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Design and Analysis of Two Elements Reconfigurable Ultra-Wideband Multi Input Multi Output (UWB-MIMO) Antenna for Wireless Applications

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Abstract. A new compact frequency tuning antenna with a single element and two polarized elements for Ultra-Wideband Multi Input Multi Output (UWB-MIMO) wireless applications is designed and analyzed using the CST package. The proposed antenna supports four PIN diodes for frequency tuning and controls the frequency band from UWB band to narrowband through their ON/OFF states. The proposed 2-elements structure is designed using FR4 substrate with overall dimensions of (30x60x1.6) mm^3, the relative permittivity of 4.3, microstrip line feed with 50 Ω, and the antenna comprises patch element with an elliptical-shaped of radii of (10, 8) mm, two stubs with equal dimensions of (10x4) mm^2 connected to the microstrip line feed by PIN diodes and half elliptical GND plane with radii of (15, 7) mm. The proposed antenna operates with three frequencies with bands under (S11 ≤ -10 dB) from (3-9.65) GHz, (6.13-7.21) GHz, and (5.45-7.6) GHz according to the PIN diodes states. These bands can be used to cover UWB, Satellite, and WiMAX applications. The maximum gain is 4.2 dB and the lowest return loss is -46 dB at 6.68 GHz. The performances behind this design are less than 0.022, around 10, less than -20 dB for the Envelope-Correlation-Coefficient (ECC), Diversity-Gain (DV), and Isolation respectively.

INTRODUCTION

In recent years there a lot of concentration on MIMO technology and diversity because both in industry and universities need for high data rate and high spectrum efficiency [1]. The wireless systems that have multiple antenna elements at both the receiver and transmitter sides are called the wireless MIMO systems as presented in figure (1). These systems are used firstly in the 1980s by computer simulations, and later they have been explored analytically from papers [2]. Several wireless communication methods can be utilized in MIMO's systems including Long-Term-Evolution (LTE), WCDMA, and IEEE 802.11-standards for wireless-local-area-networks [1]-[2]. In addition, without additional bandwidth, the MIMO system improves transmission performance and transmission rates of the wireless communications systems [3]. The data rate (capacity) for a wireless connection can be enhanced by the expansion of the number of antenna elements on the transmitter and/or receiver side of the MIMO system without requiring extra power or spectrum in rich dispersion conditions. The limited space available for tiny mobile devices limited the number of antenna components and the coefficient of correlation between MIMO antenna components may drastically decrease the overall efficiency of MIMO components through mutual connectivity. The benefits of the use of numerous antenna components on the receiver's/transmitter's sides include increased channel capacity, interference suppression, and multi-path effects reduction [1].

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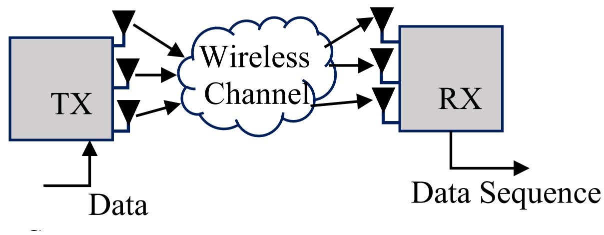


FIGURE 1. The MIMO system architecture [4].

The reconfigurable antennas are used in one or more different types for the manufacture of MIMO configurations in the same substrate and are used for the improvement of system properties within the MIMO system, including improvements in the quality of communication routes, efficient use of spectrum, compact size and reduced interference. RF switches like pin and varactor diodes, RF MEMS, switched condensers or Field-Effect-Transistors FET are used to reconfigure Frequency. [5]-[20].

Compact size, the coupling of more than 12 dB, the ECC of below 0.5, and the DV range of around 10 are the most essential criteria of the MIMO antennas [1], [7], [11], [13]-[14]. The ECC is a criteria in the MIMO antenna, which can check the similarity of the radiation pattern and quantify the field link between the antenna components and may be computed as equation (1). The variations gain (DV) is used to explain the increase of a combined signal multiple antenna system over a time-averaged SNR and may be computed using equations (2) [1], [13], [21]-[23].

$$ECC = \frac{|S_{11}^* S_{12} - S_{21}^* S_{22}|^2}{(1-|S_{11}|^2-|S_{21}|^2)(1-|S_{22}|^2-|S_{12}|^2)} \quad (1)$$

$$DV = 10 * \sqrt{(1-|ECC^2|)} \quad (2)$$

Where: ECC is the Envelope-Correlation Coefficient, S_{11}, and S_{22} are the S-parameters of the antenna, S_{12}, and S_{21} are the coupling coefficients between the antenna elements.

