Stub Loaded Rectangular Ring Shaped Tri-Band Monopole Antenna for Wireless Applications

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Abstract. This paper presents, design and equivalent circuit analysis of tri-band parasitically stub loaded rectangular ring printed monopole antenna for wireless communication applications. The printed monopole antenna is designed, fabricated and tested. The measured impedance bandwidth (S_{11}< -10 dB) is 750 MHz (2.22 – 2.97 GHz), 220 MHz (3.65 – 3.87 GHz) and 1.28 GHz (5.23 – 6.51 GHz) covering Wi-Fi, Wi-MAX and WLAN/Wi-MAX applications respectively. The electrical dimension of monopole is $0.245\lambda_0 \times 0.212\lambda_0$. The proposed antenna is simple and a low profile structure fabricated using low cost glass epoxy substrate (FR4). The overall size of antenna is 60 × 40 mm^2. Using slot cut and parasitically coupled stub loading methods, the tri-band monopole antenna has been realized and measured results are found to be in good agreement with simulated results. The equivalent circuit analysis and mutual coupling between the slots are calculated and presented.

Keywords: Equivalent circuit, Rectangular Ring, Tri-band, WLAN/Wi-MAX

1. Introduction

The speedy growth in modern wireless communication systems demands compact and multiband antennas to cover wireless applications such as wireless local area network (WLAN: 2.4-2.48 GHz, 5.15-5.35 GHz, 5.725–5.825GHz), worldwide interoperability for microwave access (Wi-MAX: 2.5 -2.69 GHz, 3.4-3.69GHz, 5.25-5.85GHz) etc. These communication systems need multiband antennas with wide bandwidth to cover the complete and desired bands of application. To meet the crucial requirements of wideband/ multiband wireless communication systems, microstrip patch antennas (MPAs) are found suitable. However, a single band and narrow bandwidth is the main limitation of the microstrip patch antenna. These limitations can be overcome by using suitable techniques such as cutting the slot inside the radiating patch or loading stub to yield compact antenna or to achieve a multiband response, respectively, and use of a thicker substrate with low relative permittivity for bandwidth enhancement. The use of a thicker substrate can enhance the operating bandwidth but at the cost of higher volumetric size [1-2]. The limitation of size in a compact and modern wireless system is ubiquitous. Through using microstrip line feed and partial ground technique, a substrate with lower thickness can be used to realize compact and wideband antennas. Therefore, many antenna researchers are motivated to design compact, multiband antennas with a wideband response for various wireless communication applications [3-20]. The use of coplanar waveguide (CPW) fed triangular monopole antenna with slit and stub for tri-band application [3], a monopole antenna having fork-shaped strips inside a rectangular ring along with defected ground is presented to cover WLAN and Wi-MAX applications [4]. CPW fed tri-band monopole antenna with stub and asymmetrical ground for linear and circular polarization [5], triangular quasi self -complementary antenna with rectangular slit cut [6], a paper-based inject printed U-slotted tri-band antenna [7], inverted L-shaped strip based bent fork-shaped compact antenna [8], a microstrip planar antenna with G-shaped slot and U-shaped stub for WLAN/WiMAX applications [9], CPW fed dual modified U slot-loaded monopole antenna for tri-band [10], U-shaped strip and L-shaped slot loaded monopole antenna [11] have been reported. The mutual coupling and coupling factor between the slots of microstrip antenna is reported [1,12]. The use of stubs or parasitic elements has used to design multiband antennas [18-19]. Some of the reported antenna is compact in size with complex design and comprises low fractional bandwidth in lower WLAN.

In this paper, a microstrip line fed rectangular ring monopole antenna loaded with a slit is proposed for tri-band WLAN/Wi-MAX operations. The slit is embedded into the rectangular ring patch to realize dual-band operations. Further, to achieve tri-band operation, parasitically coupled stub of quarter wavelength is placed on the partial ground. The proposed antenna is theoretically analyzed using the transmission line equivalent circuit and various lumped parameters are calculated. The mutual coupling and coupling factor between rectangular ring and slit of this antenna is calculated. The proposed antenna is fabricated using FR4 substrate having substrate parameters h = 1.6 mm, ε_r = 4.3, and $\tan \delta = 0.02$. The antenna is designed and simulated using the method of moments based CAD Feko [13]. The designed antenna structure is simulated using an infinite ground plane.

