the slot has two advantages: first, it affords increasing the bandwidths of PIFA at the resonance frequencies, the most increasing bandwidth occurs at the third resonance frequency at 3.6GHz; at this frequency, the length of slot is about $\lambda/4$ so it acts as a $\lambda/4$ resonator and couples its radiation to the PIFA. The current distribution on the ground plane of PIFA before and after adding slot on the ground plane at 3.6 GHz, as shown in Fig. 4. It can be seen that the slot makes the current travel a larger electrical path. Second, as can be seen in Fig. 5, the radiation pattern of E_ϕ in the Y-Z plane becomes more omnidirectional after the addition of the slot on the ground plane at the second resonance frequency.

III. DESIGN OF QUAD-BAND PIFA ANTENNA

Addition of a parasitic element has been used in [15], [20]-[21] to increase the antenna bandwidth at the high frequencies. As can be seen in Fig. 6, a parasitic element with the length of 2 mm is attached parasitic element. The height of this element is 6.1 mm from the radiating plate to above FR-4 substrate

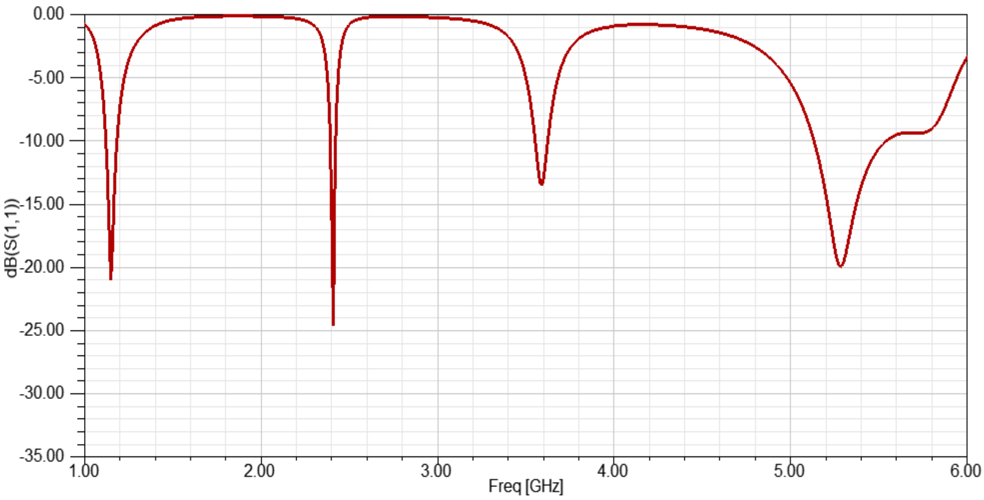


Fig. 7. Reflection coefficient magnitude of the proposed quad-band PIFA antenna for the full-wave simulation.

and it is disconnected to the ground plane. This simple element acts as a capacitive that gives coupling between the ground plane and the radiating plate to enhance the bandwidth at higher frequencies [15].

After the addition of the parasitic element, a new resonance frequency occurs at 5.3GHz, as shown in Fig. 7. This frequency band is suitable for wireless local area networks (WLAN) systems.

A. *Study of Current Distribution*

To explain how the proposed antenna works, surface current distribution at the resonance frequencies are studied. As shown in Fig. 8, the surface current distribution on the radiating plane is simulated by HFSS software at 1.15 GHz, 2.42 GHz, 3.6 GHz and 5.3 GHz bands, respectively, and amplitudes are normalized at the maximum values.

As can be seen in Fig. 8(a), at the first resonance, the surface current flows along Arm1 (L_r and W_1), whereas in Arm2 (L_r and $W_r - W_1 + W_s$), there is a null along the structure. Both current paths present a resonant length of a quarter-wavelength at the 1.15 GHz band. Also in Fig. 8(b), at the second resonance, two nulls are created on the radiating plate and three current paths have a resonant length of a quarter-wavelength at the 2.42 GHz band. The major path was along $L_r - L_s$ and W_s ; at other bands, the null is created in this path; therefore, by changing the length or width of this current path, the second resonance could be shifted to lower or higher bands independently from other resonance frequencies. As can be seen in Fig. 9, increasing and decreasing the width of path shift the resonance frequency to higher and lower frequency and increasing and decreasing the length of path shift the resonance frequency to higher and lower frequency. Here we can tune the 2.42 GHz band between 2.35-2.46 GHz by changing width and between 2.27-2.48 GHz by changing length of major path of surface current.