The primary idea for the 2-elements UWB-MIMO reconfigurable antenna is the same concept of the [21]-[23] presented antennas but with a different antenna structure and different frequency bands and applications.

This article is dedicated to developing and optimizing a novel, small UWB/narrowband 2-elements frequency tuning MIMO antenna for UWB, satellite, and WiMAX applications. The contributions of the design proposal are as follows:

1. An orthogonal 2-elements frequency tuning UWB-MIMO antenna with frequency band control using two stubs at the microstrip feeding with four PIN diodes for frequency reconfigurability.
2. A novel compact single element design with a single patch (10, 8) mm radii and a half elliptical partial GND plane (15, 7) mm radii correspondingly.
3. The proposed antenna presents frequency band control from UWB band of (3-9.65) GHz to narrowband from (5.45 to 7.6) GHz using stubs connected to the microstrip line feed through PIN diodes.

THE ANTENNA DESIGN AND THE MODELING OF PIN DIODE

The Antenna Design

The proposed antenna contains two structures one for a single element and the other 2x2 elements. The single element antenna is designed with an overall size of (30x30x1.6) mm^3 as shown in Fig. (2-a). It consists of an elliptical patch with radii of (10, 8) mm, dual stubs at the middle of the microstrip line feeding with equal areas of 10x4 mm^2 connected by using two PIN diodes and half elliptical GND plane with radii of (15, 7) mm. The second structure is designed with dual ports polarized 2-elements with an overall size of (30x60x1.6) mm^3 as presented in Fig. (2-b) with spacing between the two elements less than λ/2 (at the first resonance frequency the spacing between the two elements has been computed in relation to the lambda). The antenna is constructed on the FR-4 substratum with a thickness of (1.6 mm) and a 50 Ω microstrip feed line of εr=4.3, tan (δ) =0.002 relative dielectric constant and tangent losing, respectively. The antenna is designed using equations from equation (3) to (4) can be used for elliptical patch design and (5) for substrate design and the proposed antenna is analyzed using CST after making several parametric studies as presented in Fig. (3), to obtain the final structure and dimensions of the proposed antenna [24]-[26]. The optimum parameters of the proposed single element and 2-elements are presented in table (1) and table (2) respectively. Each element of the proposed 2-elements reconfigurable UWB-MIMO antenna having two PIN (DSM8100-000 Mesa Beam-Lead) diodes for frequency tuning and control the frequency band of the proposed antenna from UWB band to narrow band.

$$a = \frac{F}{\{1+\frac{2h}{\pi\varepsilon_r F}[ln ln\left(\frac{\pi F}{2h}\right)+1.7726]\}^{\frac{1}{2}}} \quad (3)$$

$$F = \frac{8.791 * 10^9}{\varepsilon_r f_r} \quad (4)$$

$$L = W = 6h + L_p \quad (5)$$

$$L_p = 2R_2 \quad (6)$$

Where:
R_2: The elliptical patch radius, ε_r: the dielectric permittivity, f_r: the frequency of resonant, h: the height of the substrate, L and W: are the length and width of the FR4 substrate, L_p: the patch length, and a = the radius of the elliptical patch.