2. Antenna geometry design

The geometrical design process of the proposed monopole antenna is depicted in Figure 1. Figure 2 presents the complete geometrical design of the proposed tri-band monopole antenna. The rectangular ring monopole antenna comprises

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rectangular monopole having length and width of $L \times W$. The length L of the rectangular patch is calculated using equation (1) and (2) [1-2].

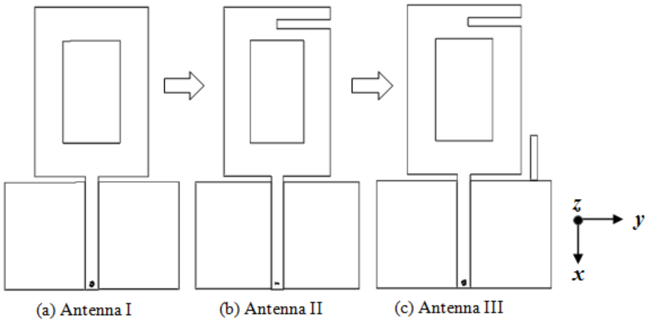
$$L = \frac{c}{4f_r\sqrt{\varepsilon_{re}}} \qquad (1)$$

where, c is 3×10^8 m/s, f_r is desired resonance frequency and ε_{re} is an effective dielectric constant given as

$$\varepsilon_{re} \approx \frac{(\varepsilon_r+1)}{2} \qquad (2)$$

The rectangular ring is realized by cutting the rectangular slot inside the patch of size 18 × 13 mm^2. The microstrip feed line having width of w_f is used to feed the antenna. The partial ground of size $L_g \times W_g$ is placed beneath the radiating patch and feed line with an optimized gap of g as shown in Figure 1(a). The designed antenna structure (Antenna I) resonates at 2.25 GHz having impedance bandwidth of about 1.34 GHz which covers Wi-Fi/WLAN (2.4-2.5 GHz/2.4- 2.48 GHz). Further, a slit of dimension $l_s \times w_s$ is incorporated into the rectangular ring to realize dual-band response as shown in Figure 1(b) (Antenna II). The location and dimension of the slit is optimized to get the desired dual-band response at 2.15 GHz and 3.46 GHz, respectively. To realize the tri-band response, a stub of approximately quarter wavelength at higher frequency is placed in the ground plane as shown in Figure 1(c) (Antenna III).

The complete geometrical design of tri-band printed monopole antenna is shown in Figure 2. The geometrical parameters with dimensions are given in Table 1.



(a) Antenna I (b) Antenna II (c) Antenna III

Fig.1. Geometrical design process (a) rectangular ring (b) slit embedded into the rectangular ring (c) stub loaded slit embedded rectangular ring antenna.

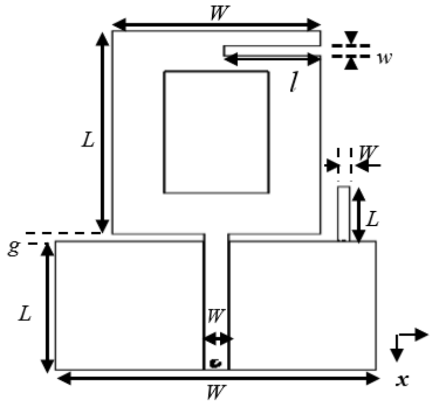


Fig.2. Geometry of tri-band monopole antenna

Table 1: Antenna geometrical parameters

Parameter	Dimension (mm)	Parameter	Dimension (mm)
L	30	l_s	12
W	26	w_s	1.5
L_g	19	L_s	8
W_g	40	W_s	1.5
g	1	w_f	3

3. Equivalent circuit analysis

From Figure 2, it is seen that the tri-band antenna comprises three main sections as (i) the microstripline fed rectangular ring microstrip patch antenna (RRMPA), (ii) slit embedded into rectangular ring antenna, and (iii) stub loaded antenna. The use of simple circuits based on lumped elements helps to gain an understanding of antenna design and analysis [20]. The analysis of the antenna is carried out using a transmission line equivalent circuit analysis. The microstrip patch antenna with a rectangular ring is fed using microstrip line. The microstrip line can be represented using two series inductors L_{ML} with shunt capacitor C_{ML} and rectangular ring microstrip patch antenna can be modelled using parallel R_1, L_1, C_1 circuit [1] as depicted in Figure 3. As the current density is maximum at the edge of microstrip patch, a slit embedded into rectangular patch does not alter the performance characteristics of microstrip patch antenna.

