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Bandwidth improvement of monopole antenna using π-shaped slot and conductor-backed plane

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Abstract
A novel design of small monopole antenna with enhanced bandwidth property for ultra-wideband (UWB) applications is presented. The antenna consists of an ordinary square radiating patch and a modified ground plane with π-shaped slot and conductor-backed plane. By cutting a π-shaped defected ground structure (DGS) and also by embedding a π-shaped conductor-backed plane in air gap distance, additional third and fourth resonances in 12 and 14.5 GHz are excited and much wider impedance bandwidth can be produced. By using these modified structures, the usable upper frequency of the antenna is extended from 10.4 GHz to 15.1 GHz. Simulated and measured results show that the antenna design exhibits an operating bandwidth (S_{11} < -10 dB) from 2.89 to 15.1 GHz, which provides a wide usable fractional bandwidth of more than 135%. The proposed antenna has an ordinary square radiating patch, therefore displays good omnidirectional radiation patterns even at higher frequencies. The antenna configuration is simple, easy to fabricate and can be integrated into UWB systems.

1. 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, omni-directional radiation pattern, constant gain, high radiation efficiency, constant group delay, low profile, easy manufacturing, etc [2-3].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. Some methods are used to obtain the multi-resonance function in the literature [4-9].

In this paper, a different method is proposed to obtain a very wideband bandwidth for the compact monopole antenna. In the proposed antenna, π-shaped slot and conductor-backed plane structures are used in the substrate backside. Regarding defected ground structures (DGS) theory, the creating slots 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. Therefore, by cutting a π-shaped slot in the ground plane, much enhanced impedance bandwidth may be achieved. In addition, based on electromagnetic coupling theory (ECT), by adding a π-shaped conductor-backed plane in the air gap distance, additional coupling is introduced between the bottom edge of the square patch and the ground plane and its impedance bandwidth is improved without any cost of size or expense. Good return loss and radiation pattern characteristics are obtained in the frequency band of interest. The designed antenna has a small size of 12×18 mm^2.

2. Microstrip 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 1.6 mm, relative permittivity of 4.4 and 0.018 loss tangent is chosen as substrate to facilitate printed circuit board integration.

The basic monopole antenna structure consists of a square radiating patch, a feed line, and a ground plane. The proposed antenna is connected to a 50-Ω SMA connector for signal transmission. The square radiating patch is connected to a feed line with width of W_f and length of L_f .The width of the microstrip feed line is fixed at 2 mm, as shown in Fig. 1. On the other side of the substrate, a conducting ground plane of W_{sub} width and L_{sub} length is placed. Final values of the presented antenna design parameters are specified in Table. 1. The three essential parameters for the design of a rectangular microstrip antenna are operation frequency (f_0): As the ultra-wideband (UWB) uses the 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 4.5 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= 4.5 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 Δ*L*, which is given as:

These parameters including the substrate is W_{sub}×L_{sub}=12×18 mm^2 or about 0.15λ×0.25λ at 4.5 GHz (the first resonance frequency of the ordinary monopole antenna). We have a lot of flexibility in choosing the length of the radiating patch. This parameter mostly affects the antenna bandwidth. As W decreases, so does the antenna bandwidth, and vice versa. This parameter is approximately $\lambda_{lower}/4$, where λ_{lower} is the lower bandwidth frequency wavelength. λ_{lower} depends on a number of parameters such as the monopole width as well as the thickness and dielectric constant of the substrate on which the antenna is fabricated. Hence, the essential parameters for the design are: f_0= 4.5 GHz (first resonance frequency), ε_r = 4.4 and h_{sub} = 0.8 mm. The dimensions of the patch along its length have now been extended on each end by a distance Δ*L*, which is given as:

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

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:

$$L_{eff} = \frac{C}{2 f_0\sqrt{\varepsilon_{reff}}} \quad (3)$$

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

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

The width W_{sub} of microstrip antenna is given

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

The last and final step in the design is to choose the length of the resonance elements. In this design, the optimized length $L_{resonance}$ is set at $0.25\lambda_{notch}$:

$$f_{resonance} = \frac{c}{4L\sqrt{(\varepsilon_r+1)/2}} \quad (6)$$

Where $L_{extra\text{-}resonance1}$= $L_1+L_2+0.5W_1-W_2$ and $L_{extra\text{-}resonance2}$=$L_3+W_5+0.5L_4$ for 3 GHz and 10.6 GHz (extra resonance frequencies), respectively.

