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Printed Monopole Antennas for Multiband Applications

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***Abstract*- In this paper, we have investigated printed rectangular monopole antennas, which is basically a printed microstrip antenna with etched ground plane for multi-band applications. In particular, we have fabricated and tested printed rectangular monopole antennas for dual-band and penta-band applications. It has been observed that printed rectangular monopole antennas are small in size and simple in design and fabrication but its performance is very good for multiband applications.**

***Index Terms*- Printed rectangular monopole antennas, Microstrip antennas and Multiband antennas**

I. INTRODUCTION

Antennas which can work properly in more than one frequency region either for transmitting or receiving electromagnetic (EM) waves, are termed as Multi-band antennas [1]. Such antennas are usually used for dual-band, tri-band, penta-band applications. Multi-band antennas are much more complex than the single band antennas in their design, structures and operations. We will investigate printed rectangular monopole antenna (PRMA), which is simply a printed rectangular microstrip antenna (RMSA) with etched ground plane [2]. Printed rectangular/square monopole antennas have been investigated for GSM/PCN frequency band. Formula to calculate roughly lower frequency of these antennas has been presented. In [3], the effect of varying the plate width, feed gap height, and microstrip feed line width on the impedance bandwidth is briefly examined. A trapezoidal ultra-wideband (UWB) antennas having a notch function is proposed in [4]. The proposed antennas cover the entire UWB band (3.1 - 10.6GHz) and notch out the IEEE 802.11a frequency band (5.15 - 5.825GHz). Some researchers have also studied printed monopole antenna like circular disk printed monopole antenna [5] for UWB applications. In this paper, we have fabricated and tested PRMA for dual-band and penta-band applications.

II. PRINTED MONOPOLE ANTENNAS: DESIGN & SIMULATIONS

We will design of RMSA at a resonant frequency of 2.4GHz. We will employ the following procedure [6] for the RMSA design. For an RMSA to be an efficient radiator, W should be taken equal to half the wavelength corresponding to the average of the two dielectric mediums (i.e., substrate and air).

$$W = \frac{c}{2 f_0 \sqrt{\frac{\varepsilon_r + 1}{2}}}$$

where f_0 is the resonant frequency of the microstrip antenna (MSA), ε_r is the relative dielectric constant of the substrate

In this design, FR4 substrate of relative permittivity of 4.4 and height h=1.6mm is used. The value of ε_e is slightly less than ε_r,

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because the fringing fields around the periphery of the patch are not confined in the dielectric substrate but are also spread in the air.

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + \frac{10h}{W}}}$$

Due to the fringing fields at the two edges, the effective length of the RMSA is given by

$$L_e = L + 2\Delta L = \frac{c}{2 f_0 \sqrt{\varepsilon_e}}$$

Because of the fringing effects, electrically the patch of the MSA looks greater than its physical dimension (extension of ΔL on both sides). A very practical approximate relation for the normalized extension of the length is given by

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{eff} + 0.3)(\frac{w}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{w}{h} + 0.8)}$$

where h is the thickness of the substrate and it is assumed to be much smaller than the dimensions of the antenna.

After calculation of the dimensions of the patch, the design process is continued with the matching of the antenna resistance to 50Ω of the input line. For impedance matching with the microstrip feed line, inset-feeding technique is generally used. Position of the inset feed point is calculated as follows:

$R_{in} = R_e \sin^2(\frac{\pi x}{L})$ for $0 \le x \le L/2$

where $R_e = \frac{1}{2(G_r \pm G_m)}$, + sign is usually chosen due to the odd field distribution between the radiating slots for the dominant TM_{010} mode and $G_r = 1/R_r$ is the slot conductance and G_m is the mutual conductance which accounts for mutual coupling between the two slots. The expressions for G_m and G_r [1] are

$$G_r = \frac{I_1}{120\pi^2}$$

$$I_1 = \int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W \cos\theta}{2}\right)}{\cos\theta} \right]^2 \sin^3\theta d\theta$$

$$= -2 + \cos(X) + X S_i(X) + \frac{\sin(X)}{X}; X = k_0 W$$

and

$$G_m = \frac{1}{120\pi^2} \times$$

$$\int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W \cos\theta}{2}\right)}{\cos\theta} \right]^2 J_0(k_0 L \sin\theta) \sin^3\theta d\theta$$