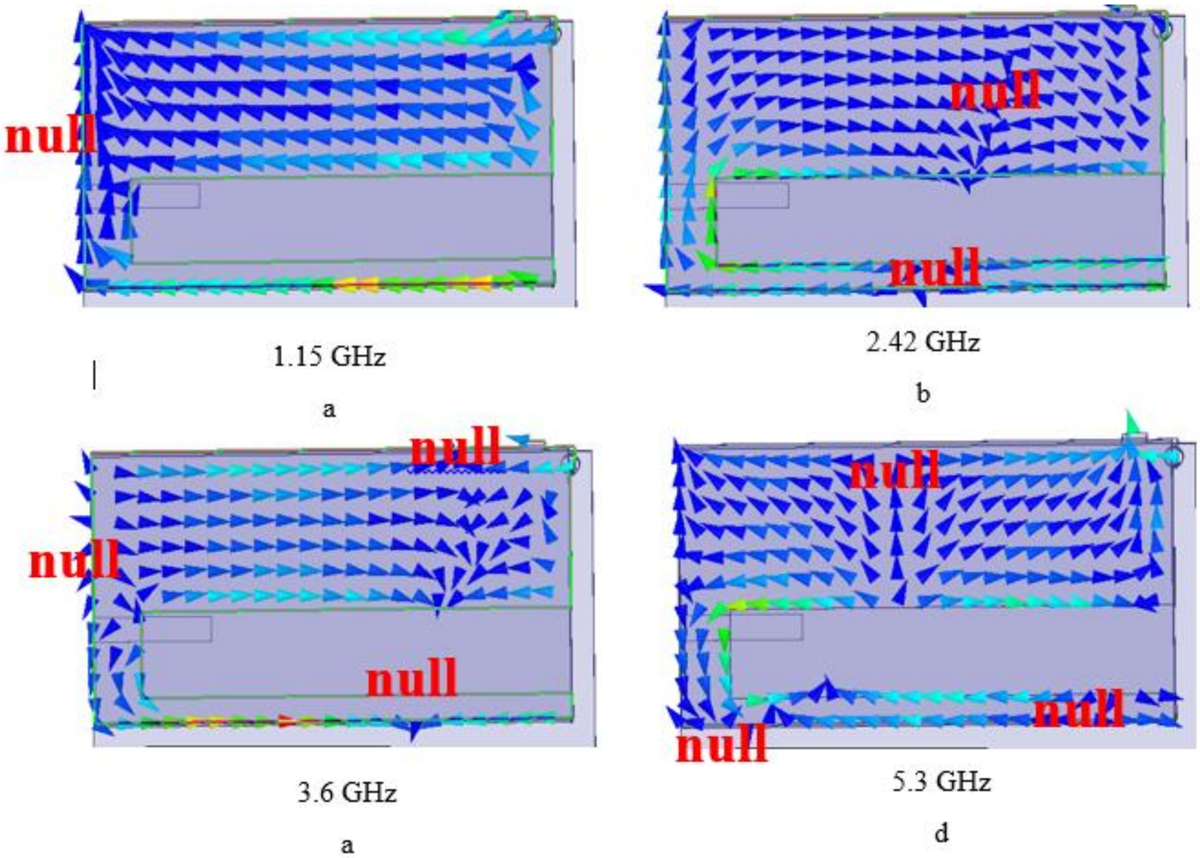


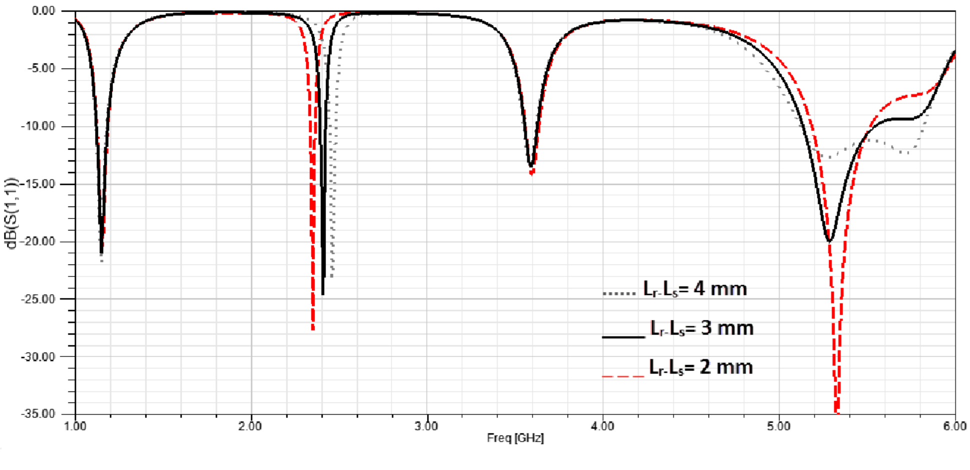
Fig. 8. Currents distribution for the proposed antenna at (a) 1.15 GHz (b) 2.42 GHz (c) 3.6 GHz (d) 5.3 GHz.

