Octave-Band Monopole Antenna with a Horseshoe Ground Plane for Wireless Communications

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***Abstract* —** In this manuscript, a new design of octave-band monopole antenna with multi-resonance characteristic is presented .The antenna consists of a fork-shaped radiating patch with three pairs of teeth, a feed-line and a horseshoe ground plane. Simulated and measured results show that the antenna design exhibits an operating bandwidth (VSWR<2) from 2 to 20 GHz, which provides a wide usable fractional bandwidth of more than 160%. The proposed antenna has a symmetrical structure, therefore displays a good omnidirectional radiation pattern even at higher frequencies. The designed antenna has a very small size of 15×17 mm^2 and the impedance bandwidth of the designed antenna is higher than the other antennas reported in the literature to date. The proposed antenna configuration is simple, easy to fabricate and can be integrated into UWB systems.

***Index Terms* —** Bandwidth enhancement, horseshoe ground plane, octave-band antenna, UWB applications.

I. INTRODUCTION

After allocation of the frequency band from 3.1 to 10.6 GHz for the commercial use of ultra-wideband (UWB) systems by the Federal Communication Commission (FCC) [1], ultra wideband systems have received phenomenal gravitation in wireless communication. Designing an antenna to operate in the UWB band is quite a challenge because it has to satisfy the requirements such as ultra wide impedance bandwidth, omnidirectional radiation pattern, constant gain, high radiation efficiency, constant group delay, low profile, easy manufacturing, etc. [2]. In UWB communication systems, one of key issues is the design of a compact antenna while providing wideband characteristic over the whole operating band. Consequently, a number of microstrip antennas with different geometries have been experimentally characterized [3-6].

Three new small wideband printed monopole antennas using rotated T-shaped slot and parasitic structures, sprocket-shaped ground plane in the upper edge of ground plane, and fractal structure to achieve the maximum impedance bandwidth were proposed in [7-9]. Some methods are used to obtain the multi-resonance function in the literature [8-12].

In this paper, a different design is proposed to obtain the very wide bandwidth for the compact monopole antenna which provides a wide usable fractional bandwidth of more than 160%. Good VSWR and radiation pattern characteristics are obtained in the frequency band of interest. The proposed antenna is successfully implemented and the simulation results show reasonable agreement with the measurement results. The designed antenna has a small dimension and the impedance bandwidth of the designed antenna is higher than the UWB antennas reported recently [3-13].

II. ANTENNA DESIGN

The structure of proposed monopole antenna fed by a microstrip line is shown in Fig. 1. The dielectric substance (*FR4*) with thickness of 1 mm with relative permittivity of 4.4 and loss tangent 0.018 is chosen as substrate to facilitate printed circuit board integration. The basic monopole antenna structure consists of a fork-shaped radiating patch, a feed line, and a semi-circular ground plane. The proposed antenna is connected to a 50-Ω SMA connector for signal transmission. Final values of the presented antenna design parameters are specified in Table 1.

The three essential parameters for the design of a rectangular microstrip monopole antenna are operation frequency (f_0); as the ultra-wideband (UWB) uses the

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frequency range from 3.1-10.6 GHz. Hence, the antenna designed must be able to operate in this frequency range. The resonant frequency selected for antenna design is 3 GHz (lower resonance frequency). The dielectric material selected for antenna design is FR4 which has a dielectric constant of the substrate (ε_r) of 4.4. A substrate with a high dielectric constant has been selected since it reduces the dimensions of the antenna, height of dielectric (h). Hence, the essential parameters for the design are: f_0 = 3 GHz, ε_r = 4.4 and h = 1.6 mm. The dimensions of the patch along its length have now been extended on each end by a distance ΔL, which is given empirically by:

$$\Delta L = 0.412h \frac{(\varepsilon_{eff} + 0.3)}{(\varepsilon_{eff} - 0.258)} \frac{\frac{W_{sub}}{h_{sub}} + 0.264}{\frac{W_{sub}}{h_{sub}} + 0.8}, \quad (1)$$

