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Analysis of a Notch Loaded Miniaturized Multifrequency Microstrip Patch Antenna

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Abstract

A miniaturized microstrip patch antenna with multifrequency operation is proposed in this paper. The effect of rectangular notch loading on microstrip patch is investigated in this paper. Two rectangular notches are introduced on the radiating patch and multifrequency response has been obtained. The first resonant frequency has been drastically reduced to 3.44 GHz due to incorporation of rectangular notches. Compared to the conventional rectangular patch antenna, the proposed antenna can achieve reduction in patch size up to 64.3% with a frequency ratio of about 1.80. The proposed antenna resonates at 3.44, 4.72, and 6.32 GHz in microwave S and C band. The characteristic parameters of the proposed antenna are investigated by method of moment-based IE3D software. Theoretical results have been validated by measured results. Good agreement is observed between the theoretical and practical results. The proposed antenna could be promising for a number of applications such as Wi-Max, INSAT, and radar communications.

Keywords*: Miniaturization, Multi-resonance effect, Rectangular Notch, Microstrip patch antenna*

1. Introduction

The wireless communication systems have been developed widely and rapidly during the last decade. The size of wireless communication devices depends on the size of the components used inside these devices. In recent years, the demand for miniaturized antennas is also increased due to rapid decrease in size of wireless communication devices. Presently, certain specific bands of frequencies are allotted for different wireless communication systems. The required multiple frequency bands cannot be covered by a single conventional antenna. Again, the usage of many antennas is usually restricted by the volume and cost constraints of the applications. So a single antenna with multiple resonant frequencies may be the alternative choice. Thus, the design of light weight miniaturized multiband antenna has attracted much attention of the antenna community for applications in modern wireless communication systems. In recent days, microstrip patch antennas are highly utilized for applications in wireless communication due to its compact, planar, low cost, and light weight features. A number of design methods have been suggested by the researchers to increase the compactness of microstrip patch antenna [1–12]. Compact operation of air substrate patch antenna with more than 50% size reduction was reported by Wong et al. [1]. Clasen et al. [2] proposed meshed antenna geometry and reported 30% size reduction. Elsdon et al. [3] reported size reduction of up

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to 40% by using planar feeding. Size reduction of about 44% was reported by implementing a sector slot on circular patch antenna [4]. A compact E shaped patch antenna with corrugated wings was proposed which results in 25% size reduction [5]. A maximum size reduction of 41% was reported by varying the dimension of slots and feeding point on microstrip patch [6]. Zhao et al. [7] designed a compact patch antenna with 29.3% size reduction using split ring resonator embedded substrate. A square microstrip antenna designed with four slits and a pair of truncated corner results in 39% reduction in antenna size [8]. Hanae et al.[9] investigated the effect of defected ground structure (DGS) on microstrip patch antenna to provide a miniaturization of 50%. An annular ring embedded L-slot rectangular microstrip patch antenna was implemented with 29.91% reduction resonance frequency [10]. A quasi fractal microstrip antenna using electromagnetic band gap structure was implemented which results in 35.6% size reduction [11]. Recently, Meng et al. [12] designed a 31% miniaturized dual band modified patch antenna. Several investigations were also carried out by the researchers for the design of multifrequency microstrip antenna to support multiple communication systems [13–17]. Multifrequency operation can be obtained by using more than one element (multiple patches) with different sizes that resonates at different frequencies [13]. A slot loaded bowtie patch antenna is also a choice for achieving multifrequency operation [14]. Spiral shaped printed antenna is also investigated for achieving multifrequency operation [15]. Multifrequency operation can also be achieved using fractal microstrip patch antenna [16]. The multi–resonance effect from a microstrip patch can also be realized by using unequal resonance patch lengths [17]. The work presented in this paper relates to design of a compact multifrequency microstrip patch antenna. Our aim is to achieve multiple resonant frequencies and also compactness from a single microstrip patch antenna. Multiple resonant frequencies are obtained due to introduction of unequal rectangular notches on the microstrip patch, and also the size of the antenna has been reduced by 64.3% in comparison to conventional rectangular microstrip antenna with same patch area. The novelty of our work is size reduction and multifrequency operation from a single antenna with considerable peak gain of about 5.25dBi.

2. Antenna Configuration

2.1 Antenna 1(Conventional Antenna)

The configuration of the conventional rectangular reference antenna is given in Figure 1. The dielectric material selected for this design is an FR4 substrate with dielectric constant ($\mathcal{E}_r$) = 4.4 and substrate height (h) = 1.5875 mm. The length and width of Antenna 1 (conventional antenna) operating at 5.5 GHz are 12 and 16 mm, respectively [18]. The coaxial probe-feed of radius 0.5 mm with a simple ground plane arrangement is located at a position *W/*2 (8 mm) and *L/*3 (4 mm) from right side edge of the patch for best impedance matching.