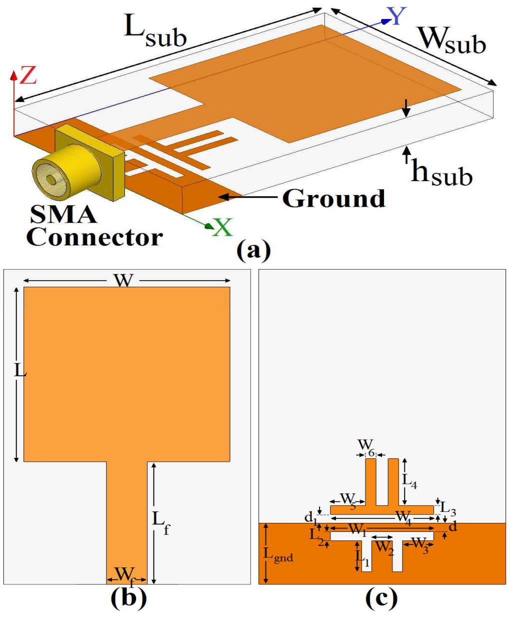

Fig. 1. Geometry of proposed monopole antenna, (a) side view, (b) top layer, and (c) bottom layer.

Table 1. *Final dimensions of the antenna parameters.*

Parameter	W_{sub}	L_{sub}	h_{sub}	W	L	W_f
(mm)	12	18	1.6	10	10	2
Parameter	L_f	W_1	L_1	W_2	L_2	W_3
(mm)	7	5.5	2	1	0.5	1.5
Parameter	L_3	W_4	L_4	W_5	L_{gnd}	W_6
(mm)	0.5	5.5	2.25	2	3.5	0.5

3. Results and Discussions

In this section, the microstrip monopole antenna with various design parameters was constructed. 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) [10], for better impedance matching.

The structure of the various antennas used for simulation studies were shown in Fig. 2. Return loss characteristics for the ordinary monopole antenna (Fig. 2(a)), antenna with a π-shaped slot (Fig. 2(b)), and the proposed antenna (Fig. 2(c)) structures are compared in Fig 3.

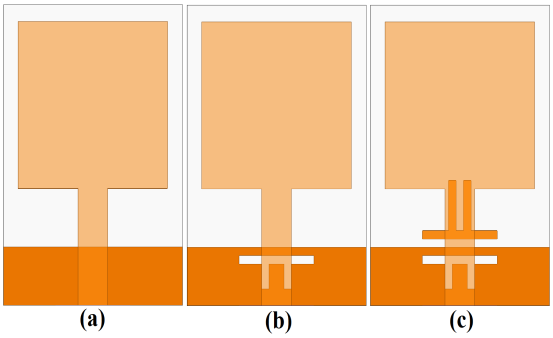

Fig. 2. *(a) Ordinary square antenna, (b) antenna with a π-shaped slot in the ground plane, (c) the proposed antenna structure.*

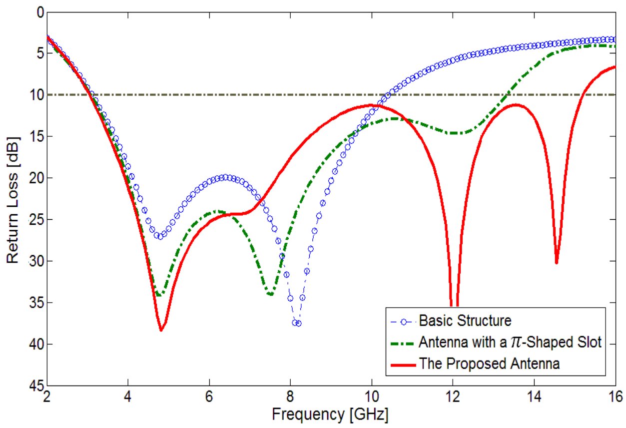

Fig. 3. *Simulated return loss characteristics for the various antenna structures shown in Fig. 2.*

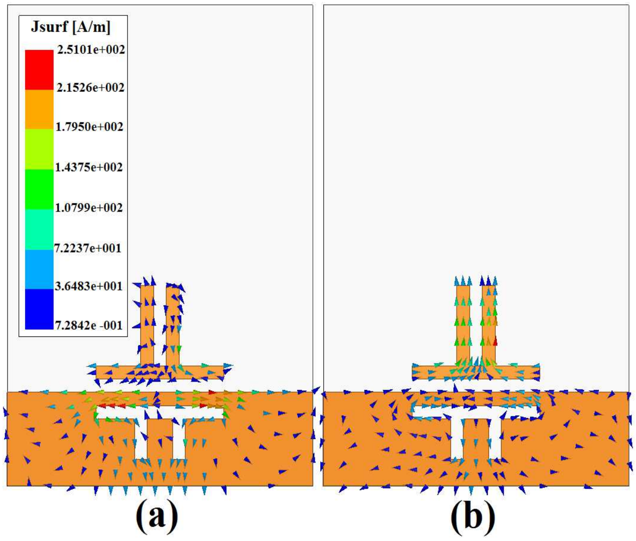

Fig. 4. *Simulated surface current distributions for the proposed antenna on the ground plane at additional resonances frequency, (a) 12GHz, (b) 14.5GHz.*

