Bandwidth Enhancement of Small Square Monopole Antennas by Using Defected Structures Based on Time Domain Reflectometry Analysis for UWB Applications

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Abstract **─** In this paper a simple printed monopole antenna with enhanced bandwidth by using defected structures for UWB applications is presented, which is designed due to time domain designing method. The proposed antenna consists of a square radiating patch with a defected mircostrip feed-line by a pair of T-shaped slits and a defected ground plane by a pair of rectangular slots with a T-shaped strip protruded inside the slots, which provides a wide usable fractional bandwidth of more than 130 % (3.06 GHz - 14.27 GHz). By cutting two modified T-shaped slits with variable dimensions on the feed-line and also by inserting a pair of rectangular slots with T-shaped protruded strip inside the slots on the ground plane, additional resonances are excited and hence much wider impedance bandwidth can be produced. This large operating bandwidth is obtained by choosing suitable dimension for the proposed defected structures. To verify the validation of the proposed antenna, the equivalent circuit based on time domain reflectometry analysis is presented. Detailed simulation and numerical investigations are conducted to understand their behaviors and optimize for broadband operation. The designed antenna has a small size of 12 × 18 mm^2, about $0.15\lambda \times 0.25\lambda$ at 4.2 GHz. The proposed antenna exhibits almost omnidirectional radiation patterns with low cross polarization level.

Index Terms **─** Defected microstrip structure (DMS), defected ground structure (DGS), square monopole antenna, and time domain reflectometry (TDR).

I. INTRODUCTION

Commercial UWB systems require small low-cost antennas with omnidirectional radiation patterns and large bandwidth [1]. It is a well-known fact that planar monopole antennas present really appealing physical features, such as simple structure, small size, and low cost. Due to all these interesting characteristics, planar monopoles are extremely attractive to be used in emerging UWB applications, and growing research activity is being focused on them.

In UWB communication systems, one of the key issues is the design of a compact antenna while providing wideband characteristic over the whole operating band. Consequently, a number of planar monopoles with different geometries have been experimentally characterized [2-3] and automatic design methods have been developed to achieve the optimum planar shape [4-5]. Moreover, other strategies to improve the impedance bandwidth have been investigated [6-8].

In this paper, a simple method for designing a novel and compact microstrip-fed monopole antenna with multi resonance performance based on time domain refelectometry for UWB applications has been presented and discussed. In this paper, for the first time, based on defected microstrip structures (DMS) and defected ground structures (DGS), for bandwidth enhancement we use a pair of T-shaped slits in the microstrip feed-line and two rectangular slots with a T-shaped strip protruded inside the slots in the ground plane (unlike other UWB antennas reported in the literature to date [4-7], this structure has an

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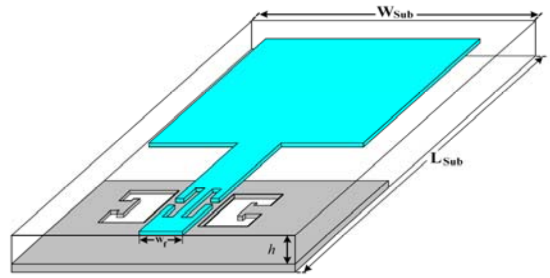
ordinary square radiating patch configuration). Furthermore, the circuit model of different parts of the antenna based on time domain reflectometry analysis is achieved and presented. The size of the designed antenna is smaller than the UWB antennas with band-notched function reported recently [2-8]. Good return loss and radiation pattern characteristics are obtained in the frequency band of interest. Simulated and measured results are presented to validate the usefulness of the proposed antenna structure for UWB applications.