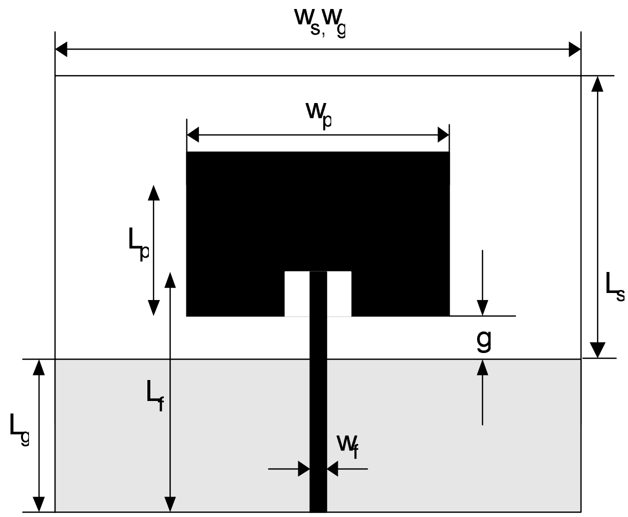
In the above formula, R_e is the resonant resistance of the patch antenna (at the edge) and R_{in} is the required input resistance, which is 50Ω for this case. Note that the antenna resistance (R_a) is highest at the edge and lowest at the center. The inset feed point x is a point in between the edge and center of the patch antenna. The feed point location is chosen at the mid-point of the width of the patch antenna to avoid higher order mode excitations. For microstrip feeding lines, the width of the microstrip lines (W_m) for 50Ω characteristic impedance, can be calculated [7] from

$$\frac{W_m}{h} = \begin{cases} \frac{8e^A}{e^{2A} - 2}; \frac{W_m}{h} < 2 \\ \frac{2}{\pi}\left[\begin{matrix} B - 1 - \ln(2B - 1) \\ + \frac{\varepsilon_r - 1}{2\varepsilon_r} \left\{ \begin{matrix} \ln(B-1) + \\ 0.39 - \frac{0.61}{\varepsilon_r} \end{matrix} \right\} \end{matrix} \right]; \frac{W_m}{h} > 2 \end{cases}$$

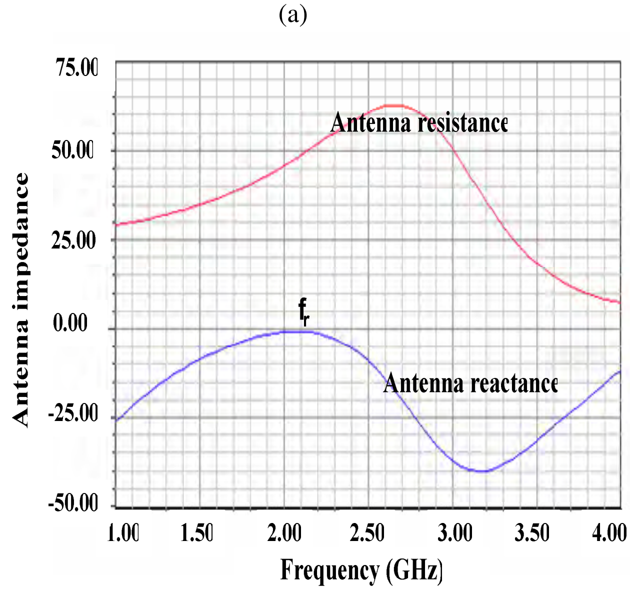
$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right);$$

$$B = \frac{377\pi}{2 Z_0 \sqrt{\varepsilon_r}}$$

In the above equation, Z_0 is usually chosen as 50 ohms, h and ε_r are fixed for a particular substrate. An in-house MATLAB program is developed based on the above design formulae and it gives the patch antenna and microstrip line dimensions for a given specification like frequency of operation, substrate parameters, etc. As mentioned earlier, for printed monopole antenna, some portion of the ground plane is removed as shown in Fig. 1(a).



(a)



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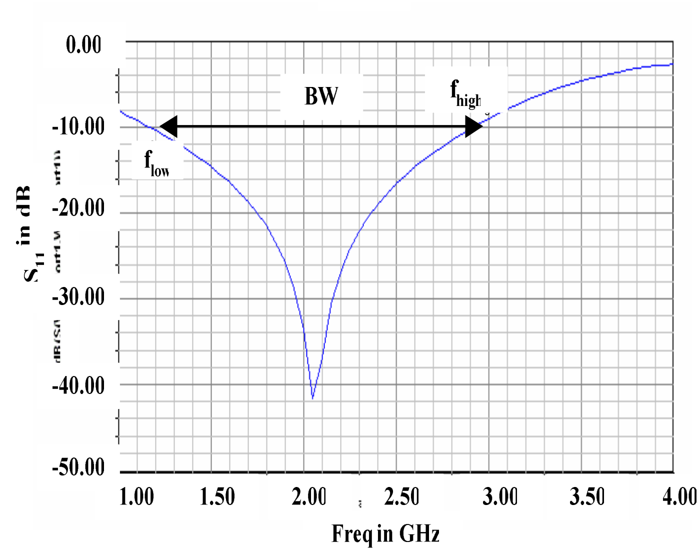