2.2 Antenna 2 (Proposed Antenna)

The configuration of antenna 2 (proposed antenna) is shown in Figure 2. The proposed antenna is also designed with a similar FR-4 substrate. Two unequal rectangular notches are introduced at the left side and top edge of the patch to reduce the size of the antenna by reducing the resonant frequency and also to obtain multiple frequencies from the antenna. The addition of rectangular notches improves the gain and reflection coefficient of the proposed antenna at multiple resonant frequencies. The coaxial probe is fed at an optimized location (X = 2 mm, Y = −1 mm) from patch centre (X = 0 mm, Y = 0 mm) for achieving multifrequency operation with best impedance matching. The method of moment based electromagnetic simulator IE3D [19] is applied for parametric investigation in the proposed antenna design. The optimal dimensions of the proposed antenna are given as: L = 12 mm, W = 16 mm, W_1 = 4 mm, L_1 = 5 mm, L_2 = 2 mm, W_2 = 4 mm. The fabricated prototype of the proposed antenna is shown in Figure 3.

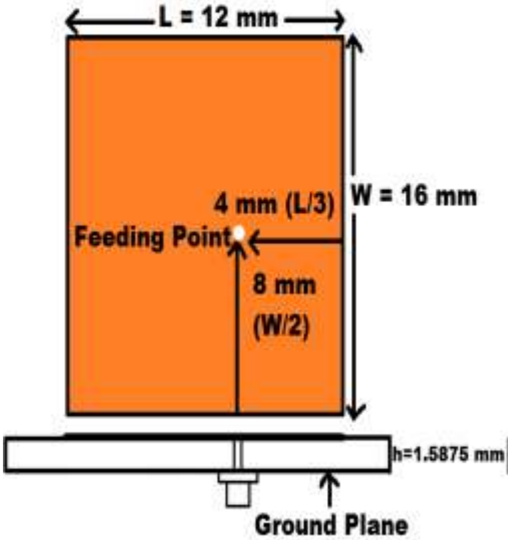

Figure 1. Configuration of Antenna 1 (Conventional Antenna)

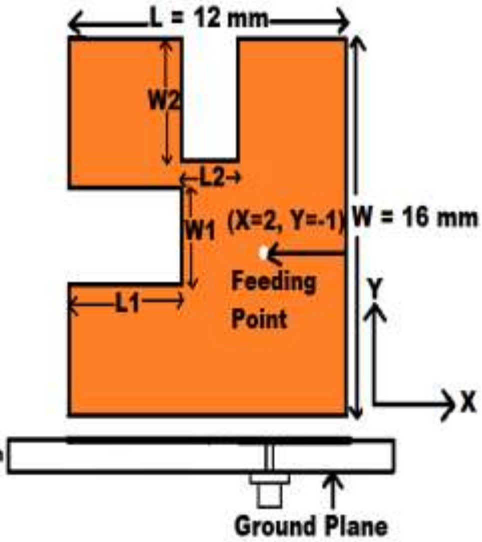

Figure 2. Configuration of Antenna 2 (Proposed Antenna)

(a) (b)

Figure 3. Fabricated Prototype of the Proposed Antenna (a) Patch, (b) Ground Plane

3. Effect on Each Optimized Slot on the Performance of the Proposed Antenna

The effect of each optimized notch on the resonant characteristics of the proposed antenna is analyzed using IE3D software. Figure 4 shows the different stages of modifications and corresponding simulated reflection coefficients. The Case I represent the conventional reference antenna (antenna without notch) which resonates at 5.5 GHz. But the resonance characteristics of the conventional rectangular antenna changes significantly due to the presence of unequal rectangular notches. In case II (presence of top notch), the antenna resonates at two different frequencies 4.72 and 6.66 GHz with S_{11} below −10 dB. Another resonance is observed at 4.38 GHz with S_{11} parameter −6.27 dB. At the final stage i.e., case III (proposed antenna), the first resonant frequency is achieved at 3.44 GHz with improved reflection coefficient (S_{11} parameter) of −16 dB, due to addition of second (left) rectangular notch. The second resonant frequency remains same (i.e., 4.72 GHz) with better reflection coefficient (−17 dB). The third resonant frequency is slightly shifted to 6.32 GHz with reflection coefficient −24 dB.

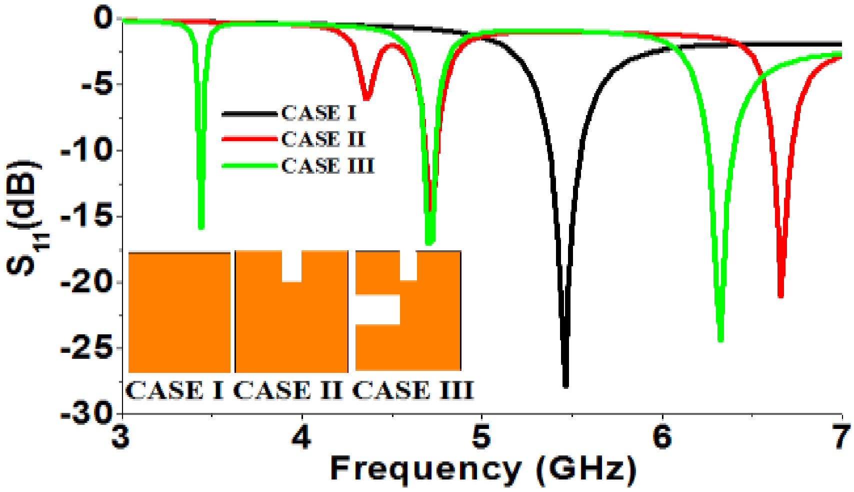

Figure 4. S_{11} Variations of the Antenna in Different Cases

The variations of resonant frequency, reflection coefficient (S_{11} parameter), VSWR and gain in different cases of evolution of proposed antenna are summarized below in Table 1.