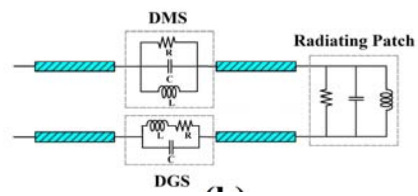
II. ANTENNA DESIGN

The square monopole antenna fed by a 50 Ω microstrip line is shown in Fig. 1, which is printed on an FR4 substrate with the width of W_{sub} = 12 mm and the length of L_{sub} = 18 mm, thickness of 0.8 mm, permittivity of 4.4, and loss tangent of 0.018. The basic antenna structure consists of a square patch, a feed line, and a ground plane. The square patch has a width of W = 10 mm. The patch is connected to a feed line with the width of W_f = 1.5 mm and the length of L_f = 7 mm, as shown in Fig. 1. On the other side of the substrate, a conducting ground plane with the width of W_{sub} = 12 mm, and the length of L_{gnd} = 4 mm, is placed. The proposed antenna is connected to a 50 Ω SMA connector for signal transmission. In order to design a novel antenna, we proposed a new compact monopole antenna with a defected microstrip feed-line and defected ground structure. In this structure, by cutting the two T-shaped slit of suitable dimensions at the microstrip feed-line, it is found that much enhanced impedance bandwidth can be achieved for the proposed antenna. In addition, the defected microstrip structure is playing an important role in the broadband characteristics of this antenna, because it can adjust the electromagnetic coupling effects between the patch and the ground plane, and improves its impedance bandwidth without any cost of size or expense. This phenomenon occurs because, with the use of a defected structure in transmission line distance, additional coupling is introduced between the bottom edge of the square patch and the ground plane [9].

Regarding defected ground structures (DGS), creating slots in the ground plane provide an additional current path. Moreover, this structure changes the inductance and capacitance of the input impedance, which in turn leads to a change in the bandwidth. The DGS applied to a microstrip line causes a resonant character of the structure transmission with a resonant frequency controllable by changing the shape and size of the slot [10]. Therefore, by cutting two T-shaped slots at the ground plane and carefully adjusting its parameters, much enhanced impedance bandwidth may be achieved.



(a)



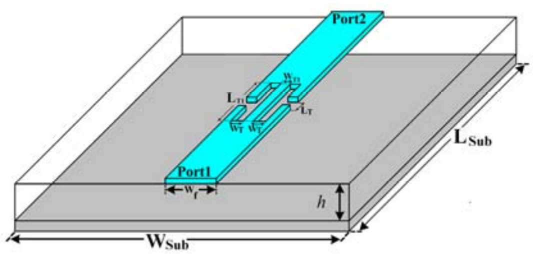
(b)

Fig. 1. (a) Geometry of the proposed square monopole antenna with defected structures and (b) the proposed antenna equivalent circuit.

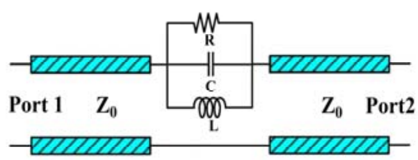
III. DEFECTED TRANSMISSION LINE

A. Defected structures (DGS and DMS) and its equivalent circuit models

Recently, the defected ground plane structures (DGS) and defected microstrip structure (DMS) have been proposed for suppression of spurious response in the microstrip structures [11-12]. These configurations provide band-stop characteristics. The proposed DMS and DGS with their equivalent circuit models are shown in Figs. 2 and 3, respectively, which is printed on an FR4 substrate of thickness 0.8 mm, permittivity 4.4, and loss tangent 0.018. The corresponding geometrical parameters of the proposed structures are denoted in Figs. 2 (a) and 3 (a). In this study, the defected structure on the ground plane and feed-line will perturb the incident and return current and induce a voltage difference on the ground plane and microstrip feed-line. These two effects can be modeled as a parallel LC circuit [13]. The resistance in equivalent circuits represents the loss of the slot and slit, which is small in general. In the proposed DMS equivalent circuits, R is the series resistance due to conductor losses and dissipation arising from current flowing in the silicon substrate, also in the proposed DGS equivalent circuits, R is the parallel resistance due to substrate dissipation. The shunt parasitic results from a combination of capacitances are due to the gap distance between defected structures edges and underlying substrate. If there are multiple conducting edges, then there should be one C corresponding to each gap distance.