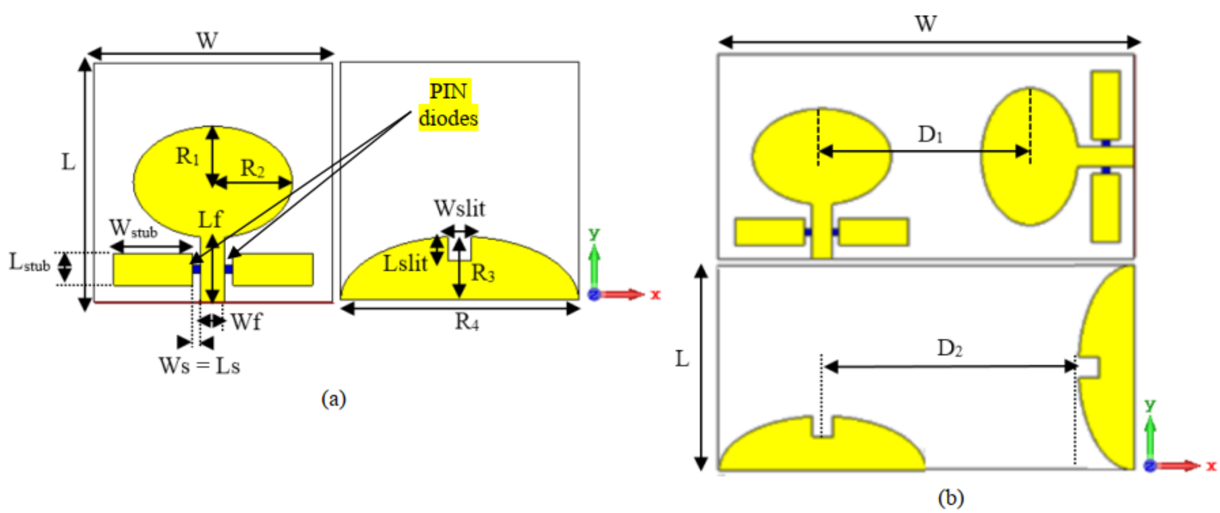
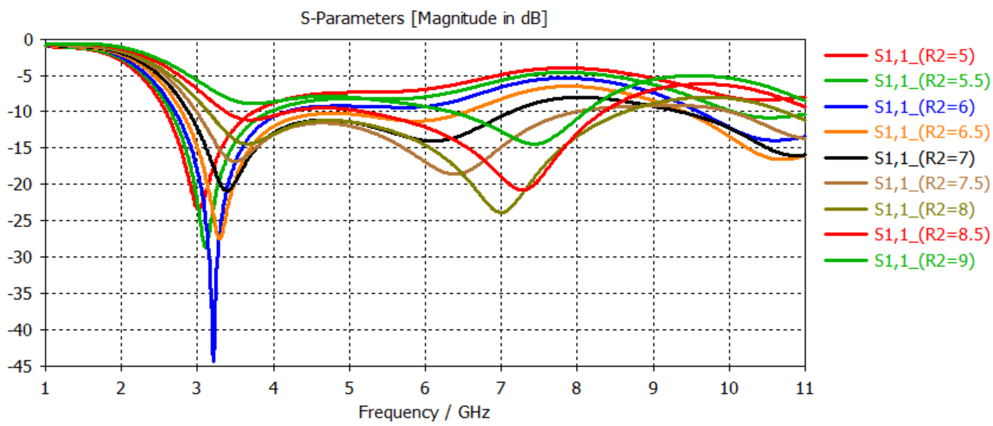
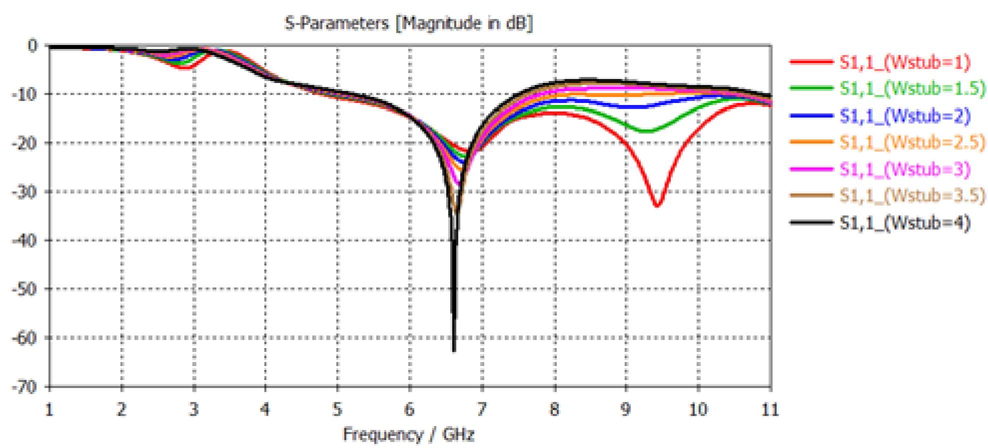