The parallel R_1, L_1 and C_1 can be expressed as [1],

$$C_1 = \frac{\varepsilon_0\varepsilon_r LW}{2h} cos^{-2}\left(\frac{\pi y_0}{L}\right) \qquad (3)$$

$$L_1 = \frac{1}{C_1\omega_0^2} \qquad (4)$$

$$R_1 = \frac{Q}{\omega_0 C_1} \qquad (5)$$

where, Q is quality factor and expressed as [14],

$$Q = \frac{c\sqrt{\varepsilon_{re}}}{4f_r h} \qquad (6)$$

In equations (3), (4), (5) and (6), c is velocity of light in free space and given by 3×10^8 m/s, f_r is resonance frequency, h is substrate thickness, ω_0 is angular frequency, L and W are length and width of rectangular microstrip antenna and ε_{re} is effective dielectric constant and expressed as [1, 14].

$$\varepsilon_{re} = \frac{(\varepsilon_r+1)}{2} + \frac{(\varepsilon_r-1)}{2\sqrt{1+12\frac{h}{W}}} \qquad (7)$$

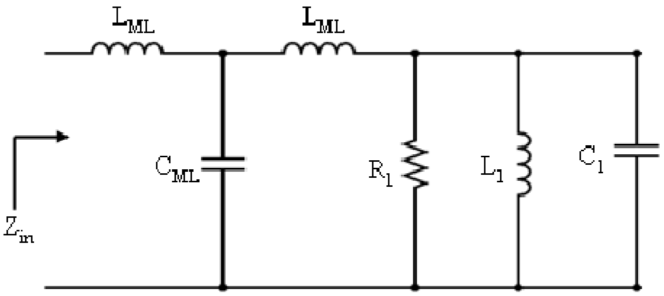


Fig.3. Equivalent circuit of microstrip line fed RRMPA

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The calculated values of L_1 and C_1 are 9.28 *pF* and 0.45 *nH*, respectively. The microstrip feed line is represented as series inductance and shunt capacitance and can be expressed as [1]

$$C_{ML} = w_f(9.5\varepsilon_r + 1.25)\frac{w_f}{h} + 5.2\varepsilon_r + 7.0 \qquad (8)$$

$$L_{ML} = 100.h.\left(4\sqrt{\frac{w_f}{h}} - 4.21\right) \qquad (9)$$

In equation (8) and (9), w_f is width of microstrip feed line and calculated as given in [15]. In further analysis, a slit of length l_s and width w_s is embedded into the RRMPA. This slit introduces a new band at around 3.5 GHz. The slit is perpendicular to the direction of vertical current and can be modeled as radiation resistance with reactance, as presented in Figure 4. The slit offers capacitive as well as inductive reactance X_c and X_L, respectively. The introduction of new frequency can be represented by it radiation resistance.

As, the slit can be modeled as resonator, its equivalent inductance and capacitance can be expressed using modified equations [1, 16].

$$L = \frac{h\mu_0\pi}{8}\left(\frac{l_s}{w_s}\right) \qquad (10)$$

$$C = \frac{\varepsilon_0\varepsilon_r l_s w_s}{h} \qquad (11)$$

In equation (10) and (11), $\mu_0 = 4\pi \times 10^{-7}$ H/m and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. The estimated values of slot inductance and capacitance are 6.31 *nH* and 0.42 *pF* respectively.

To realize tri-band response, a parasitically loaded quarter wavelength stub is added to the ground plane beneath RRMPA. This stub contributes third resonance frequency at around 6 GHz. This stub can be modeled as a parasitically connected resonator, which is excited by the fringing field of RRMPA.

The inductance L_{st} and capacitance C_{st} for resonator can be expressed by [17].

$$C_{st} = \frac{2W_s\varepsilon_r}{L_s h\omega_0^2} \qquad (12)$$

$$L_{st} = \frac{1}{C_1\omega_0^2} \qquad (13)$$

where, L_s and W_s are length and width of stub, respectively. The calculated values for inductance and capacitance are 0.99 *mH* and 7.58 × 10^{-19} *F*, respectively. This resonator is parasitically coupled with main RRMPA; therefore, a fringing capacitance exists between RRMPA and stub. This fringing capacitance is expressed as [1].

$$2C_f = \sqrt{\frac{\varepsilon_{re}}{c.Z_0}} - C_p \qquad (14)$$

where, Z_0 is characteristics impedance equal to 50 Ω and parasitic capacitance is calculated using equation (15) [1].