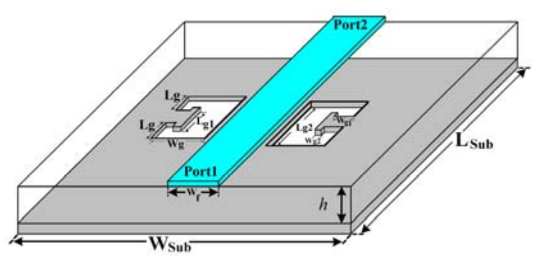


(a)

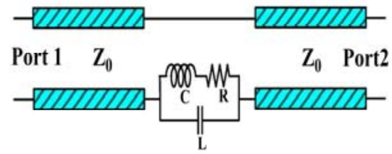


(b)

Fig. 2. (a) Geometry of the proposed DMS, with $W_T = 0.3$ mm, $W_{T1} = 0.4$ mm, $L_T = 0.4$ mm, and $L_{T1} = 3$ mm and (b) equivalent circuit model.



(a)



(b)

Fig. 3. (a) Geometry of the proposed DGS, with $W_g = 3$ mm, $W_{g1} = 1$ mm, $W_{g2} = 1$ mm, $L_g = 2.6$ mm, $L_g = 1$ mm, and $L_{g2} = 2$ mm and (b) equivalent circuit model.

In this work, the final step in the design is to choose the length of the DGS and DMS resonators. A good starting point is to choose it to be equal to $\lambda_m/4$, where λ_m is the guided wavelength in the microstrip line. In this design, the optimized length $L_{resonance}$ is set to resonate at 0.25 $\lambda_{resonance}$, where $L_{resonance\ DGS} = W_g + W_{g1} + W_{g2} + 0.5\ L_{g2} + L_g$ and $L_{resonance\ DMS} = 0.5\ W_{T1} + W_T + L_{T1} + 0.5\ (L_{T1} - L_T)$. $\lambda_{resonance\ DGS}$ and $\lambda_{resonance\ DMS}$ correspond to the DGS resonance frequency (12 GHz) and the DMS resonance frequency (13.9 GHz), respectively. Simulated insertion and return loss characteristics for the proposed DMS and DGS shown in Figs. 2 (a) and 3 (a), with their resonances frequencies are shown in Fig. 4.

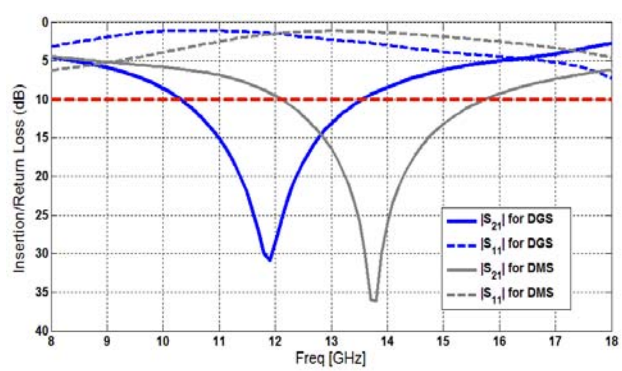


Fig. 4. Simulated insertion and return loss characteristics for the proposed DMS and DGS shown in Figures 2 (a) and 3 (a).

B. Time domain reflectometry analysis

In this section, the proposed defected structures with mentioned design parameters were simulated, and then the TDR results of their input impedance are presented and discussed, in both equivalent circuit and full-wave analysis cases.

The simulated full-wave TDR results are obtained using the Ansoft simulation software high-frequency structure simulator (HFSS) [15].