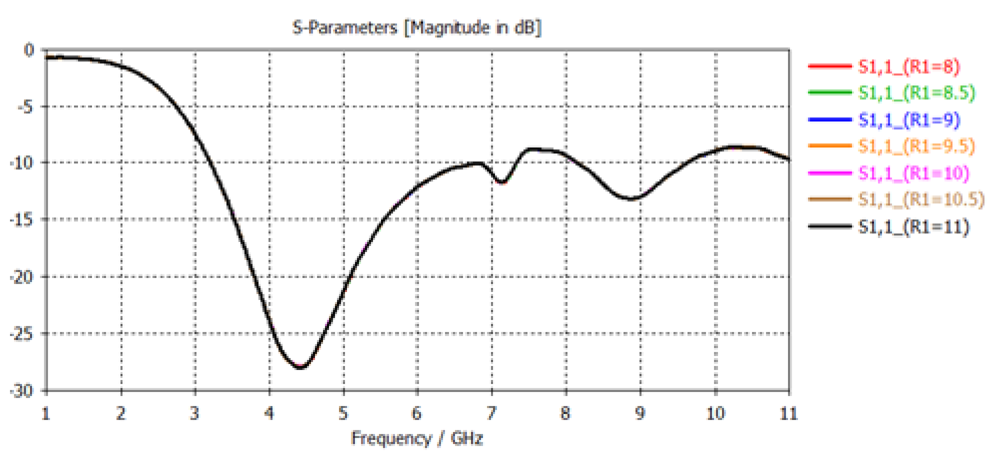
FIGURE 2. The structure of the UWB and UWB-MIMO antennas, (a) single element, (b) 2-elements


S-Parameters [Magnitude in dB]
Frequency / GHz
S1,1_(R2=5)
S1,1_(R2=5.5)
S1,1_(R2=6)
S1,1_(R2=6.5)
S1,1_(R2=7)
S1,1_(R2=7.5)
S1,1_(R2=8)
S1,1_(R2=8.5)
S1,1_(R2=9)

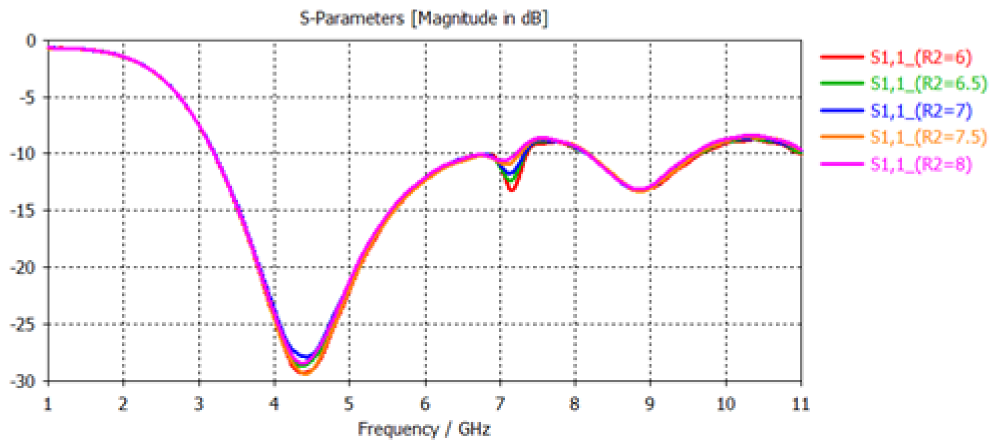
(a)


S-Parameters [Magnitude in dB]
Frequency / GHz
S1,1_(Wstub=1)
S1,1_(Wstub=1.5)
S1,1_(Wstub=2)
S1,1_(Wstub=2.5)
S1,1_(Wstub=3)
S1,1_(Wstub=3.5)
S1,1_(Wstub=4)

(b)


S-Parameters [Magnitude in dB]
Frequency / GHz
S1,1_(R1=8)
S1,1_(R1=8.5)
S1,1_(R1=9)
S1,1_(R1=9.5)
S1,1_(R1=10)
S1,1_(R1=10.5)
S1,1_(R1=11)

(c)



(d)

FIGURE 3. The antenna optimization using parametric study of the UWB-MIMO antenna, (a) R_3= 7 mm, (b) L_{stub}= 4 mm, (c) R_1=10 mm, (d) R_2= 8 mm.