Table 1. Variations of Simulated Results in Different Cases of Evolution of Proposed Antenna

Different Cases	Resonant Frequency (GHz)	S_{11} (dB)	Gain (dBi)	VSWR
Case I	$f_1 = 5.5$	−26.5	4.27	1.099
Case II	$f_1 = 4.36$ $f_2 = 4.72$ $f_3 = 6.66$	−6.27 −14.6 −21	0.199 4.96 3.0	2.88 1.45 1.19
Case III (Proposed)	$f_1 = 3.44$ $f_2 = 4.72$ $f_3 = 6.32$	−16 −17 −24	4.75 5.25 4.75	1.38 1.32 1.12

4. Theoretical Considerations

A simple rectangular microstrip patch antenna can be modeled as a parallel combination of RLC circuit. The current flows from the feeding point to the top and bottom edges of the patch. The equivalent circuit a conventional rectangular microstrip patch antenna is shown in Figure 5, where R_1, L_1 and C_1 can be defined as [20]

$$C_1 = \frac{\varepsilon_e \varepsilon_0 LW}{2h} cos^{-2}(\pi x_0/L) \qquad (1)$$

$$L_1 = \frac{1}{\omega^2 C_1} \qquad (2)$$

$$R_1 = \frac{Q_r}{\omega C_1} \qquad (3)$$

Where, L = Length of the rectangular patch, W = Width of the rectangular patch, x_0 = feed point location along the length of the patch, h = thickness of the substrate material and Q $=\frac{C\sqrt{\varepsilon_e}}{4fh}$, where c = velocity of light, f = design frequency and ε_e = effective permittivity of the medium which is given by [20] as:

$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+10\frac{h}{w}\right]^{-1/2}$ (4) Where, ε_r= relative permittivity of the substrate.

The rectangular notches agitate the surface current path, initiating an inductive and capacitive effect that is responsible for multi–resonance characteristics of the proposed antenna. Due to the effect of the notches, two types of current paths, one is the normal patch current and resonates at the design frequency of the initial patch; however, the other current flows around the notches consequently alter the resonance frequency. With the introduction of notches, the resonance behavior of the antenna changes because each notch introduces additional series inductance (ΔL_1, ΔL_2) and series capacitance (ΔC_1, ΔC_2) that modify the equivalent circuit of the rectangular microstrip patch antenna as shown in Figure 6, in which the additional series inductances and series capacitances can be calculated as [21].

$$\Delta L_1 = \frac{h\mu_0\pi}{8}\left(\frac{L_{n1}}{L}\right)^2 \quad (5)$$

$$\Delta C_1 = \left(\frac{L_{n1}}{L}\right).C_s \quad (6)$$

$$\Delta L_2 = \frac{h\mu_0\pi}{8}\left(\frac{L_{n2}}{L}\right)^2 \quad (7)$$

$$\Delta C_2 = \left(\frac{L_{n2}}{L}\right).C_s \quad (8)$$

Where, $\mu_0 = 4\pi \times 10^{-7}$ H/m, L_{n1} = depth of the horizontal slot, L_{n2} = depth of the vertical slot, C_s = gap capacitance given by [22]. The simplified circuit model of proposed antenna is shown in Figure 7, where, $C_2 = \frac{C_1.(\Delta C_1+\Delta C_2)}{(C_1+\Delta C_1+\Delta C_2)}$, $L_2 = L_1 + \Delta L_1 + \Delta L_2$. Due to multi path of current flowing there exist multi resonant frequency.

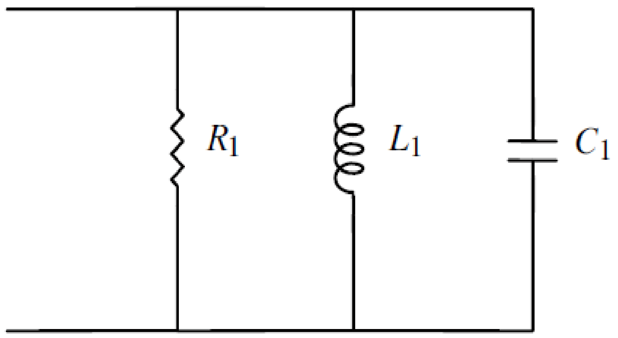

Figure 5. Equivalent Circuit of the Conventional Rectangular Patch Antenna for Normal Current Path

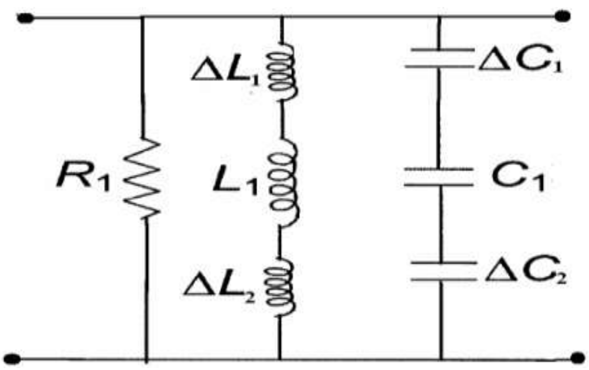

Figure 6. Equivalent Circuit of the Proposed Antenna due to the effect of notches