In order to calculate the TDR results for the proposed equivalent circuits, the impedance of these circuits in Laplace domain can be represented as in equations (1) and (2),

$$Z_{DGS} = \frac{Ls + R}{LCs^2 + RCs + 1} \quad (1)$$

$$Z_{DMS} = \frac{RLs}{RLCs^2 + Ls + R}. \quad (2)$$

Assuming that the characteristic impedance of the microstrip line is Z_0, we can write the reflection coefficient through a defected structure as in equation (3), which is observed at the source end, i.e., port 1,

$$\Gamma_Z(s) = \frac{Z(s)}{Z(s) + 2Z_0}. \quad (3)$$

Therefore, the reflected waveform for the proposed DGS and DMs can be written as,

$$\Gamma_{DGS}(s) = \frac{Ls + R}{2Z_0LCs^2 + (2Z_0RC + L)s + R + 2Z_0} \quad (4)$$

$$\Gamma_{DMS}(s) = \frac{RLs}{2Z_0RLCs^2 + (2Z_0C + RL)s + 2Z_0R}. \quad (5)$$

A step voltage source with rise time τ_r and amplitude V_0, can be expressed as in [13],

$$V_{in}(s) = \frac{V_0}{2\tau_r}\frac{1}{s^2}\left(1 - e^{-\tau_r S}\right). \quad (6)$$

Therefore, the reflected waveform in Laplace domain can be written as,

$$V_{TDR}(s) = V_{in}(s)\Gamma_{DGS,DMS}(s). \quad (7)$$

In TDR measurements, the impedance follows as,

$$Z_{TDR} = Z_0 \times (V_{in}(t) + V_{TDR}(t))/(V_{in}(t) - V_{TDR}(t)). \quad (8)$$

In which Z_0 is the characteristic impedance of the transmission line at the terminal.

Figures 4 and 5 show the simulated reflection waveform observed at port 1 of the defected structures, as shown in Figs. 2 and 3, and with a 50 termination on port 2. The excitation source is a step wave with amplitude of 1 V and rise time of 15 psec. The corresponding result predicted by the equivalent circuit model is also shown in these figures and good agreement is seen. As shown in Figs. 5 and 6, TDR curves have started from t = 0.4 nsec, with an impedance just under 50 Ω. This is indeed the characteristic impedance of the microstrip line. At impedance discontinuities, part of the input signal is reflected. These reflections, after traveling back, reach terminal port1 and are observed there [13]. From these observations, the characteristic impedances along the transmission line can be computed. The optimal dimensions of the equivalent circuit models parameters are specified in Table 1.

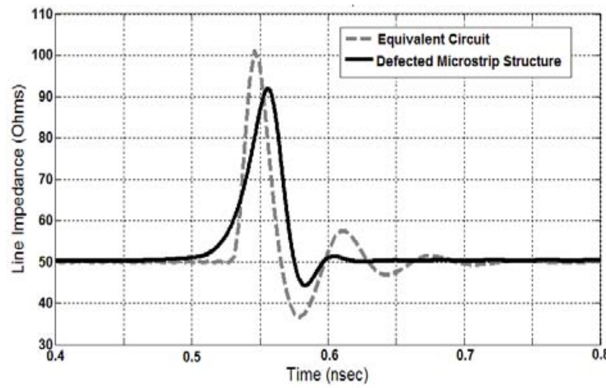


Fig. 5. The reflected waveforms simulated by HFSS and predicted by equivalent circuit model of the proposed defected microstrip structure shown in Fig. 2.

Table 1: Equivalent circuit model parameters.

Element	DMS	DGS
L	4.8 (nH)	0.75 (nH)
C	2.05 (pF)	15.75 (pF)
R	2.5 (Ω)	1.35 (Ω)

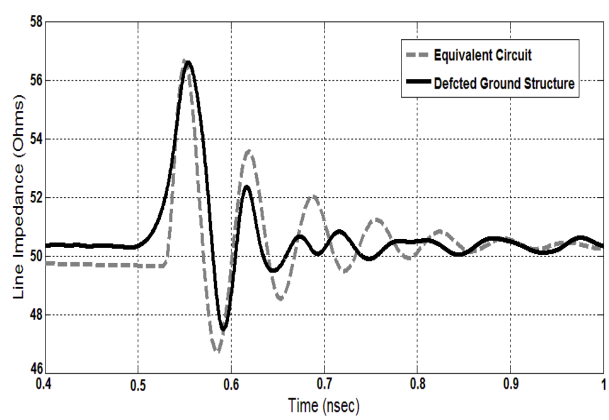


Fig. 6. The reflected waveforms simulated by HFSS and predicted by equivalent circuit model of the proposed defected ground structure shown in Fig. 3.