TABLE 1. The optimized factors of the single element UWB-ANTENNA

Parameters	Values in mm	Parameters	Values in mm
W	30	L_f	21
L	30	W_f	10
R_1	10	L_s	0.7
R_2	8	W_s	0.7
R_3	15	t	0.035
R_4	7	h	1.6
L_1	2	W_1	8
L_{slit}	3	W_{slit}	3

TABLE 2. The optimized factors of the two elements UWB-MIMO-ANTENNA

Parameters	Values in mm	Parameters	Values in mm
W	30	L_f	21
L	30	W_f	10
R_1	10	L_s	0.7
R_2	8	W_s	0.7
R_3	15	t	0.035
R_4	7	h	1.6
L_1	2	W_1	8
L_{slit}	3	W_{slit}	3
D_1	13	D_2	22

The Modelling of PIN Diode

Frequency reconfiguration with two ON/OFF operational modes is done using a PIN diode. The ON-status of the switch is achieved by forwarding bias, acting in the form of a short circuit with modest impedance, which allows the current to pass through the switch while the OFF-state has a very large impedance and functions as an open circuit. The PIN diode is depicted in Fig (4) which shows the equivalent electrical circuit. The ON-status of the PIN diode operates as a 3.5 ohms resistor with an inductor of 0.15 nH in series, while the OFF-status combines 1 Kohm in conjunction with a capacitance of 0.025 pf and all in parallel with a 0.15 nH inductive inductor [21]-[25].

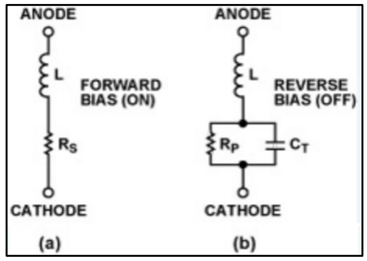


FIGURE 4. The equivalent electrical circuit of the PIN diode at (a) ON-status (b) OFF-status

RESULTS AND DISCUSSION

Using CST software, the simulation results for the proposed UWB-MIMO reconfigurable antenna are produced. There are three S-parameters of an antenna as shown in figure (5), as per the PIN diodes states from (3-9.65) GHz, (6.13-7.21) GHz, and GHz (5.45-7.6) reconfigurable bands under input reflection coefficient S11 less than -10 dB. These bands can be used to cover UWB, Satellite, and WiMAX applications according to the PIN diodes states with the lowest return loss of -46 dB at 6.68 GHz. The UWB band with (3-9.65) GHz is obtained at the OFF state while narrow bands (6.13-7.21) GHz and (5.45-7.6) GHz are obtained with all switches at the ON-state and the other when only a single switch at each element at the ON-state while the other are at the OFF-state. The maximum simulated gain is 4.2 dBi as presented in figure (6). The suggested antenna operates with all resonant frequencies for the worst coupling case, envelope-correlation-coefficient (ECC), and diversity-gain (DV) of under -20 dB, less than 0.022, and approximately 10 respectively, as shown in figure (7), figure (8-a), and figure (8-b) respectively, to meet the requirements of the MIMO system. The suggested antenna works on all reconfigurable bands that satisfy the practical criteria with a VSWR of less than 2. Figures (9) and (10) show the three PIN diodes conditions that can illustrate the 3D radiation pattern and the surface current distribution of the suggested antenna. As illustrated in figure (10), when the PIN diodes in the ON states change from UWB to a narrow band, where the surface current can pass into the stub. The suggested UWB-MIMO reconfigurable antenna has a lot of performance is shown in table (3).