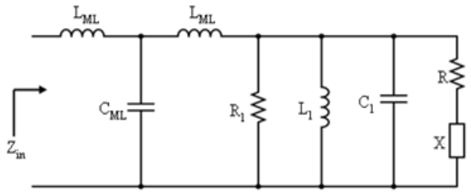

Fig.4. Equivalent circuit of microstrip line fed RRMPA with slot

$$C_p = \varepsilon_0\varepsilon_r\frac{W_s}{h} \qquad (15)$$

The estimated value of fringing capacitance is 7.35 μF. The transmission line equivalent circuit of the proposed antenna is depicted in Figure 5.

The investigation also carried out to calculate the coupling factor between the two slots, viz. rectangular ring and horizontal slit. The calculated coupling factors is about 0.195 which is sufficiently less [12]. As the coupling factor is low, horizontal slit is independently resonating near 3.5 GHz and does not affect the performance of the antenna. The coupling factor between the two slots is expressed using the equations (16), (17) and (18) [1,12].

$$f_g = \frac{g_m}{g_s} \qquad (16)$$

$$g_m = \frac{k_0}{\pi\eta_0}\left\{\left(1 - \frac{s^2}{24}\right)J_0(l) + \frac{s^2}{24}J_2(l)\right\} \qquad (17)$$

$$g_s = \frac{k_0}{2\eta_0}\left(1 - \frac{s^2}{24}\right) \qquad (18)$$

In equations (16), (17) and (18), g_m is mutual conductance, g_s is per unit length self- conductance, $S = k_0.h$, η_0 is 120 π and $l = k_0.\ q$. The separation between two slots with reference to their center is denoted by q=12 mm. In the next section, the detailed results of the proposed antenna are presented and discussed.

4. Results and discussion

The return loss characteristics of all the three antennas is compared and shown in Figure 6. Antenna I resonating at 2.25 GHz realizes the impedance bandwidth of 53.38 % (1.84 – 3.18 GHz), which is useful for lower WLAN/Wi-Fi application. Slit embedded rectangular ring monopole antenna (Antenna II) exhibits dual-band response at 2.15 GHz and 3.46 GHz having a bandwidth of 35.3% (1.8-2.57 GHz) and 23.9 % (3.16-4.02 GHz), respectively. It is observed that the resonant frequency shifted towards the lower side with some deprivation in impedance bandwidth. In antenna III, the stub of quarter wavelength at higher resonating frequency acts as monopole and contributes to third resonant frequency. The realized tri-band frequencies are 2.25 GHz (1.87-2.8 GHz), 3.51 GHz (3.2 - 4 GHz) and 6.04 GHz (5.4 – 6.5 GHz). The proposed design of monopole antenna exhibits impedance bandwidth of 39.82 %, 22.2 %, and 18.4 % at 2.25 GHz, 3.51 GHz and 6.04 GHz, respectively.

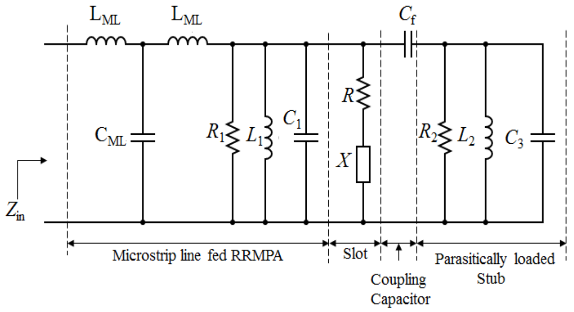

Fig.5. Equivalent circuit of proposed antenna

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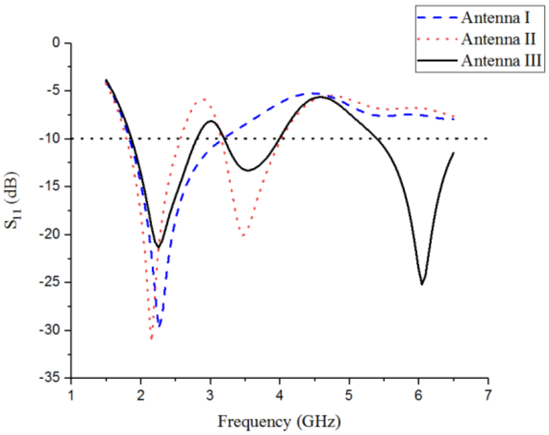


Fig.6. Return loss characteristics of antenna I, antenna II and antenna III.