As shown in Fig.3, by cutting a π-shaped slot in the ground plane, a new additional resonance at 12 GHz can be generated. Also by adding a π-shaped conductor backed plane, another new resonance at 14.5 GHz is achieved. By using these structures, the usable upper frequency of the monopole is extended from 10.4 GHz to 15.1 GHz. The simulated current distributions on the ground plane for the proposed antenna at the additional resonances frequencies are presented in Fig. 4. It can be observed in Fig. 4 (a) and 4(b) the current concentrated on the edges of the interior and exterior of the π-shaped slot and conductor backed plane which the antenna impedance changes at 12 and 14.5 GHz due to the resonant properties of the embedded structure. [11-13].

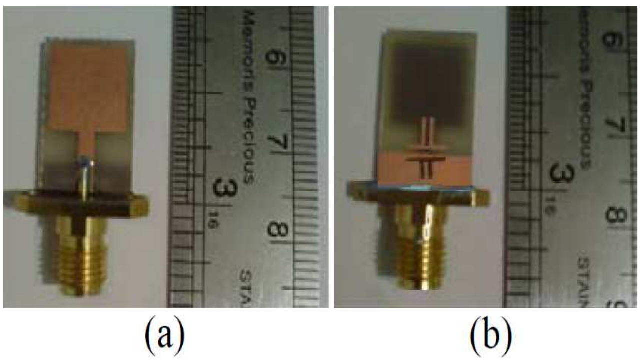

Fig. 5. *Prototype of the realized antenna, (a) top view, (b) bottom view.*

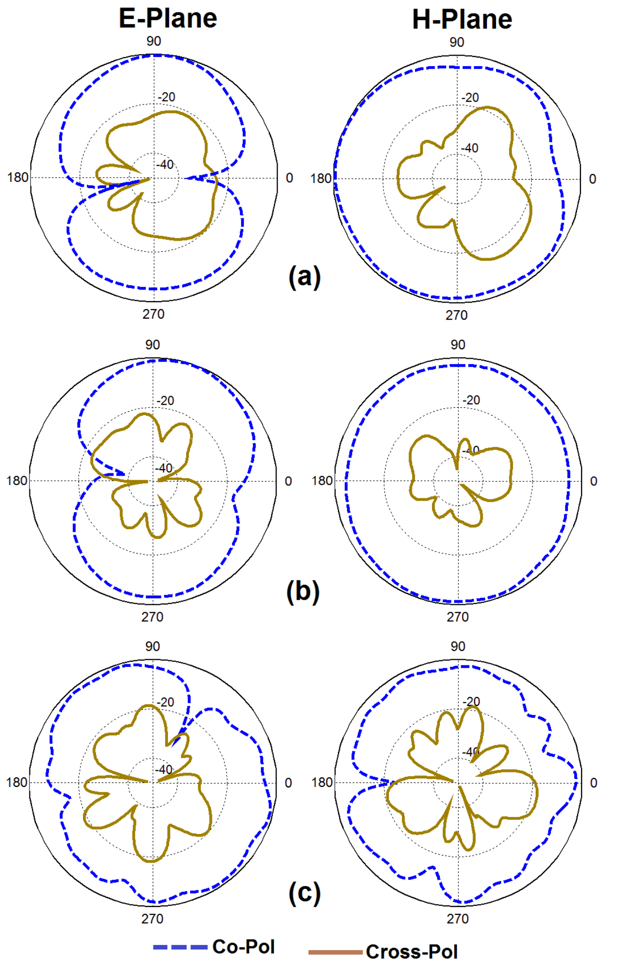

Fig. 6. Measured radiation patterns for the proposed antenna, (a) 6 GHz, (b) 10 GHz, and (c) 14 GHz.

The proposed antenna with final design as shown in Fig. 5 was built and tested. Fig. 6 depicts the measured radiation patterns of the proposed antenna 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 quasi-omnidirectional radiation pattern can be observed on x-z plane over the whole UWB frequency range, especially at the low frequencies. The radiation patterns on the y-z plane display a typical figure-of-eight, similar to that of a conventional dipole antenna. It should be noticed that the radiation patterns in E-plane become imbalanced as frequency increases because of the increasing effects of the cross polarization. The patterns indicate at higher frequencies, more ripples can be observed in both E- and H-planes owing to the generation of higher-order modes. The cross-polarization component also increases at higher frequencies due to the increased horizontal surface currents [14-18].

Fig. 7 shows the measured and simulated return loss characteristics of the proposed antenna. The fabricated antenna has the frequency band of 2.89 to 15.1 GHz.