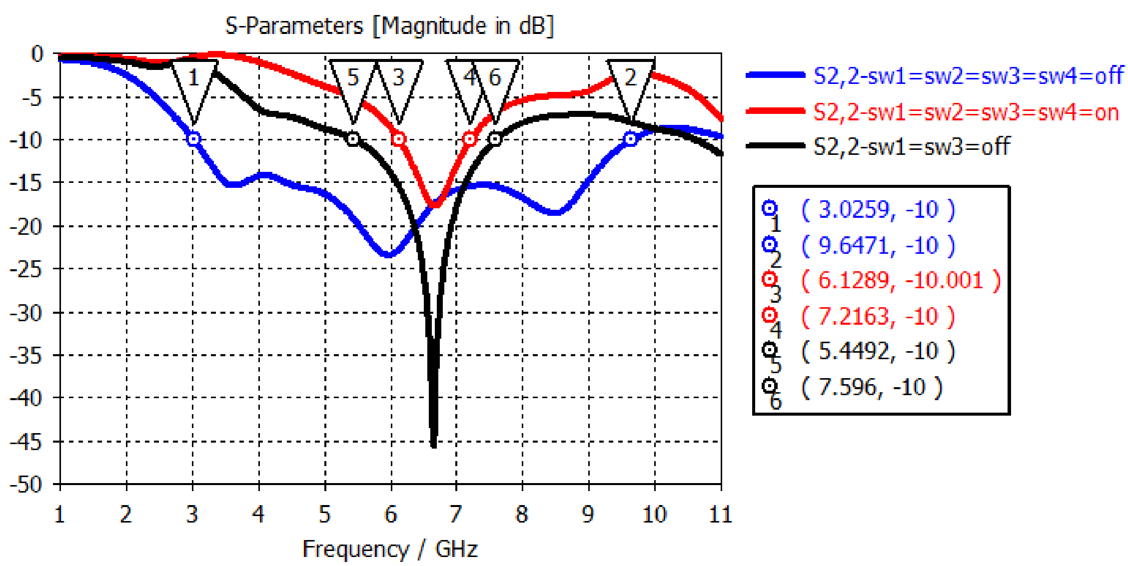


FIGURE 5. The reconfigurable bands of the suggested 2-elements UWB-MIMO antenna

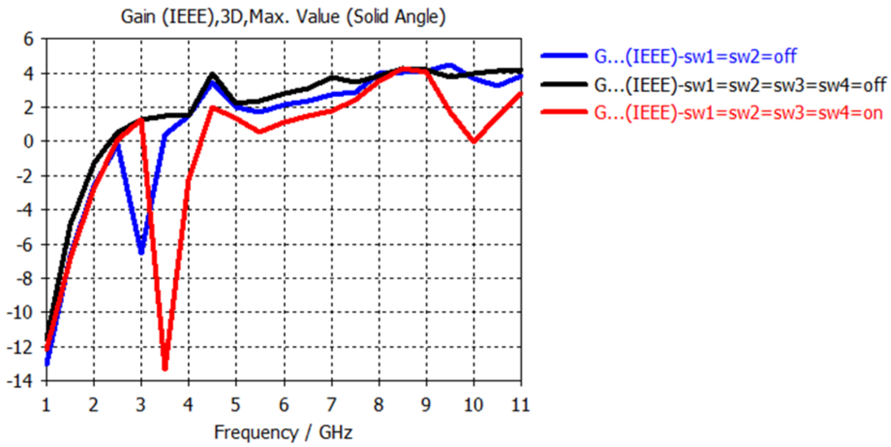


FIGURE 6. The obtained simulation gain relation with the frequency

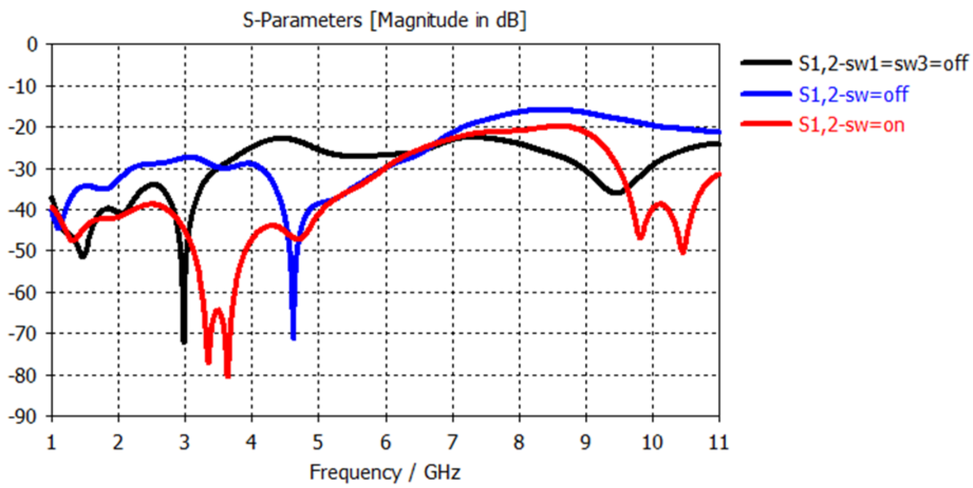
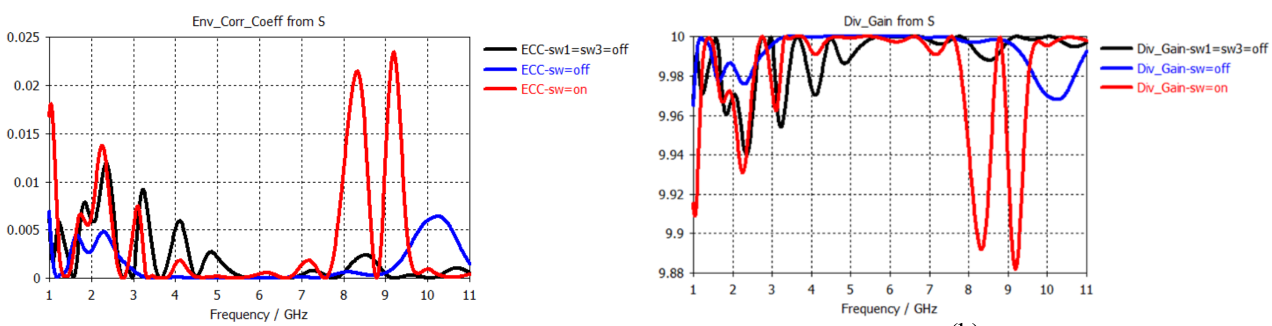


FIGURE 7. The relation between coupling and frequency of the 2-elements UWB-MIMO antenna