The variation in second resonance frequency with the change in slit dimensions is depicted in Figure 7. It is observed that by varying the length of slit, middle resonance frequency is shifted towards the higher side, while the change in slit width does not alter resonance frequency. It is also observed that the slit length changes the impedance at higher frequency.

The addition of quarter wavelength stub to partial ground plane yields third resonance at 6.04 GHz, covering higher WLAN (5.725-5.825 GHz) wireless application with 18.4% impedance bandwidth. The effect of variation of stub width is studied and depicted in Figure 8. It is observed that varying the width of the stub, the resonance frequency of third resonance shifted slightly towards the higher frequency side. The surface current distributions at all three resonance frequencies are shown in Figure 9. It is depicted from Figure 9 (a) that the rectangular ring contributes to the lower resonance frequency. The slot of nearly quarter wavelength contributing second resonance frequency and stub placed at ground generates third resonance frequency as current density is higher at slit and stub as shown in Figure 9 (b) and (c), respectively.

The simulated radiation patterns in E- and H- planes for tri-band monopole antenna are shown in Figure 10. The antenna offers peak gain of about 1.7 dBi, 1.35 dBi and 1 dBi at 2.25 GHz, 3.5 GHz, and 6.04 GHz, respectively.

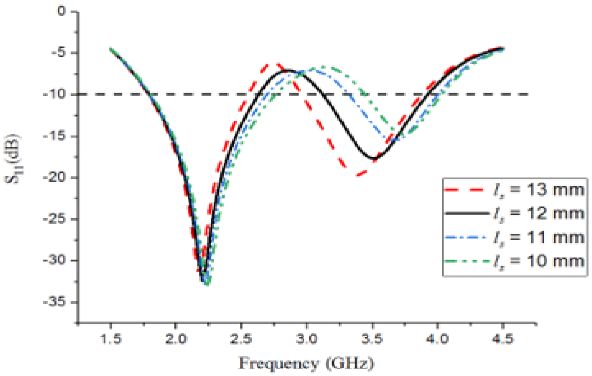


Fig.7. Effect of variation of slot length on middle resonance frequency.

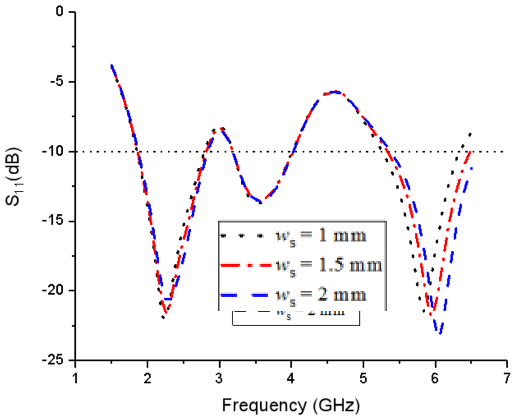
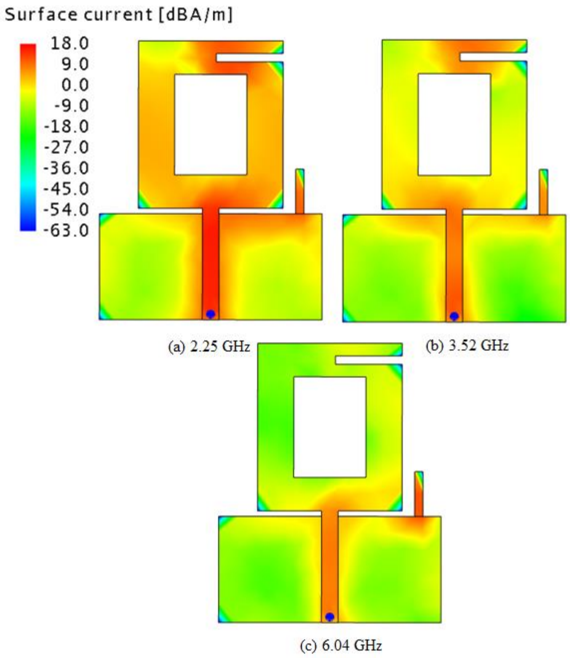