where h_{sub} is the height of dielectric, W_{sub} is the width of the microstrip monopole antenna and $\varepsilon_{r\,eff}$ is the effective dielectric constant. Then, the effective length (L_{eff}) of the patch can be calculated as follows:

$$L_{eff} = L + 2\Delta L. \quad (2)$$

For a given resonant frequency f_0, the effective length is given as:

$$L_{eff} = \frac{C}{2 f_o \sqrt{\varepsilon_{reff}}}. \quad (3)$$

For a rectangular microstrip antenna, the resonance frequency for any TM_{mn} mode is given by as:

$$\varepsilon_{eff} = \frac{(\varepsilon_r + 1)}{2} \frac{(\varepsilon_r - 1)}{2} \frac{1}{(1 + 12\frac{h}{w})^{\frac{1}{2}}}. \quad (4)$$

The width W_{sub} of microstrip antenna is given by:

$$W = \frac{C}{2 f_0 \sqrt{\frac{(\varepsilon_r + 1)}{2}}}. \quad (5)$$

The design steps for the proposed UWB microstrip and calculations are given as follows:

Step 1: Calculation of the width (W_{sub}): the width of the microstrip monopole antenna is given by Eq. (5) by substituting $c = 3\times10^8$ m/s, ε_r = 4.4 and f = 3 GHz, we get: W_{sub} = 15 mm.

Step 2: Calculation of effective dielectric constant ($\varepsilon_{r\,eff}$): Eq. (4) gives the effective dielectric constant by substituting ε_r = 4.4, W = 15 mm and h = 1.6 mm, we get: $\varepsilon_{r\,eff}$ = 4.2703.

Step 3: Calculation of the effective length (L_{eff}): Eq. (3) gives the effective length by substituting ε_r = 4.4, C = 3e8 m/s and f_0 = 3 GHz, we get: L_{eff} = 10.3696 mm.

Step 4: Calculation of the length extension (ΔL): Eq. 1 gives the length extension by substituting $\varepsilon_{r\,eff}$ = 4.2703, W = 15 mm and h = 1.6 mm, we get: ΔL = 0.0190 mm.

Step 5: Calculation of actual length of patch (L_{sub}): the actual length is obtained by Eq. 2 as, substituting L_{eff} = 10.369 mm and ΔL = 0.0190, we get: L_{sub} = 10.3316 mm which is fixed in L_{sub} = 10 mm.

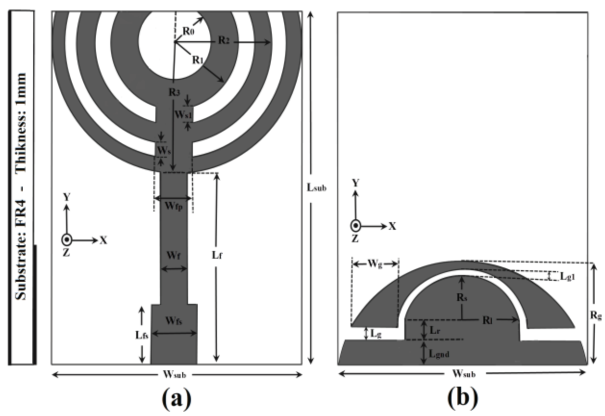

Fig. 1. Structure of the proposed antenna: (a) top layer, and (b) bottom layer.