At the third frequency, three null and major current paths are created along Arm1 and Arm2, as can be seen in Fig. 8(c), with the resonant length of a quarter-wavelength at the 3.6 GHz band. Finally, at the fourth resonance frequency, three null and major current paths are created along Arm1, as shown in Fig. 8(d), with the resonant length of a quarter-wavelength at the 5.3 GHz band.

B. Addition of an L-shaped Slot on the Radiating Plate

As the final design to improve the radiation pattern of PIFA at the 3.6 GHz, an L-shaped slot is embedded on the radiating plate of PIFA. The slot has a narrow width of 2 mm and the arms had the length of 8 mm and 11.5 mm; also, they were perpendicular to each other.

The surface current distribution on the radiation patch after the addition of the slot is presented in Fig. 10, which is more unidirectional at Arm1. Current surface at the 2.42 GHz band has the minimum value along the L-shaped slot; therefore, it is not shifted at others bands, and the 1.15 GHz band just moves toward the 1.1 GHz band. New resonance frequencies are 1.1 GHz, 2.42 GHz, 3.6 GHz and 5.3 GHz.



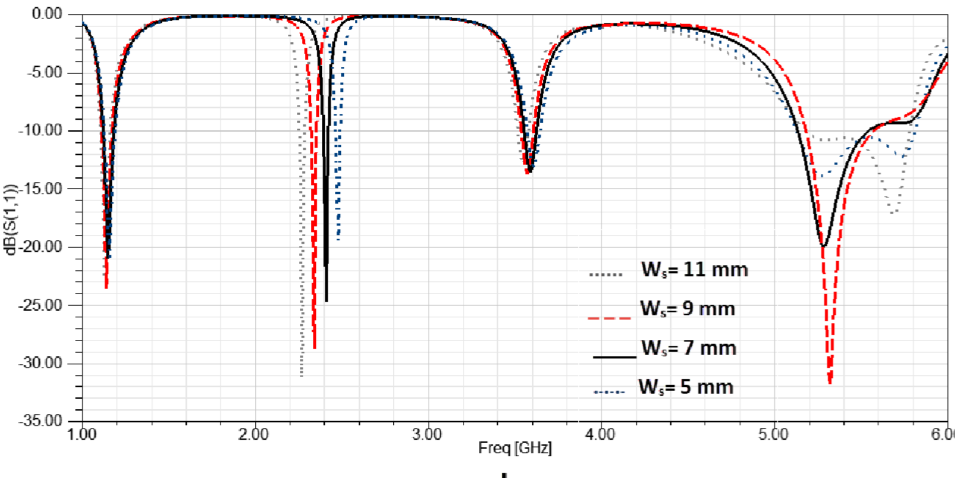


Fig. 9. Parametric studies of independent control for 2.42 GHz band (a) by changing length *Lr – Ls*, (b) by changing width *Ws.*

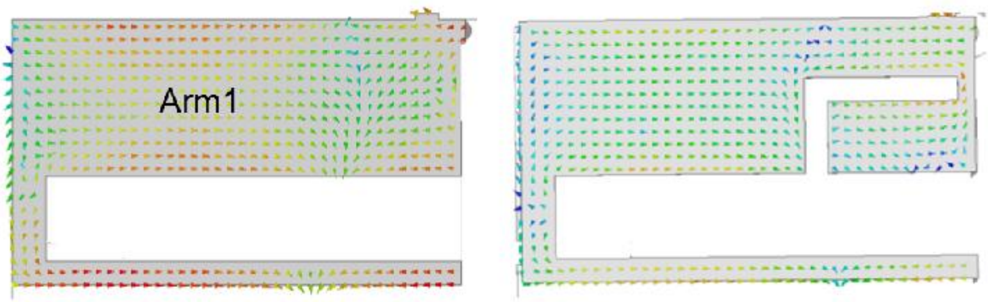
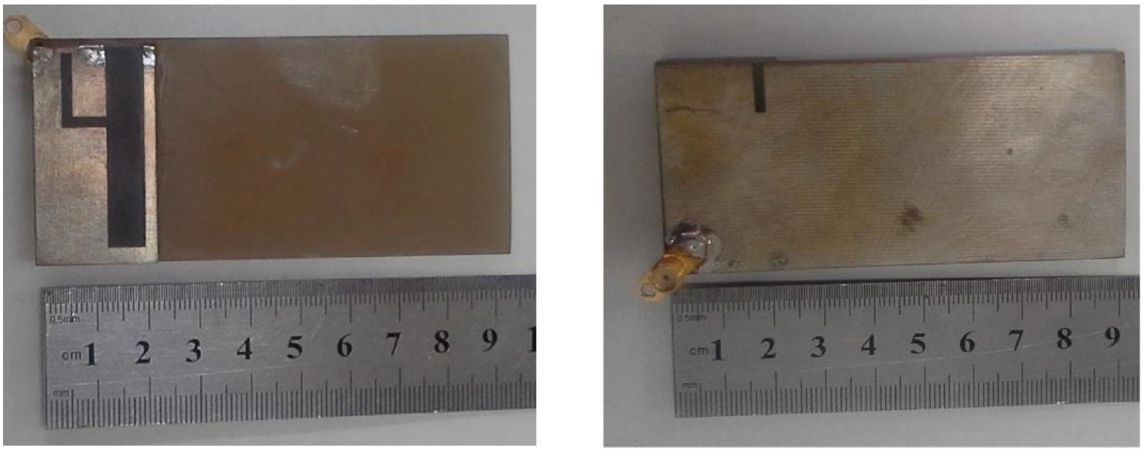