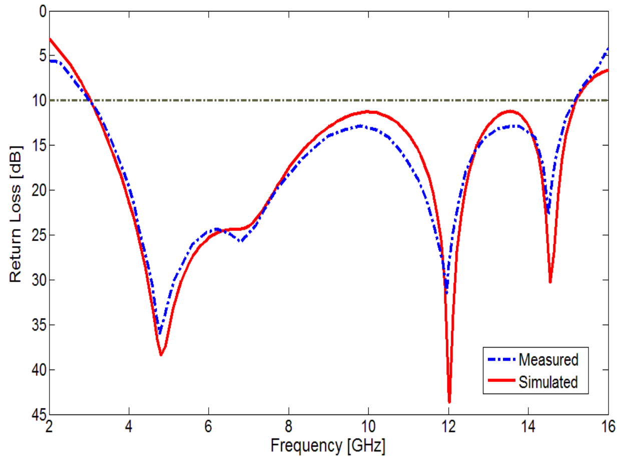

Fig. 7. Measured and simulated return loss characteristics comparison of the proposed antenna

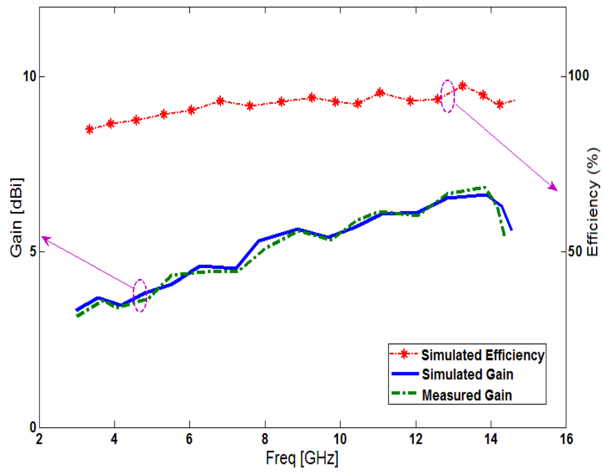

Fig. 8. Measured and simulated radiation efficiency and gain of the proposed antenna.

The simulated radiation efficiency characteristic of the proposed antenna is shown in Fig. 8. Results of the calculations using the software HFSS indicated that the proposed antenna features a good efficiency, being greater than 87% across the entire radiating band. In addition, the simulated and measured maximum gains of the antenna against frequency are illustrated in Fig. 8. The antenna gain has a flat property which increases by the frequency. As seen, the proposed antenna has sufficient and acceptable gain level in the operation bands [19-23].

In the UWB communication systems, antennas should be able to transmit the electrical pulse with minimal distortion. If group delay variation exceeds more than 1 *ns*, phases are no more linear in far field and phase distortion occurs which can cause a serious problem for UWB applications. Fig. 9 shows the simulated group delay property of the proposed monopole antenna. As illustrated the variation is less than 0.25±0.4 over the frequency band from 3 to 14.5 GHz. It shows that the antenna has low-impulse distortion and is suitable for UWB applications [24-27].

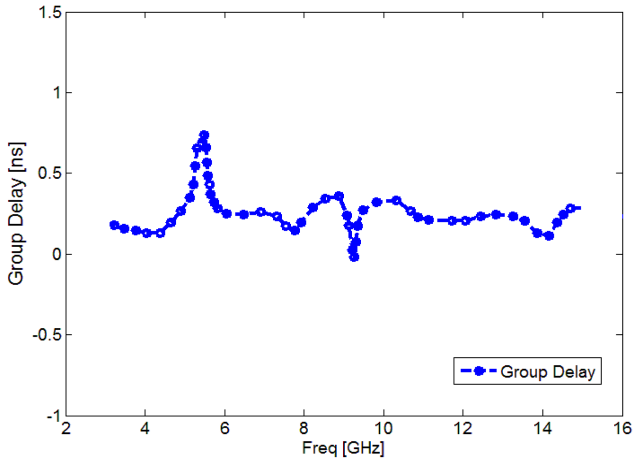

Fig. 9. *Simulated group delay characteristic of the proposed antenna.*

4. Conclusion

In this study, a new design of microstrip monopole antenna for UWB applications is proposed which provides a very wide bandwidth. The presented antenna consists of an ordinary square radiating patch and a modified ground plane with π-shaped slot and conductor backed plane. The fabricated antenna has the frequency band of 2.89 to over 15 GHz. The antenna has an ordinary square radiating patch, therefore displays a good omni-directional radiation pattern even at higher frequencies and also its radiation efficiency is greater than 85% across the entire radiating band. The proposed antenna has sufficient and acceptable group delay and gain levels in the operation bands. The proposed antenna is successfully implemented and the simulation results show reasonable agreement with the measurement results.

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