Table 1: Final parameters values of the antenna

Param.	mm	Param.	mm	Param.	mm
W_{sub}	15	L_{sub}	17	R_g	5.5
W_{fs}	1.6	L_{fs}	2.6	W_f	0.7
L_f	7	W_{fp}	1	W_s	0.6
W_{s1}	0.6	R_3	7.5	R_2	6.2
R_1	4.7	R_0	3.2	W_g	2.7
L_g	0.6	L_{gnd}	1.6	L_r	1.4
R_s	2.13	R_1	4	L_{g1}	0.19

Regarding defected ground structures (DGS) theory, creating slits in the ground plane provide additional current paths. Moreover, these structures change the inductance and capacitance of the input impedance, which in turn leads to change the bandwidth [3-5]. Therefore, by converting a semi-circular ground plane to the horseshoe structure, much enhanced impedance bandwidth can be achieved. In addition, based on electromagnetic coupling theory (ECT), by increasing the teeth of fork-shaped radiating patch, additional coupling is introduced between the patch and the ground plane and impedance bandwidth of the antenna is improved without any cost of size or expense [7].

III. RESULTS AND DISCUSSIONS

In this section, the microstrip monopole antenna with various design parameters was constructed, and the numerical and experimental results of the input impedance and radiation characteristics are presented and discussed. The analysis and performance of the proposed antenna is explored by using Ansoft simulation software high-frequency structure simulator (HFSS) [14], for better impedance matching.

The structure of the various antennas used for simulation studies were shown in Fig. 2. VSWR characteristics for the fork-shaped antenna with a semi-circular ground plane (Fig. 2 (a)), the antenna with a horseshoe ground plane (Fig. 2 (b)), and the proposed antenna (Fig. 2 (c)) structures are compared in Fig. 3.

As shown in Fig. 3, by using a horseshoe ground plane additional resonances at 11 and 16.7 GHz can be achieved. In addition, by increasing the teeth of fork-shaped radiating patch new resonance at 12.5 GHz is generated. By using these structures, the antenna exhibits an operating bandwidth from 2 to 20 GHz. Also, the input impedance of the proposed antenna on a Smith-Chart is shown in Fig. 4.

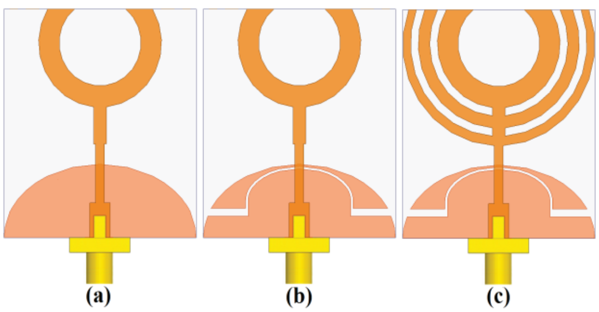

Fig. 2. (a) Fork-shaped antenna with a semi-circular ground plane, (b) the antenna with a horseshoe ground plane, and (c) the proposed antenna structure.

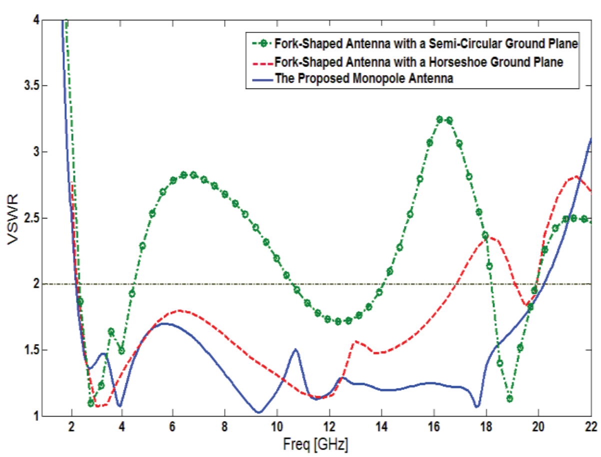

Fig. 3. Simulated VSWR characteristics for the various structures shown in Fig. 2.