IV. RESULTS AND DISCUSSION

The planar monopole antenna with various design parameters were constructed, and the numerical and experimental results of the input impedance and radiation characteristics are presented and discussed. The parameters of this proposed antenna are studied by changing one parameter at a time while others are kept fixed. Figure 7 shows the structure of various antennas used for simulation studies. Return loss characteristics for ordinary square patch antenna (Fig. 7 (a)), with two modified T-shaped slits with variable dimensions on the feed-line (Fig.7 (b)), and with two modified T-shaped slits with variable dimensions on the feed-line and a pair of rectangular slots with T-shaped protruded strip inside the slots on the ground plane (Fig. 7 (c)) are compared in Fig. 8. As shown in Fig. 8, it is observed that by using this modified element including two modified T-shaped slits with variable dimensions on the feed-line and a pair of rectangular slots with T-shaped protruded strip inside the slots on the ground plane, additional third and fourth resonances are excited, respectively, and hence the bandwidth is increased**.**

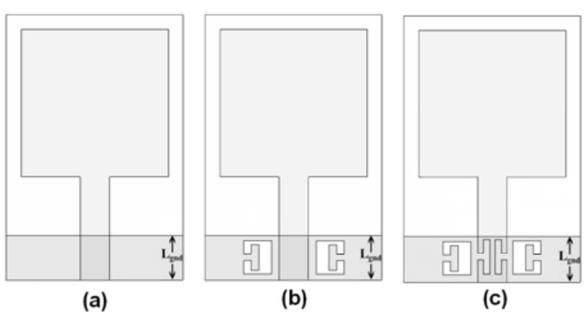


Fig. 7. (a) The ordinary square monopole antenna, (b) the square antenna with defected ground structure, and (c) the proposed antenna.

As shown in Fig. 8, in the proposed antenna configuration, the ordinary square monopole can provide the fundamental and next higher resonant radiation band at 4.2 GHz and 8.1 GHz, respectively, in the absence of these defected structures. The upper frequency is affected by using the rectangular slots with T-shaped protruded strip inside the slots on the ground plane. This behavior is mainly due to the change of surface current path by the dimensions of T-shaped slits at third resonance frequency (12.05 GHz), as shown in Fig. 9 (a). In addition, by inserting two modified T-shaped slits with variable dimensions on the feed-line the impedance bandwidth is effectively improved at the upper frequency [13]. As shown in Fig. 9 (b), the current concentrated on the interior and exterior edges of the two modified T-shaped slits at fourth resonance frequency (13.91 GHz). Therefore, the antenna impedance changes at this frequency, due to the resonant properties of the T-shaped slits. It is found that by using these slits, the fourth resonance occurs at 13.91 GHz in the simulation. Also input impedance of the various monopole antenna structures that shown in Fig. 7, on a Smith chart is shown in Fig. 10.