(c)

Fig..1. (a) Geometry of printed rectangular monopole antenna (b) Antenna impedance vs frequency (c) Simulation results of printed rectangular monopole (s_{11} vs frequency)

The gap between the ground plane and the patch is called the feed gap denoted as ‘g’, which is a critical parameter for controlling antenna performance. The rectangular monopole antenna dimensions are calculated for 2.4GHz operation: Width of the patch (W_p) = 38.01mm, Length of the patch (L_p)= 29.396mm, Width of the substrate (W_s)= 2 × 38.01 = 76 mm, Length of the substrate (L_s)= 2 × 29.396 = 58.8 mm. The gap between the ground plane and patch antenna, g, values were varied from 1, 2, 3 and 3.5 respectively and the length of the ground plane was changing correspondingly L_g=(14.7-g)mm. The ground plane width was taken twice the patch antenna width. It is observed that as value of g increases the antenna impedance, bandwidth (BW) and antenna radiation efficiency (η) also increases as shown in Table I. Here initially the gap (g) between the patch and the ground plane is 1mm and it is increased up to 3.5mm in order to get the antenna resistance (R_a) to be 50 ohms for maximum antenna performance. Note that even if our initial design for RMSA was for

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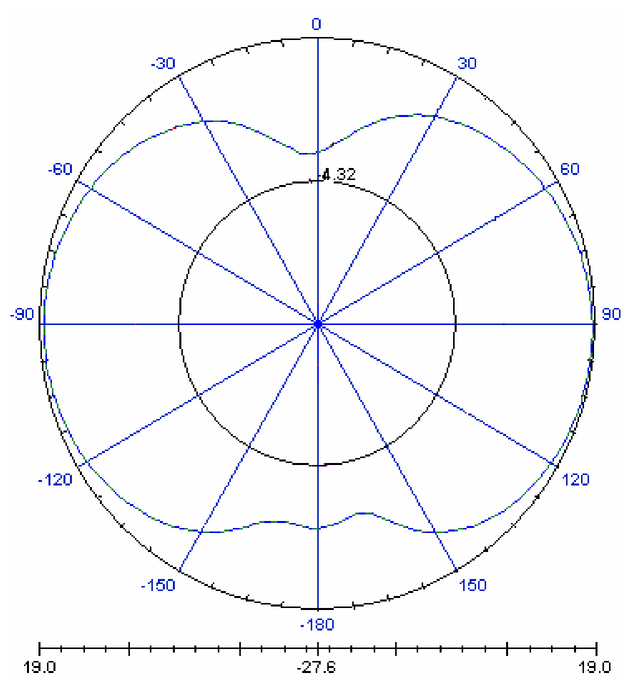
L_g (mm)	g (mm)	f_{low} (GHz)	f_{high} (GHz)	f_r (GHz)	R_a (Ω)	BW (%)	η (%)
13.7	1	2.2	3.0	2.62	90	31	75
12.7	2	1.6	3.1	2.45	65	61.2	91.5
11.7	3	1.5	3.1	2.2	55	73	94.0
11.2	3.5	0.9	3	1.8	50	116	95.6

2.4 GHz, after the ground plane removal the frequency of operation for the patch antenna will be shifted (mostly dependent on the parameter g). Even the radiation pattern for the printed rectangular monopole antenna will be different from the conventional RMSA as we will see later. Next we try to reduce the size of the ground plane and substrate of the printed monopole antenna so that the overall patch antenna dimension is smaller. The antenna performance depending on the various parameters for this case is tabulated in Table II. We have chosen the following dimensions: W_p = 38.01mm, L_p = 30mm, W_s = 42.01mm, L_s = 35.5 mm, W_g = 42.01mm and L_g = (14.7-g) mm. The value of g was increased from g=3, 3.5, 4.5, 5, 5.5. It was observed that the antenna resistance is exactly 50 ohm for g=5.5. The IE3D simulated antenna impedance vs frequency as well as scattering parameter vs frequency for the printed rectangular monopole antenna is shown in Fig 1(b) and 1(c). Note that in Fig. 1(b), the antenna is resonating when the imaginary part of the antenna impedance is crossing zero axis at 2.1GHz (i.e. the resonance frequency of the antenna denoted by f_r) and the antenna impedance (or rather) resistance is read at that frequency. We can observe that the antenna impedance is 50ohm at that frequency hence the antenna is properly matched to the input microstrip line. The operational bandwidth (BW) of the antenna is the frequency region where the s_{11} parameter is below -10dB and from Fig. 1(b) we can see that the start frequency of the BW, f_{low} is 1.2GHz and the end frequency of the BW, f_{high} is 2.9GHz. The radiation patterns of the printed rectangular monopole antenna are also depicted in Fig. 2(a) and 2(b). The E-plane radiation pattern is in the form of 8 and the H-plane radiation pattern is in the shape of O, similar to what has been reported in [2].