Fig. 8 Effect of stub width variation on return loss

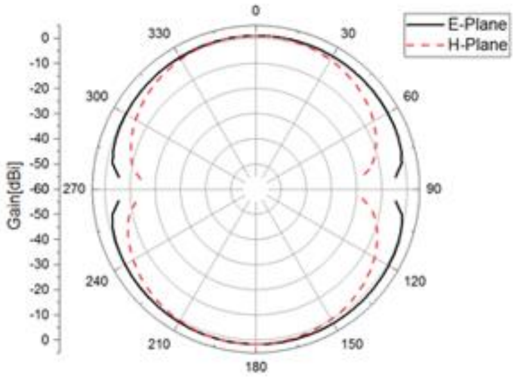


(a) 2.25 GHz (b) 3.52 GHz

(c) 6.04 GHz

Fig. 9 Surface current distribution (a) 2.25 GHz, (b) 3.5 GHz, (c) 6.04 GHz

The observed radiation pattern is in broadside direction for all three frequencies. The simulated efficiency and gain are shown in Figure 11. The observed efficiency of proposed antenna is near to 80 to 85 % for lower and middle resonance frequency, respectively and 65% for higher frequency.



(a)

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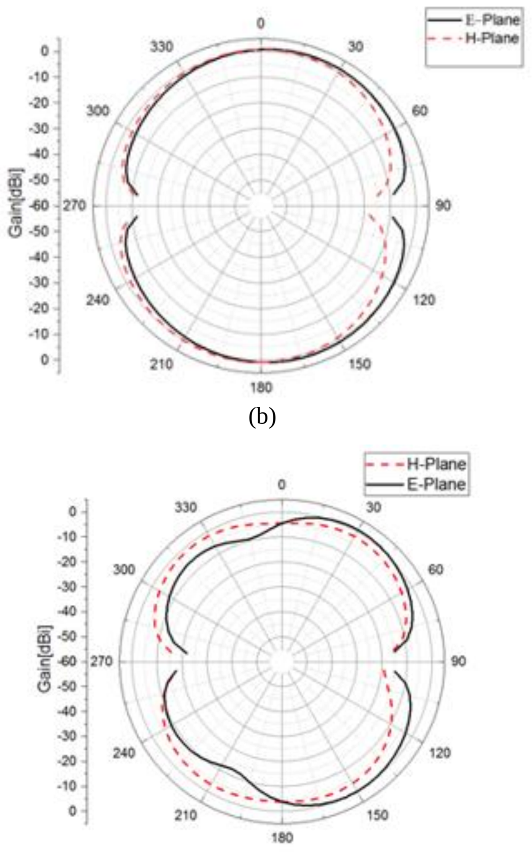


(b)

(c)

Fig.10. Radiation pattern (a) 2.25 GHz, (b) 3.5 GHz, (c) 6.04 GHz

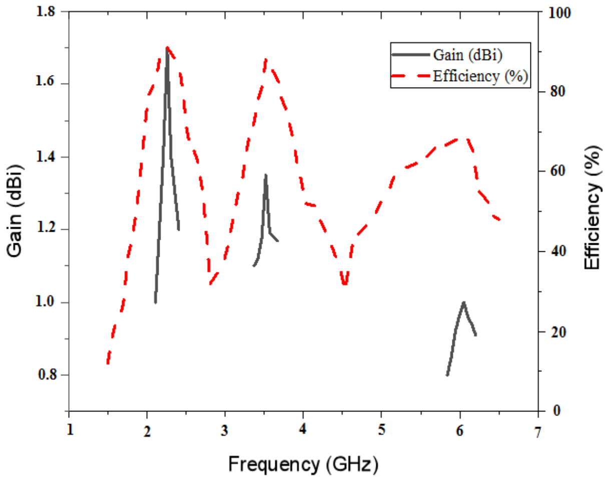


Fig.11. Simulated gain and efficiency

The designed and simulated antenna structure is fabricated using FR4 substrates. The fabricated antenna structure is tested using R & S ZVL VNA. The measured results are found to be in good agreement with simulated results. The measured and simulated results are compared and presented in Figure set up shown in inset. The measured bandwidth 28 % (2.22 – 2.97 GHz), 5% (3.65-3.87 GHz) and 20 % (5.23 – 6.51 GHz). The performance of the proposed antenna is compared with previously reported antenna designs and compared in Table 2.