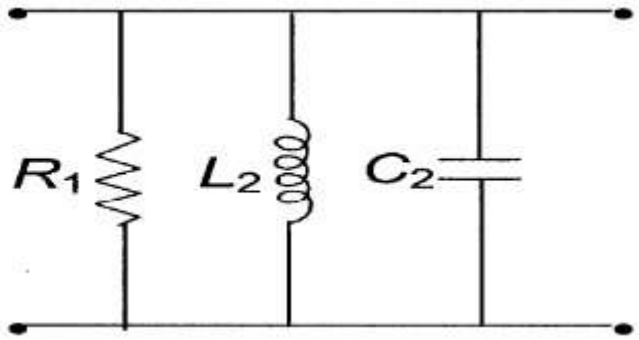

Figure 7. Equivalent Circuit of the Proposed Antenna due to Current Path around the Notches

5. Parametric Study and Analysis of the Proposed Antenna

The parametric study of the proposed antenna has been carried out using MOM based IE3D software to study the effects of various parameters on the performance of the antenna. The effects of the parameters are analyzed by slightly changing only one structural parameter from the reference design at the time of simulation while all other parameters remain fixed.

5.1 Effect of Antenna Parameter W_1

The impact of design parameter W_1 is shown in Figure 8. It is clearly seen that the first resonant frequency can be varied by changing the value of W_1 parameter. An optimum value of W_1 = 4 mm is selected as a notch parameter for the design of the antenna. Further increase of W_1 than proposed dimension will slightly shift the first resonant frequency to a lower value but the reflection coefficient (S_{11} parameter) is not under –10 dB level, which indicates poor impedance matching. The second and third frequency band remains almost unchanged with the variation of W_1 parameter.

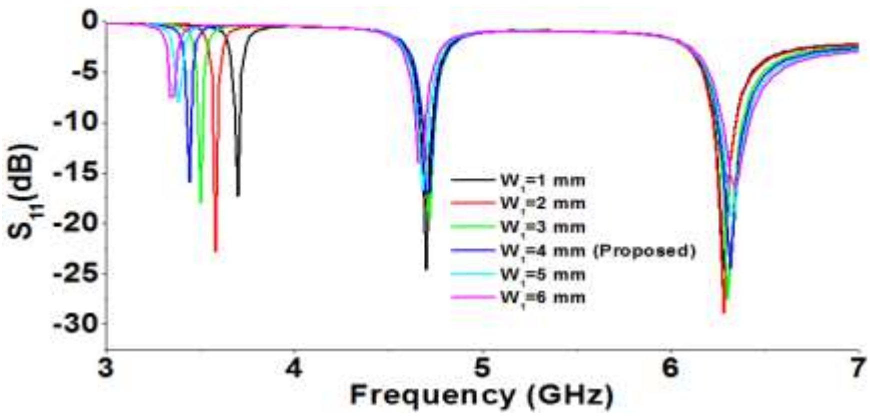

Figure 8. S_{11} Variations for Different Values of W_1

5.2 Effect of Antenna Parameter L_1

The effect of design parameter L_1 on the resonant characteristics of the proposed antenna is shown in Figure 9. Maximum shifting of the first resonant frequency with good impedance matching is obtained for the proposed dimension. So, an optimum value of L_1 = 5 mm is selected as a notch parameter for which maximum size reduction is obtained. When L_1 is increased to 6 mm, the first resonant frequency is decreased to 3.14 GHz with S_{11} of only −7 dB, which suggests poor impedance matching. The excitation of first resonant frequency is not possible with further increase in L_1 parameter of the proposed antenna. It is observed that the shifting of second and third resonant frequency depends inversely on the dimension of L_1 parameter of the antenna.