Table I Printed monopole antenna performance for various feed gap and ground plane length (W_s=W_g=76.0mm)

Table II Printed monopole antenna performance for various feed gap and ground plane length (W_s=W_g=42.01mm)

L_g (mm)	g (mm)	f_{low} (GHz)	f_{high} (GHz)	f_r (GHz)	R_a (Ω)	BW (%)	η (%)
11.7	3	1.5	2.5	1.8	85	55.55	65.26
11.2	3.5	1.2	2.4	2	68	65	80.65
10.2	4.5	1.3	2.9	2.2	60	72.72	98.19
9.7	5	1.1	2.8	2.0	56	85	98.34
9.2	5.5	1.2	2.9	2.1	50	115	98.581



(a)

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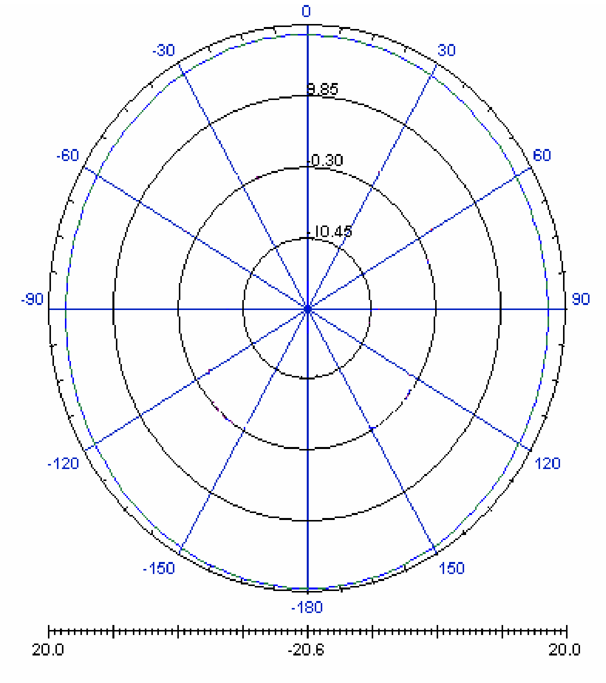
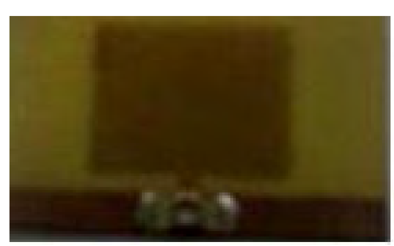


(b)

Fig. 2. (a) E-plane and (b) H-plane radiation patterns at 1.9GHz

III. PRINTED MONOPOLE ANTENNAS FOR MULTIBAND APPLICATIONS: EXPERIMENTAL RESULTS

As usual the printed monopole antennas are fabricated after doing a lot of simulations in IE3D software. First a number of simulations were run for the printed monopole antennas by varying various parameters. It has been observed that value of the feed gap (g) is one of the most crucial parameters for controlling antenna performance besides patch antenna dimensions and other parameters. Optimal dimensions for the dual-band operation for the printed rectangular monopole antennas are: length of the patch (L_p) = 29.422mm, width of the patch (W_p) = 38.01mm, width of the microstrip feed line (W_f) = 3.059mm, length of the microstrip feed line (L_f) = 20.6mm, inset feed point from the edge of the patch antenna = 8.5525mm, length of the substrate (L_s) = 34.4mm, width of the substrate (W_s) = 76mm, height of the substrate (h) = 1.6mm, metal thickness of the patch (t) = 0.035mm and feed gap (g) = 4.3475mm (refer to Fig. 1(a)). The backside view of the photograph of the fabricated rectangular printed monopole antenna is shown in Fig. 3 (a) which clearly that some portion of the ground plane metal has been etched unlike the conventional microstrip antenna ground plane. That's why such antennas behave as monopole antennas. As it can be seen from the return loss vs frequency plot in Fig. 3(b), the reflection coefficient (s_{11}) is below -10dB for the Global Positioning System (GPS) applications at 1176.45 MHz, 1227.6 MHz, 1371.913 MHz, 1381.05MHz and around 9.5dB for Digital Audio Broadcasting (DAB) applications from 1452 MHz to 1490 MHz. The dimensions of the penta-band printed rectangular monopole antenna illustrated in Fig. 1 (a) using FR4 substrate after doing an extensive simulation study were calculated as W_p=38.01mm, L_p=30mm, substrate width chosen are W_s=42.01mm, L_s=35.5mm, gap between the ground plane and patch antenna g=5.5mm. The inset feeding technique is not required for this case since the antenna was properly matched without this. The scattering parameters s_{11} in dB versus frequency in MHz from 800MHz to 3000MHz for the compact printed rectangular monopole antenna is obtained using Network Analyzer and is plotted in Fig. 3(c). The printed rectangular monopole antenna bandwidth is from 1.1GHz to 2.12GHz at the mid frequency of 1.5GHz (%B.W. = 73.15). Note that the present L band (1-2GHz) printed rectangular monopole antenna can work well for penta-band applications, viz. digital communication system (DCS, 1710-1880MHz), personal communication system (PCS, 1850-1990MHz), universal mobile telecommunication system (UMTS, 1920-2170MHz), global positioning system (GPS, 1575.42MHz, 1227.60MHz, 1371.913 MHz, 1381.05MHz) and digital audio broadcasting (DAB L Band, 1452 MHz to 1490 MHz).