Fig. 10. Distribution current with and without the L-shaped on the radiating plate.



a b

Fig. 11. Fabricated antenna prototype multi-band PIFA (a) Front view (b) back view.

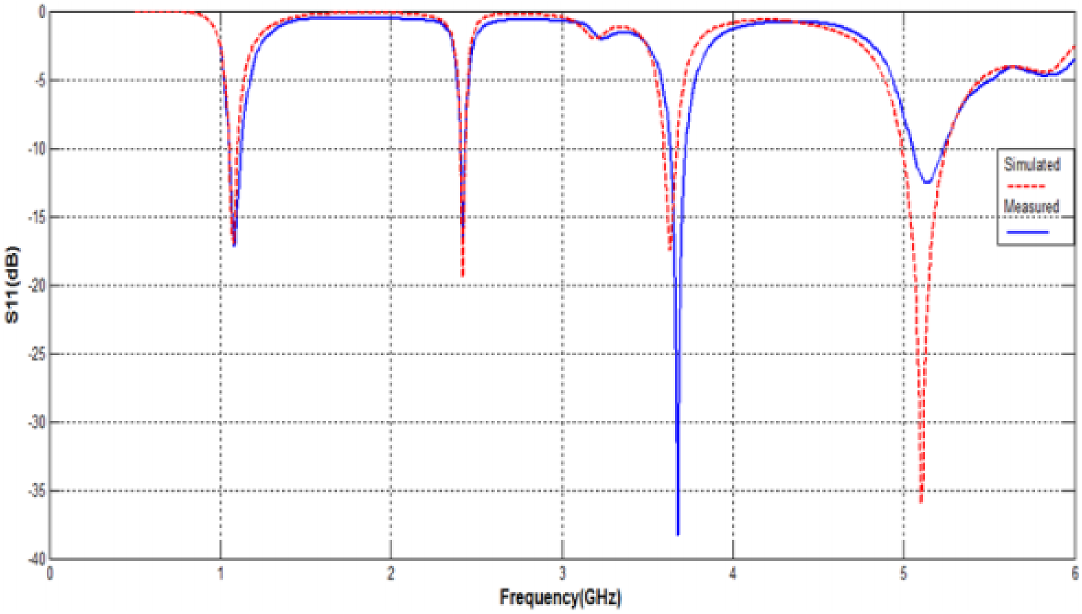


Fig. 12. The simulated and measured reflection coefficient of PIFA antenna.

IV. Simulation and Measurement Results

The radiation patterns of antenna were measured in KAN anechoic chamber and the reflection coefficient was measured by Vector Network Analyzer (VNA). The fabricated PIFA antenna is shown in Fig. 11. The simulated and measured reflection coefficient for the antenna with a good agreement are depicted in Fig. 12. The antenna can operate in the four bands 1.1 GHz, 2.42 GHz, 3.6 GHz and 5.3 GHz, which are usable and practical for wireless applications such as Bluetooth, WLAN and WiMAX.

Table II. Simulated and measured bandwidths of the antenna.