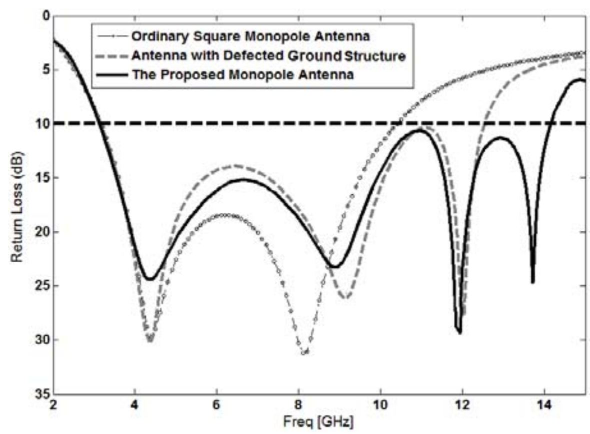
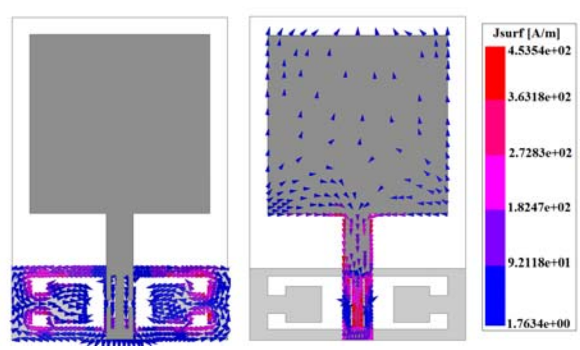


Fig. 8. Simulated return loss characteristics for the antennas shown in Fig. 6.



(a) (b)

Fig. 9. Simulated surface current distributions plane for the proposed monopole antenna (a) on the ground at the third resonance frequency (12.05 GHz) and (b) on the radiating patch at the fourth resonance frequency (13.91 GHz).

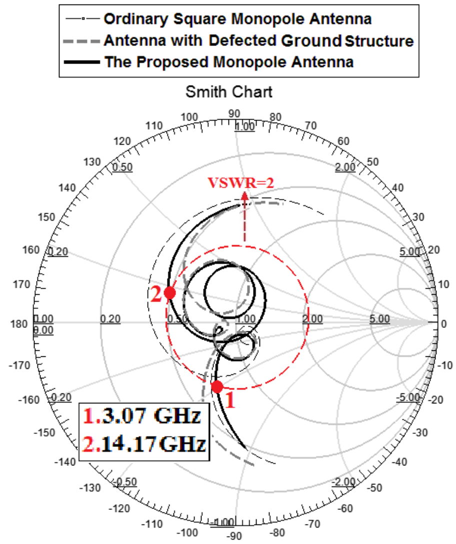


Fig. 10. The simulated input impedance on a Smith chart of the various antenna structures shown in Fig. 6.

The proposed antenna with optimal design, as shown in Fig. 11, was built and tested. Figure 12 shows the measured and simulated return loss characteristics of the proposed antenna. The fabricated antenna has the frequency band of 3.06 GHz to over 14.27 GHz. As shown in Fig. 12, there exists a discrepancy between the 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 and the wide range of simulation frequencies. In order to confirm the accuracy of return loss characteristics for the designed antenna, it is recommended that the manufacturing and measurement processes need to be performed carefully, besides, SMA soldering accuracy, and the FR4 substrate quality needs to be taken into consideration.

Figures 13 and 14 show the measured radiation patterns at resonance frequencies including the co-polarization and cross-polarization in the *H*-plane (*x-z* plane) and *E*-plane (*y-z* plane). The main purpose of presenting the radiation patterns is to demonstrate that the antenna actually radiates over a wide frequency band. It can be seen that the radiation patterns in *x-z* plane are nearly omnidirectional even at higher frequencies, and also the cross-polarization level is low for the four frequencies.

Fig. 11. Photograph of the realized printed square monopole antenna.

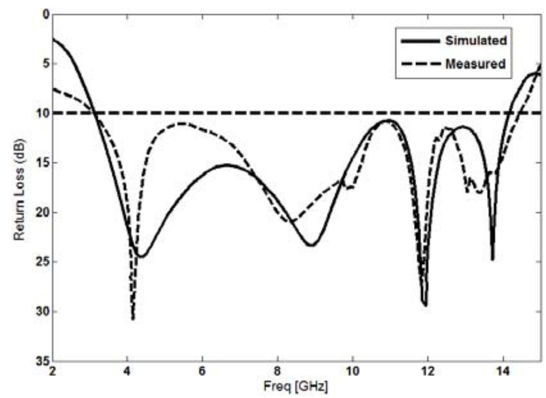


Fig. 12. Measured and simulated return loss for the proposed antenna.