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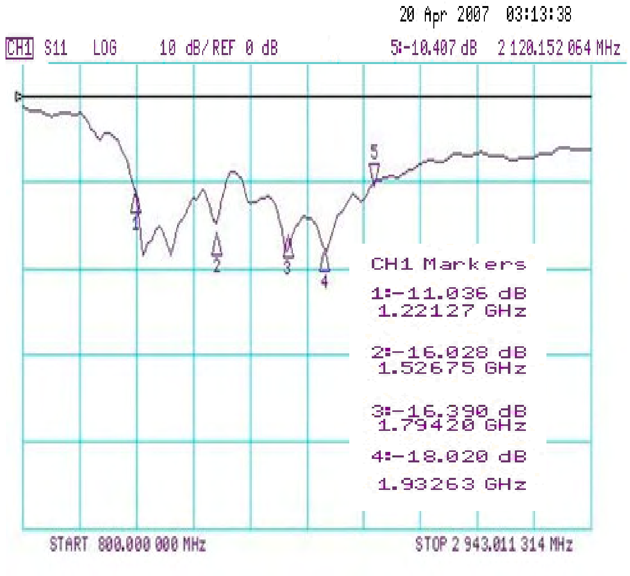

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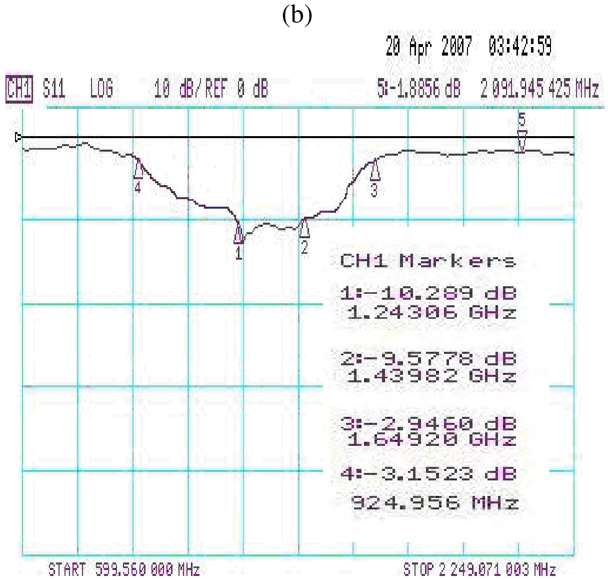

(c)

Fig. 3. (a) Photograph of the fabricated printed rectangular monopole antenna (backside view) (b) Experimental results of fabricated printed rectangular monopole for dual-band applications (s_{11} vs frequency). (c) Experimental results of fabricated printed rectangular monopole for penta-band applications (s_{11} vs frequency)

V. CONCLUSION

In this paper, we have investigated printed monopole antennas, which is basically a printed microstrip antenna with etched ground plane for multi-band applications. Printed monopole antennas are less fragile, planar and can be integrated with the integrated circuits unlike monopole antennas which have non-planar or protruded structures above the ground plane. In particular, we have fabricated and tested printed monopole antennas for dual-band, tri-band and penta-band applications. Printed rectangular monopole antennas are studied first for such application. Then double-T printed monopole antennas are studied. It has been concluded that the printed monopole antennas are one of the versatile candidates for multiband applications.

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