Frequency(GHz)	Simulated bandwidth (MHz)	Measured bandwidth (MHz)
1.1	48	71
2.42	29	29
3.6	75	91
5.3	264	178

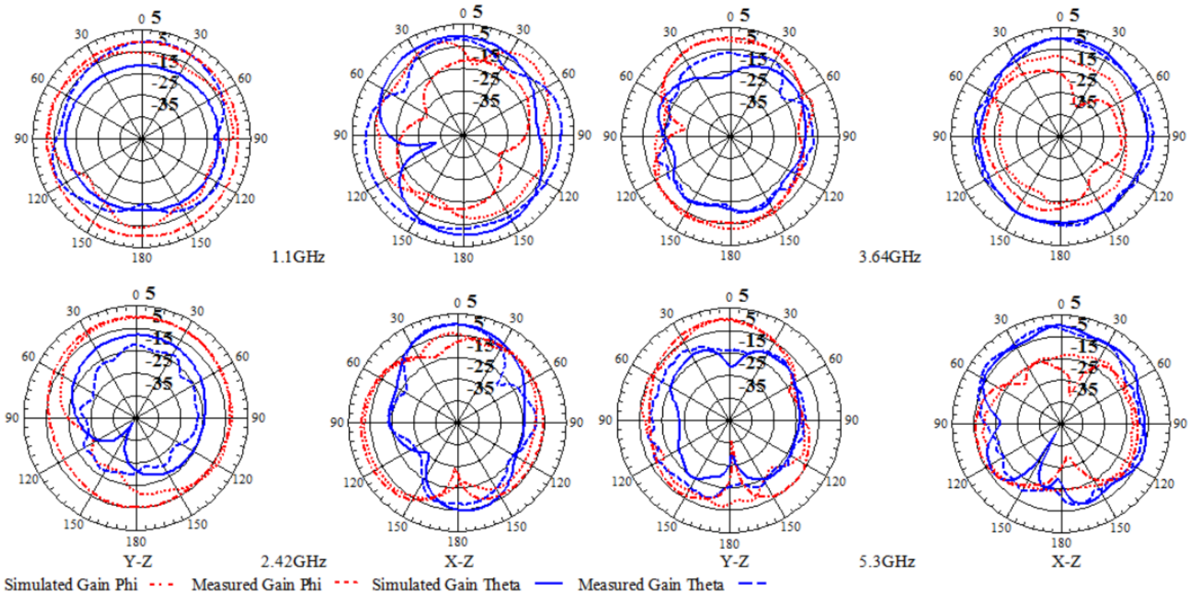


Fig. 13. The simulated and measured radiation pattern of multi-band PIFA at the resonance frequencies.

In Table II, the simulated and measured bandwidths defined by -10 dB for all resonance frequencies are presented. The bandwidths are increased at 3.6 GHz and 5.3 GHz bands because of the coupling between the radiating plate and the ground plane by creating the slot on the ground plane and the element parasitic, respectively.

Radiation patterns of the fabricated multi-band PIFA can be seen in Fig. 13. The simulated and measured gain of E_ϕ and E_θ in both Y-Z and X-Z planes have been shown. E_θ in both X-Z palne and E_ϕ in Y-Z plane are refer to co-polar, respectively, also E_ϕ in both X-Z palne and E_θ in Y-Z plane are refer to cross-polar, respectively. Simulated gain in 1.15 GHz, 2.42 GHz, 3.6 GHz and 5.3 GHz are 1.5 dB, 2.2 dB, 1.1 dB and 3.05 dB in X-Z palne, respectively. Also, simulated gain in 1.15 GHz, 2.42 GHz, 3.6 GHz and 5.3 GHz are 1.45 dB, 1.6 dB, 3.56 dB and 4 dB in Y-Z palne, respectively. As can be seen, The radiation patterns are close to the omnidirectional pattern because the slot on the ground plane and the L-shaped slot on the radiating plate give omnidirectional patterns and increasing the bandwidths in the resonance frequencies.

V. CONCLUSION

In this paper, the design of a multi-band PIFA antenna was presented. The antenna had a U-shaped patch shorted to the ground plane through two shorting walls. A slot was created on the ground plane of the antenna to improve the bandwidth at the third resonance frequency and the radiation pattern at the second resonance frequency in the Y-Z plane. A conductor strip, as a parasitic element, was attached to the U-shaped patch of the antenna and a new frequency band was added to the three previous frequency bands of the antenna. The PIFA antenna had been manufactured and its reflection coefficient (S11) and radiation patterns at resonance frequencies were measured and compared with the simulation results. The antenna can be used both indoor and outdoor wireless video, wireless cameras and wireless security applications at the 1.1 GHz band, Bluetooth, Wi-Fi and Wireless Local Area Network (WLAN) at the 2.42 GHz band, Microwave Access (m-WiMAX) at the 3.6 GHz band, and WLAN at the 5.3 GHz.

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