(a) (b)

FIGURE 8. The simulated Envelope-Correlation-Coefficients (ECC) and the Diversity-Gain of the 2-elements UWB-MIMO antenna, (a) ECC, (b) DV.

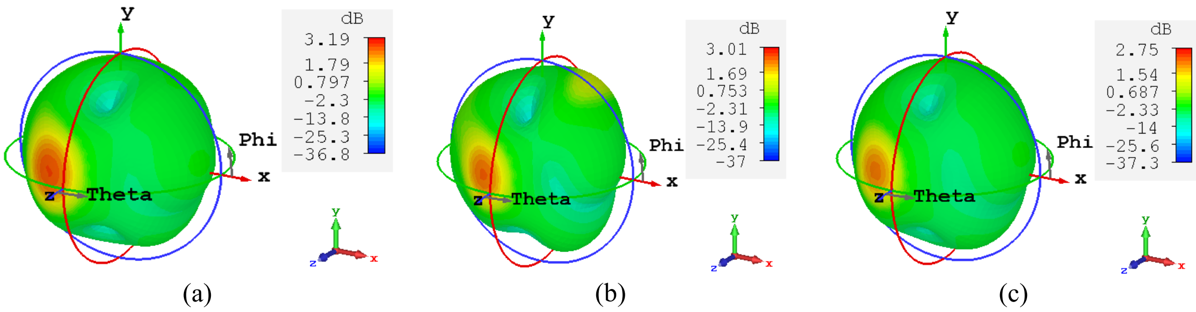


FIGURE 9. The 3D radiation pattern of the suggested antenna at: (a) all switches in off-state (at 6 GHz), (b) switch-1 on and switch-2 off (at 6.6 GHz), (c) all switches in on-state (at 6.68 GHz).