V. CONCLUSION

In this paper, a novel compact printed monopole antenna with multi resonance characteristics with a novel time domain method to extract the RLC equivalent circuits of the defected structures has been proposed for UWB applications. The analytic formulations for the equivalent circuit models are obtained based on time-domain reflectometry theory, Laplace transform. The fabricated antenna covers the frequency range of UWB systems between 3.06 GHz to 14.27 GHz. The proposed antenna has a simple configuration and is easy to fabricate. Experimental results show that the proposed antenna could be a good candidate for UWB application.

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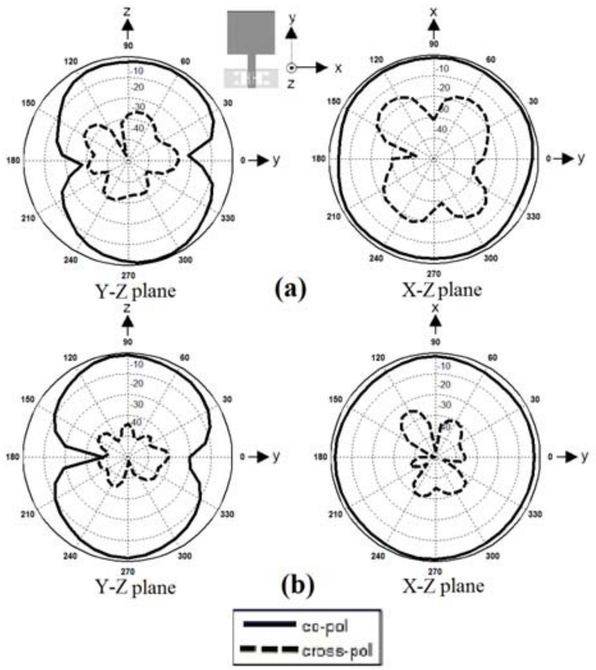

Fig 13. Measured radiation patterns of the proposed antenna; (a) first resonance frequency (4.13 GHz) and (b) second resonance frequency (9.35 GHz).

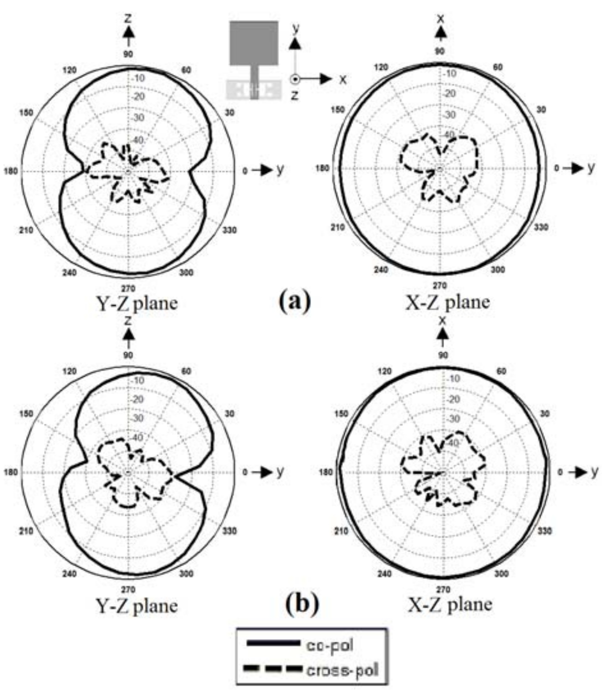

Fig 14. Measured radiation patterns of the proposed antenna; (a) third resonance frequency (12.05 GHz) and (b) fourth resonance frequency (13.91 GHz).

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