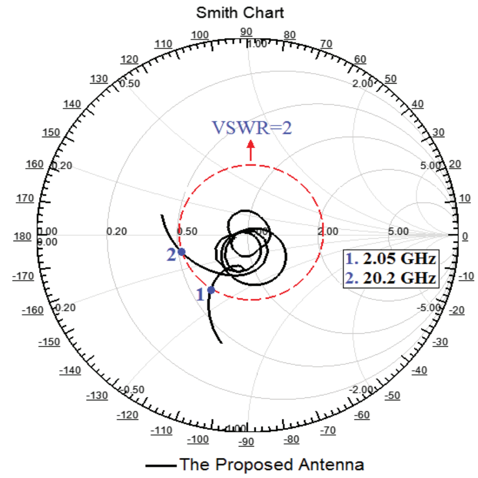

Fig. 4. Simulated input impedance on a Smith-Chart for the proposed antenna.

The simulated current distributions for the proposed antenna at the additional resonances frequencies are presented in Fig. 5. It can be observed in Fig. 5 (a) and 5 (b), that the directions of surface currents are reversed in compared to each other, which the antenna impedance changes at 4 and 12 GHz due to the resonant properties of the horseshoe ground plane structure. Also, the simulated current distribution at the middle resonance frequency (10 GHz) is presented in Fig. 5 (c). As shown in Fig. 5 (c), the current concentrated on the edges of the interior and exterior of the teeth of fork-shaped radiating patch at 10 GHz [15-18].

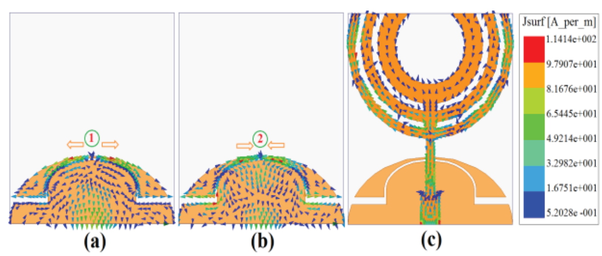

Fig. 5. Simulated surface current distributions for the proposed antenna; (a) 4 GHz, (b) 12.5 GHz, and (c) 17.5 GHz.

As illustrated in Fig. 6, the proposed antenna was designed and fabricated. Figure 7 shows the measured and simulated VSWR characteristics of the proposed antenna. The fabricated antenna has the frequency band of 2 GHz to over 20 GHz.

However, as seen, there exists a discrepancy between measured data and the simulated results. This discrepancy is mostly due to a number of parameters such as the fabricated antenna dimensions as well as the thickness and dielectric constant of the substrate on which the antenna is fabricated, the wide range of simulation frequencies. In a physical network analyzer measurement, the feeding mechanism of the proposed antenna is composed of a SMA connector and a microstrip line (the microstrip feed-line is excited by a SMA connector); whereas, the simulated results are obtained using the Ansoft simulation software (HFSS), that in HFSS by default, the antenna is excited by a wave port that it is renormalized to a 50-Ohm full port impedance at all frequencies. In order to confirm the accurate return loss characteristics for the designed antenna, it is recommended that the manufacturing and measurement processes need to be performed carefully. Moreover, SMA soldering accuracy and FR4 substrate quality need to be taken into consideration [19-22].

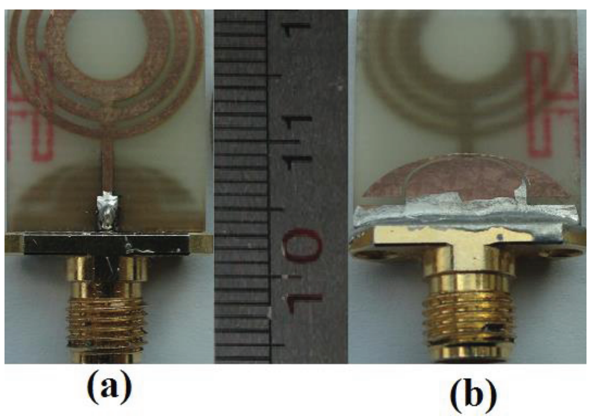

Fig. 6. Photograph of the fabricated antenna: (a) top view, and (b) bottom view.