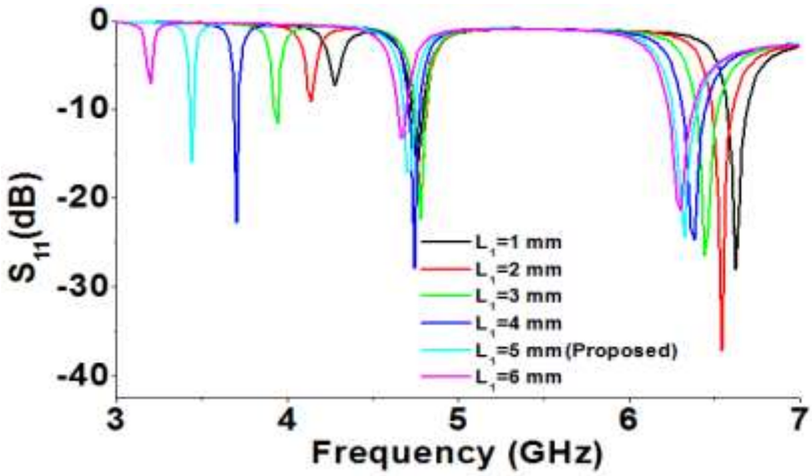

Figure 9. S_{11} variations for different values of L_1

5.3 Effect of Antenna Parameter W_2

Figure 10 illustrate the variations of S_{11} parameter versus frequency due to change in notch parameter W_2. The first resonant frequency can be shifted to a lowest value of 3.34 GHz but the value of reflection coefficient (S_{11} parameter) at 3.34 GHz decreases to −7.29 dB due to impedance mismatching. The value of S_{11} should be at least −10 dB for an antenna to radiate in the far field region. So, an optimum value of 4 mm is selected for W_2 to achieve an optimal design of the proposed antenna. The notch parameter 'W_2' has a great impact on resonant frequency of the second mode. The second resonant frequency can be tuned from 5.45 to 4.35 GHz by increasing the values of W_2 parameter from 1 to 5 mm. The third resonant frequency can also be easily adjusted by changing the values of the design parameter W_2.

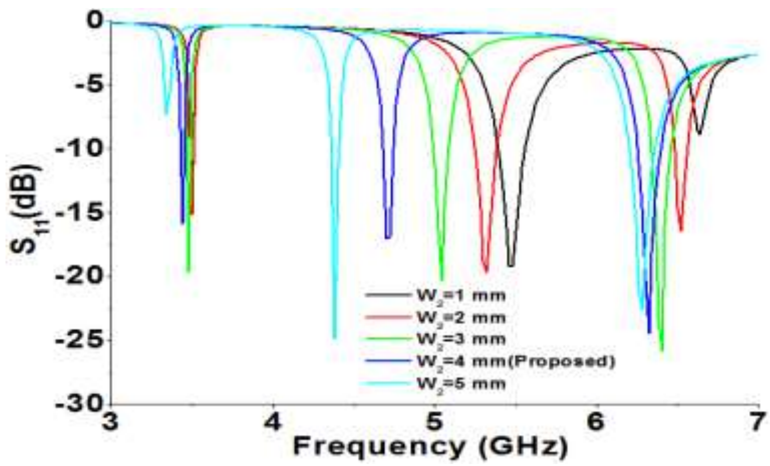

Figure 10. S_{11} Variations for Different Values of W_2

5.4 Effect of Antenna Parameter L_2

The variations of S_{11} curves for different values of antenna parameter L_2 are illustrated in Figure 11. The resonant frequency of the second mode can be easily tuned from 4.86 to 4.58 GHz by changing the dimension of parameter L_2 from 1 to 4 mm. The first and third resonant frequency remains unchanged due to variations in L_2 parameter. But maximum reflection coefficient for the first resonant frequency is observed at L_2 = 2 mm. So, L_2 = 2 mm is selected as an optimum value for the design of the antenna.

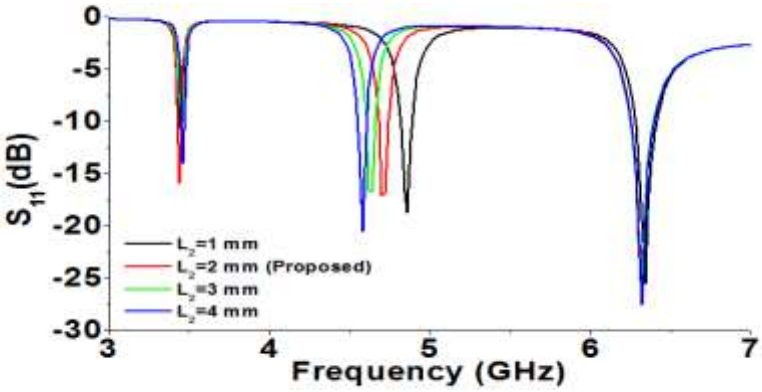

Figure 11. S_{11} Variations for Different Values of L_2

The function of the geometrical mechanism of the proposed antenna at three resonant modes can also be explained with the help of the surface current distributions for different resonant frequencies. The surface current distribution of the conventional is shown in Figure 12(a). The surface current distributions of the conventional antenna changes due to presence of notches on the radiating patch. The surface current distributions in the notch loaded antenna (proposed antenna) are studied and displayed in Figures 12(a) – 12(d). It is clearly seen from Figure 12(b) that for 3.44 GHz operation, the surface current is largely concentrated around the left rectangular notch (W_1, L_1) for which it is generated. For the 4.72 GHz excitation [see Figure 12(c)], large surface current distribution is observed around the top rectangular notch (W_2, L_2) for which it is mainly generated and controlled. Finally, it is verified from Figure 12(d) that for third resonant mode at 6.32 GHz, surface current is much strongly distributed around both of the rectangular notches (W_1, L_1, and W_2, L_2) of the proposed antenna. So, the excitation of third resonant mode is influenced by the dimensions of both of the notches. Thus, both from the S_{11} characteristic curves and surface current distributions, we can clearly comprehend the function of the related geometrical mechanism of the proposed antenna at three resonant modes. The current mainly concentrates at the edges of the notches. The current path increases due to lengthening of the surface current around the notches which leads to the miniaturization of the proposed antenna by decreasing the resonant frequency. The number of resonant frequency increases due to the disturbance caused to the mean current paths of any resonant mode.