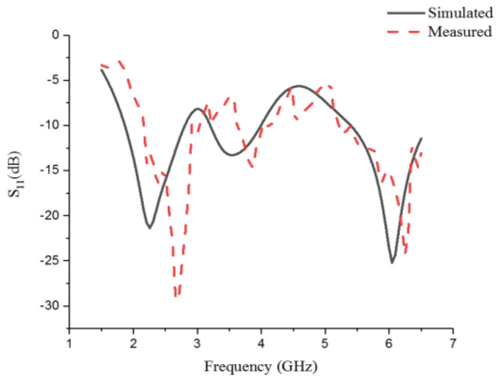
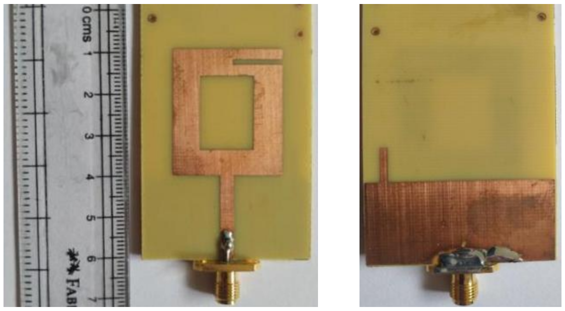
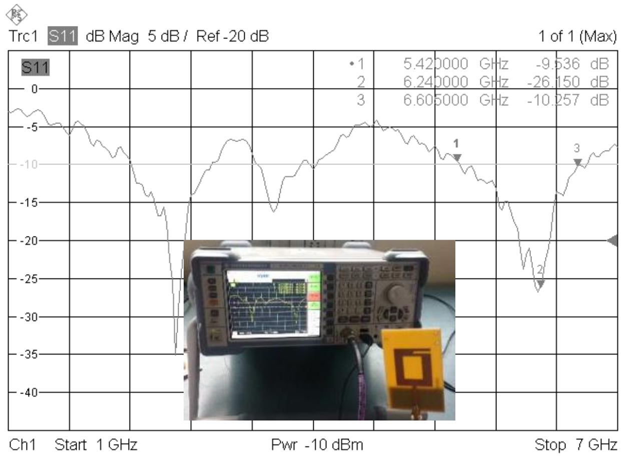


Fig.12. Simulated and measured return loss



(a) (b)

Fig.13 Fabricated prototype (a) top side (b) bottom side



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•1   5.420000  GHz   -9.536  dB
 2   6.240000  GHz  -26.150  dB
 3   6.605000  GHz  -10.257  dB
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Fig.14. Measured return loss and experimental setup

5. Conclusion

In this paper, design of tri-band microstrip antenna for wireless communication applications is presented. The antenna resonates at 2.25 GHz, 3.5 GHz and 6.04 GHz with simulated and measured impedance bandwidth of 39.82 %, 22.2 %, 18.4 % and 28 %, 5 % and 20 % respectively. The designed antenna radiates in broadside direction for all three bands with maximum gain of 1.7 dBi. The antenna fulfills broadband response for tri-band applications. The antenna is tested and measured results are found in good agreement. The performance of proposed antenna is compared with previously reported results and presented. The antenna can be useful for wireless applications.

Table 2: Performance comparison with previously reported work

Ref.	Size (mm^2)	ε_r	Thickness h (mm)	Band-I Fractional Bandwidth (%)	Band-II Fractional Bandwidth (%)	Band-III Fractional Bandwidth (%)
[3]	40 × 36	3.55	1.52	19.37	6.93	7
[4]	34 × 18	4.4	1.6	8.73	8.74	24.11
[6]	40 × 29	4.4	1	20.35	9.3	14
[7]	12 × 37.3	3.2	0.44	3.21	28.1	36
[9]	29 × 25	4.4	1.6	4.9	9.1	31.65
Proposed Work	60 × 40	4.3	1.6	28.9	5.85	21.8

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Biography of the authors

Mandar P. Joshi received B.E. in Electronics and Telecommunication Engineering from North Maharashtra University, Jalgaon and M.E. in Electronics from Dr. Babasaheb Ambedkar Marathwada University, Aurangabad (MS) India in 2003 and 2012 respectively. Presently, he is working as Assistant Professor in E & TC at GES’s R. H. Sapat College of Engineering, Management Studies and Research, Nashik (MS), India. His research interest includes microstrip patch antennas for Wi-Fi, WLAN, Wi-MAX, BAN, broadband microstrip antennas, wearable microstrip antenna.

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