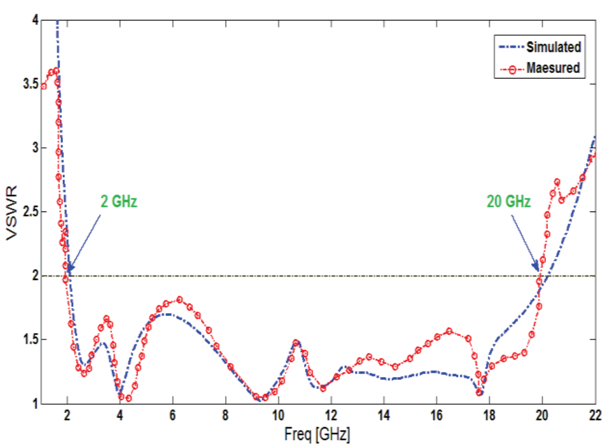

Fig. 7. Measured and simulated VSWR characteristics of the proposed antenna.

Figure 8 depicts the simulated radiation patterns including the co-polarization and cross-polarization in the H-plane (x-z plane) and E-plane (y-z plane). It can be seen that nearly omnidirectional radiation pattern with low cross-polarization level can be observed on x-z plane. The radiation patterns on the y-z plane are like a small electric dipole leading to bidirectional patterns in a very wide frequency band. With the increase of frequency, the radiation patterns become worse because of the increasing effects of the cross-polarization [23-30].

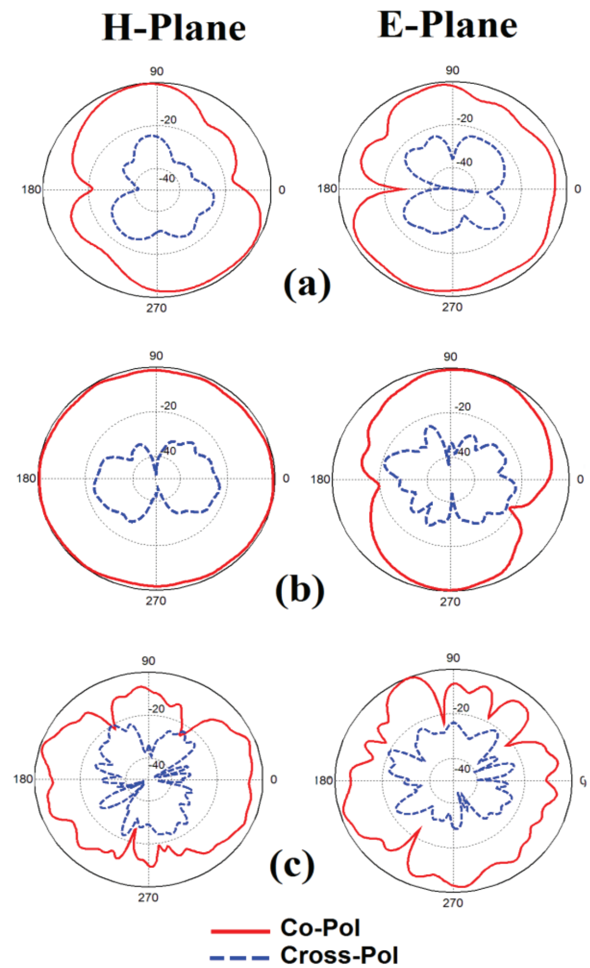

Fig. 8. Simulated radiation patterns for the proposed antenna at: (a) 4 GHz, (b) 12.5 GHz, (c) 14 GHz, and (d) 17.5 GHz.

IV. CONCLUSION

In this paper, a new design of microstrip monopole antenna with simple configuration is proposed which provides a very wide bandwidth for various UWB applications. The presented antenna consists of a fork-shaped radiating patch with three pairs of teeth, a feed-line and a horseshoe ground plane. The fabricated antenna has the frequency band of 2 to over 20 GHz. Good VSWR and radiation pattern characteristics are obtained in the frequency band of interest.

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