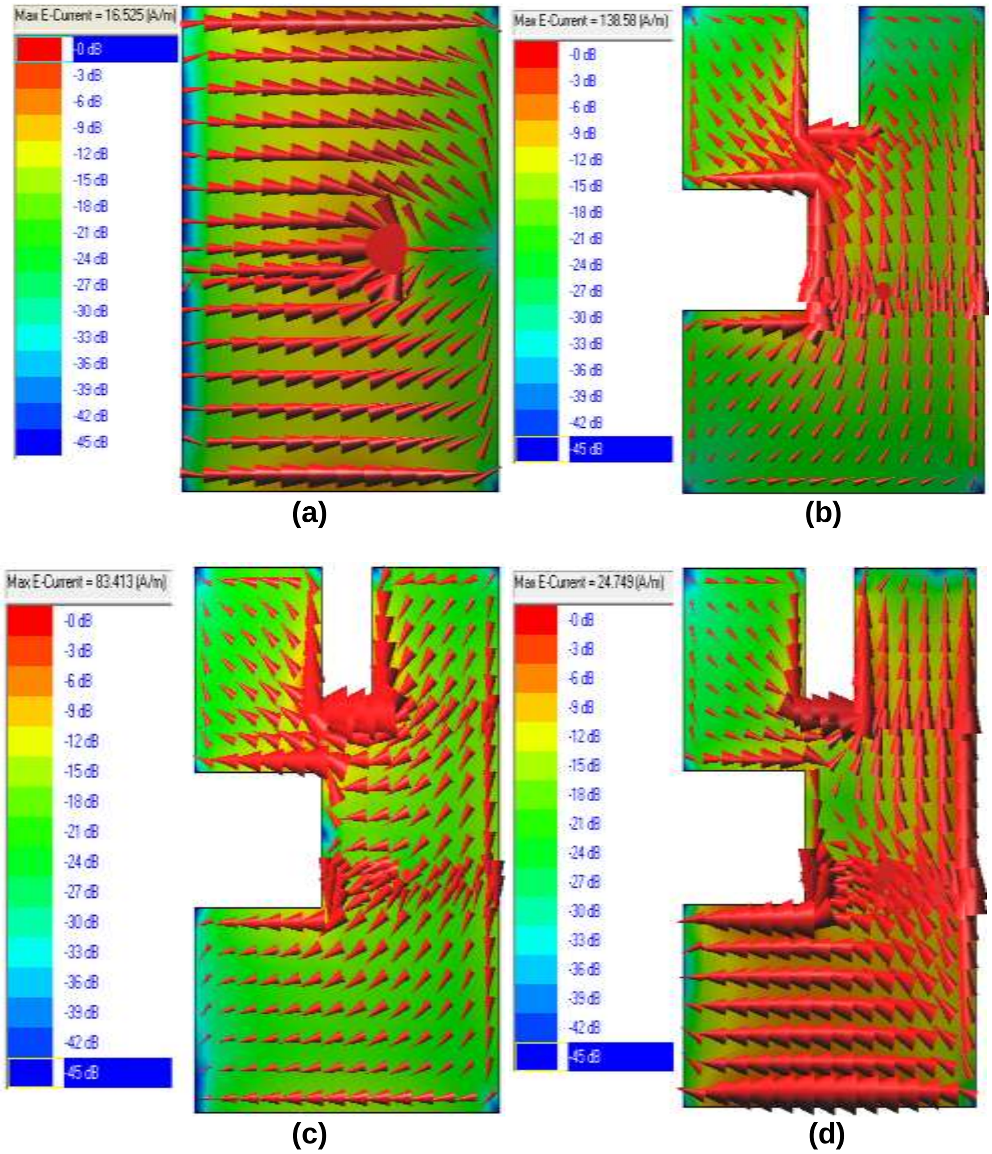

Figure 12. Surface Current Distribution of Antenna1 (Conventional) at (a) 5.5 GHz and Antenna 2 (Proposed) at (b) 3.44 GHz (c) 4.72 GHz (d) 6.32 GHz

6. Results and Discussion

The reflection coefficient of the proposed antenna was measured using Agilent E5071B vector network analyzer. The comparison of the measured and simulated reflection coefficient (S_{11} parameter) of the proposed antenna is shown in Figure 13. A significant improvement of frequency reduction is achieved in proposed microstrip antenna with respect to the conventional antenna structure. Due to the presence of notches in the antenna, the simulated results show that the first resonant frequency is reduced to 3.44 GHz with S_{11} of about −16 dB, the second resonant frequency is obtained at 4.72 GHz with S_{11} −17 dB, and third resonant frequency is obtained at 6.32 GHz with S_{11} of about −24 dB, respectively. The measured result shows that the first resonant frequency is achieved at 3.42 GHz with S_{11} of about −14 dB. The second and third resonant frequencies were measured at 4.76 and 6.16 GHz with S_{11} of about −16, and −20 dB, respectively. The small discrepancy between the measured and simulated result is due to the effect of improper soldering of SMA connector or fabrication tolerance. The simulated VSWR of the proposed antenna is shown in Figure 14. The VSWR of the proposed antenna is within 1.4:1 which signifies much less reflected power due to better impedance matching and practically considerable mismatch loss throughout different resonant frequencies. The simulated gain and directivity of the proposed antenna is depicted in Figure 15. The simulated peak gain of about 5.25dBi is achieved at 4.72 GHz. The directivity of the proposed antenna lies above 6.0dBi for all of the operating frequencies. The total and radiation efficiency of the proposed antenna is shown in Figure 16. It is found that for lower frequency of operation, the radiation efficiency of the antenna is about 75%. Peak radiation efficiency of about 77% is achieved at 4.72 GHz. The radiation patterns of the proposed antenna are shown in Figure 17 (a) – (b). The proposed antenna offers stable unidirectional radiation patterns in both E and H plane at respective frequencies with acceptable cross polarization level. The maximum radiation is exactly concentrated along 0°. The proposed antenna shows linear polarization in the broadside direction. The measured result of the proposed antenna is shown in Table 2.