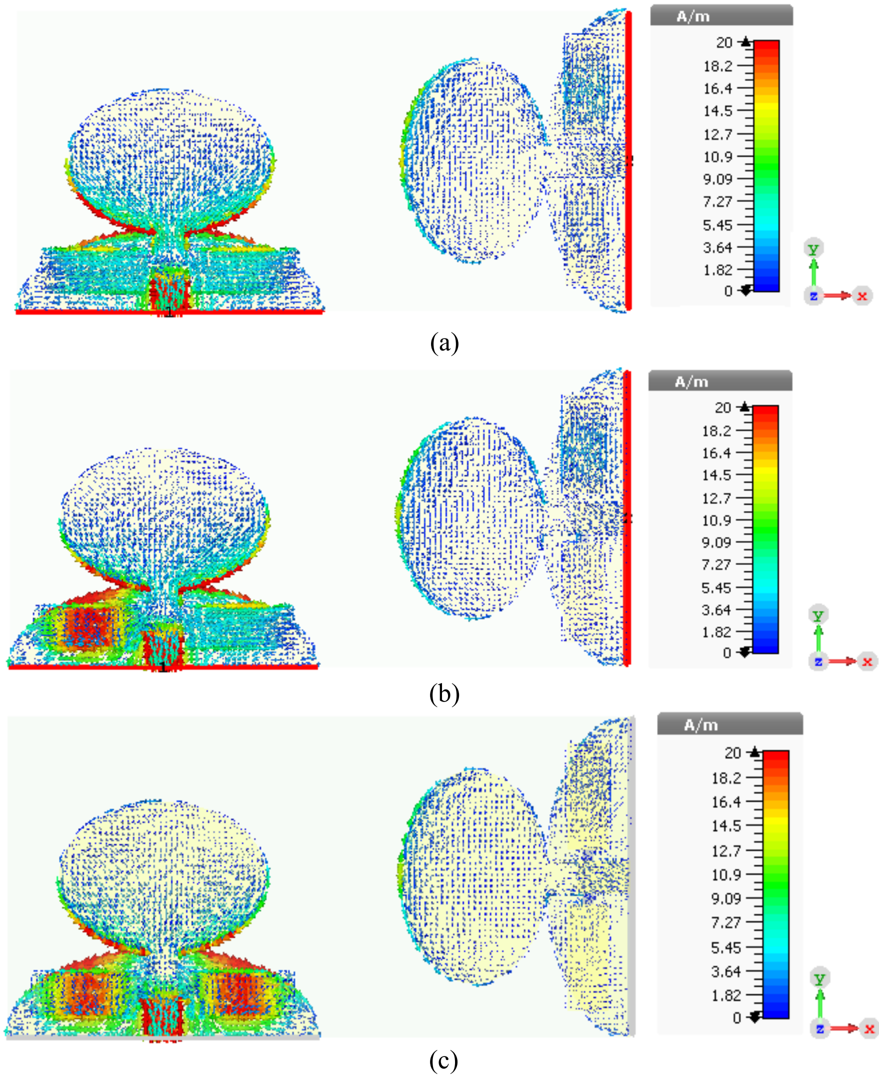


FIGURE 10. The obtained surface current distribution of the suggested antenna, (a) all switches in off-state (at 6 GHz), (b) switch-1 on and switch-2 off (at 6.6 GHz), (c) all switches in on-state (at 6.68 GHz)

TABLE 3. The properties of 2x2 elements reconfigurable UWB-MIMO reconfigurable antenna

PIN diode states	Frequency bands (GHz)	S11 (dB)	Gain (dB)	Isolation (dB)	ECC	DV
All switches off	3-9.65	-23.4	2.14	-29.8	$3.14x10^{-5}$	9.9998
All switches on	6.13-7.2	-17.6	1.6	-24.4	$4.44x10^{-5}$	9.9997
Switch-1 and Switch-3 off	5.45-7.6	-46	3.13	-25.2	$1.85x10^{-5}$	9.9999

There are some discussions about the simulation results of the proposed antenna they can summarize as below:

1. As presented in figure (5), the S_{11} parameter changes from UWB mode to the narrow band because of using stubs at the feeding connected with PIN diodes.
2. As shown in figure (6), the simulated gain degraded from 1.5 dBi to -13 dBi at 3.5 GHz and from 4 dBi to 0 dBi because of the coupling between the two elements.
3. As presented in figure (8-a), the ECC has a worst case of 0.022 less than 0.5 which accomplishes the requirements of the MIMO system.
4. As presented in figure (8-b), the DV has a worst case of 9.89 at 9.2 GHz around 10 which also performs the requirements of the MIMO system.

CONCLUSIONS

This article proposes a novel small two components frequency reconfigurable UWB-MIMO antenna that can function with UWB/narrow band for wireless applications such as UWB, satellite, and WiMAX systems. The frequency reconfigurability is done by utilizing two stubs at each component linked by PIN diodes. For all resonant frequencies, the suggested antenna is compact and has numerous acceptable performances, for example, the isolation between the two components below -20 dB, ECC below 0.022, and DV around 10.

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