6.1 Process of Size Reduction Calculation

6.1.1 Antenna 1 (Conventional Reference Antenna)

Resonant Frequency (f_r) = 5.45 GHz, The dimension of the patch = 16 (W) ×12 (L) mm^2. The area of the conventional reference patch = 192 mm^2.

6.1.2 Antenna 2 (Notch Loaded Patch without Modified Ground Plane)

Resonant frequency (f_r) = 3.44 GHz, The dimension of the patch = 20.3 (W) × 26.5 (L) mm^2, The new area of the patch = 537.95

$$\text{Size reduction} = \frac{\text{New area of the patch} - \text{area of the conventional reference patch}}{\text{New area of the patch}} \times 100\%$$

$$= \frac{(537.95 - 192)}{537.5} \times 100\% = 64.30\%$$

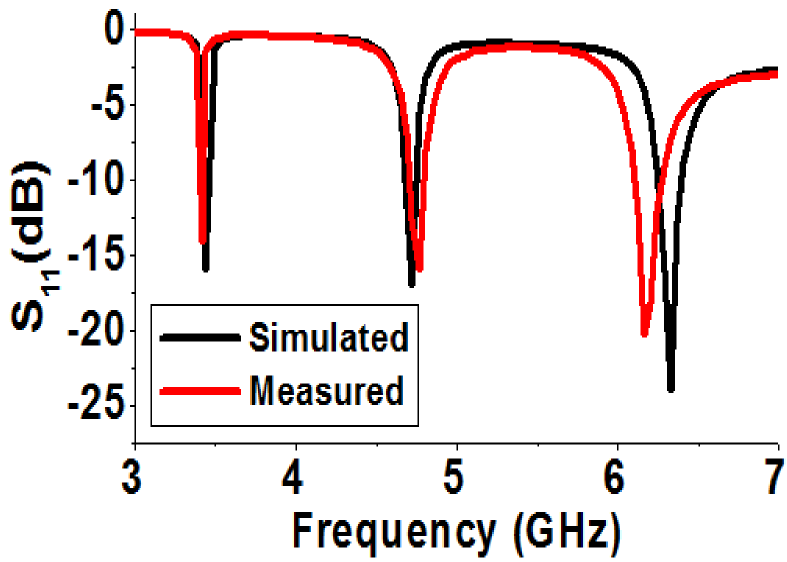

Figure 13. Reflection Coefficient (S_{11} parameter) of the Proposed Antenna

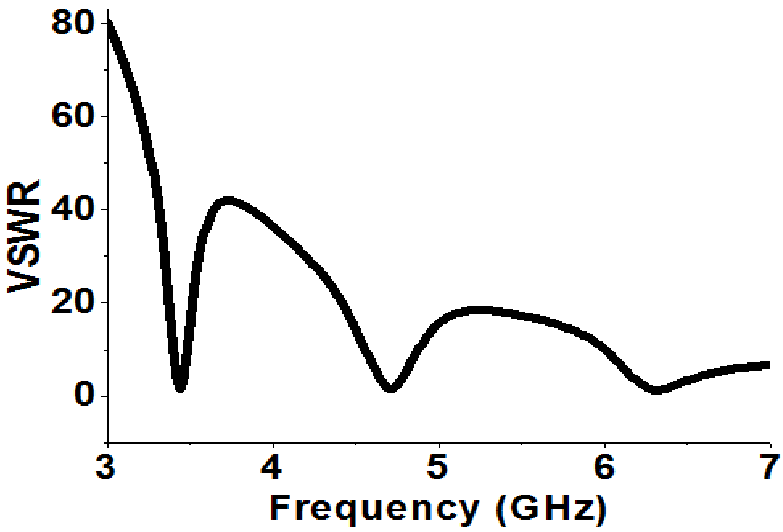

Figure 14. VSWR of the Proposed Antenna

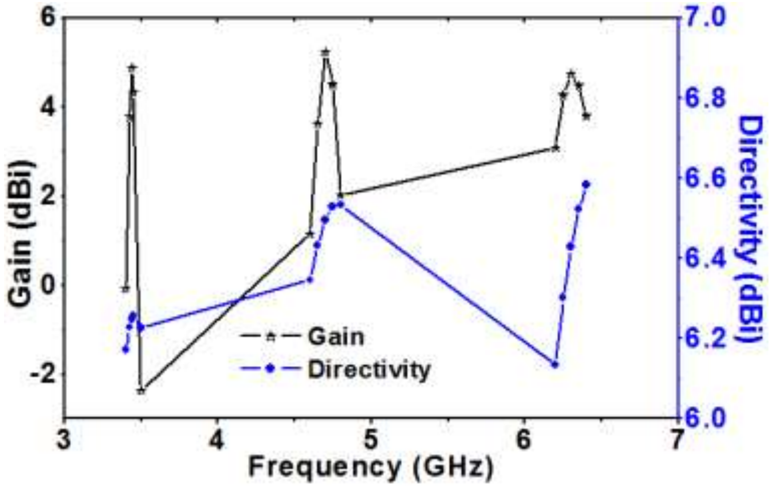

Figure 15. Gain and Directivity of the Proposed Antenna

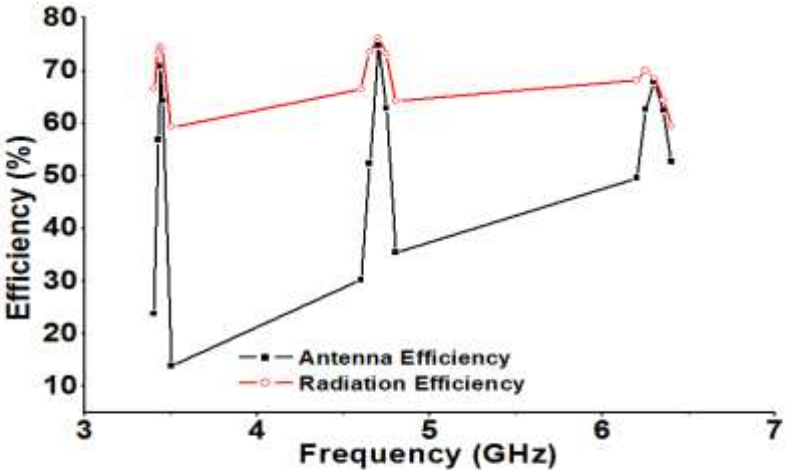

Figure 16. Plot of Efficiency versus Frequency of the Proposed Antenna

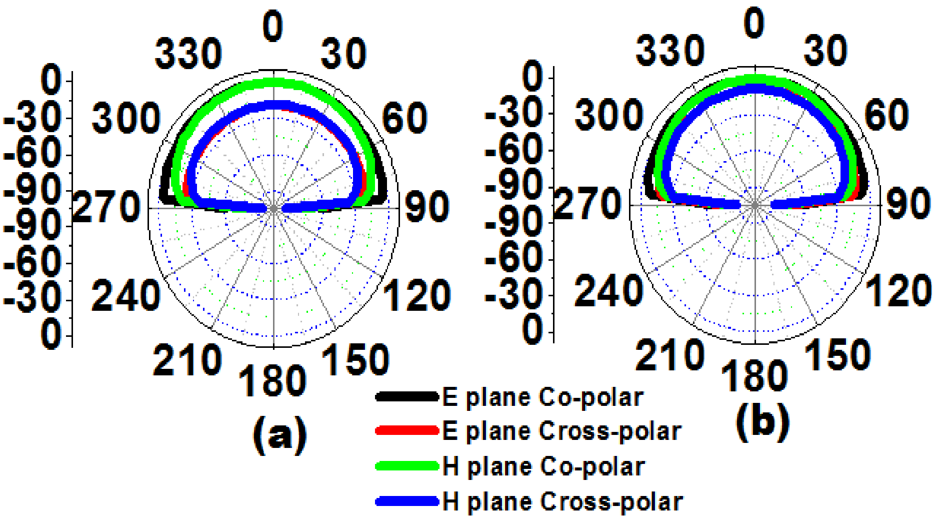

Figure 17. Radiation Pattern at (a) 3.44 GHz, (b) 4.72 GHz

Table 2. Measured Results of the Proposed Antenna

Antenna	Resonant freq. (GHz)	S_{11} (dB)	−10dB Band width (MHz)	Gain (dBi)	Frequency Ratio
Proposed Antenna	$f_1 = 3.42$ $f_2 = 4.76$ $f_3 = 6.16$	−14 −16 −20	40 100 180	5.0 4.9 5.5	$f_2/f_1 = 1.391$ $f_3/f_1 = 1.801$

7. Conclusion

This paper describes analysis and implementation of a rectangular notch loaded multifrequency printed antenna. The proposed antenna radiates three distinct frequencies i.e. 3.44, 4.72, and 6.32 GHz with increased frequency ratio. The designed multifrequency antenna also offers 64.3% size reduction compared to the conventional reference antenna. An optimization between miniaturization and impedance matching is maintained in this work. Furthermore, good stable broadside radiation pattern and acceptable gain are also obtained across the operating frequencies. The proposed antenna is suitable for a number of modern wireless communication systems such as Wi-MAX (3.3–3.6 GHz), INSAT system (4.5–4.8 GHz), and microwave S & C band applications.

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