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Frequency Reconfigurable U-Slot Antenna for SDR Application

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Abstract—In this paper, a novel frequency reconfigurable U-slot microstrip antenna with T-shaped feed line for Software Defined Radio applications is proposed. The proposed antenna, indexed as A-I in this paper, operates at three different frequencies: 1.85 GHz, 1.9 GHz and 2.4 GHz depending on the switching states of PIN diodes. Furthermore, to strengthen the proposed design concept and strategy another improved antenna (A-II) is designed and tested. In comparison to antenna A-I, the improved antenna design (A-II) utilizes four slots/PIN diodes in order to increase the number of reconfigurable frequency states. Depending on the switch states of four PIN diodes, antenna A-II operates on five different reconfigurable frequency bands centered at: 1.5 GHz, 1.6 GHz, 1.8 GHz, 1.9 GHz and 2.24 GHz. The measured results show a return loss better than 22 dB, maximum gain of 2.5 dB and maximum efficiency of 78%. Moreover, radiation pattern for the proposed antennas is stable at all operating frequencies.

1. INTRODUCTION

In recent years, development of smart components for SDR (Software Defined Radio) communication system have attracted the attention of researchers [1–3]. These smart components can sense, learn and be aware of their dynamic environment and are also capable of overcoming the serious effects of propagation fading. The reconfigurable antenna is one of the most important components in SDR communication system. Reconfigurable antennas have the ability to modify their characteristics in real time [1–4]. Based on their ability, different kinds of reconfigurable antennas are used in SDR to improve the performance of communication system, e.g., frequency reconfigurable [4, 5], pattern reconfigurable [4], polarization reconfigurable [6, 7] antenna, etc.

Having a critical look at the available literature it can be concluded that the use of frequency reconfigurable antennas dramatically reduces the overall system overheads [4–10]. In frequency reconfigurable slot antenna, frequency tuning is done by scaling the antenna dimensions electrically, by the integration of micro-electro-mechanical systems (MEMS) switches [8], PIN diodes [9, 10], varactor diodes [11], etc. Majid et al. [12] presented a switchable slot in the antenna ground plane for realizing nine frequency switching from 1.98 GHz to 3.59 GHz using 5 PIN diodes. In [13], a frequency and pattern reconfigurable microstrip slot antenna is reported. In [14], a pixel slot antenna which can reconfigure its resonating frequency in six different bands ranging from 2.2 GHz to 4.75 GHz using five PIN diode is reported. In [15], unequal U-slot antenna loaded with two varactors for 6 different frequencies switching between 2.3 GHz and 3.6 GHz is reported. These reported methods for achieving frequency reconfigurability require complex biasing circuits leading to an increased complexity of overall structure.

Therefore, in this paper, reconfigurable U-slot antennas are proposed, which cover the widely used frequency bands. From hardware perspective, the proposed antenna offers lower circuit complexity and

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ease of reconfiguration. Hence, such antennas can be used for SDR application so that after sensing the environment, antenna can adaptively tune its resonant frequency to various applications such as 2.4 GHz for Bluetooth, 1.9 GHz for GSM and Wireless LAN, 1.8 GHz for GSM, PHS, and WLL, 1.6 GHz for satellite communication (uplink frequency), Iridium satellite LLC and GLONASS (GLObal NAvigation Satellite System), 1.5 GHz for GPS and satellite communication (downlink frequency) applications, etc. Further, to validate the proposed work, both simulated and measured results are presented in the respective sections below.

2. ANTENNA GEOMETRY

Figure 1 shows the structure of the proposed antenna design A-I. The antenna is fabricated on an FR4 substrate with a thickness 1.6 mm and permittivity 4.4. The U-slot antenna is etched on the bottom layer and excited by T-shaped feed line fabricated on the top layer. Feed line is chosen as T-shape so that U-slot antenna can be symmetrically excited. Physical dimensions of antenna A-I are: $L_1 = 58.4$ mm, $L_4 = 8$ mm, $L_5 = 9.8$ mm, $W_2 = 3.4$ mm corresponding to U-slot, and $L_2 = 31$ mm, $L_3 = 26.4$ mm, $W_1 = 3$ mm corresponding to feed line. In addition, thin slits of width 0.30 mm are used to provide DC isolation, on which capacitors are mounted to provide RF continuity. Two slots of width 0.4 mm are used to mount PIN diodes. For antenna A-II, the design is the same except that two extra slots with dimension $L_6 = 9.5$ mm, $L_7 = 10.5$ mm are introduced, thus, this antenna A-II will have more combinations of switching states which result in more frequencies of operation as shown in Fig. 2. It is noteworthy here that all the other dimensions of antenna A-II remain the same as that of antenna A-I.

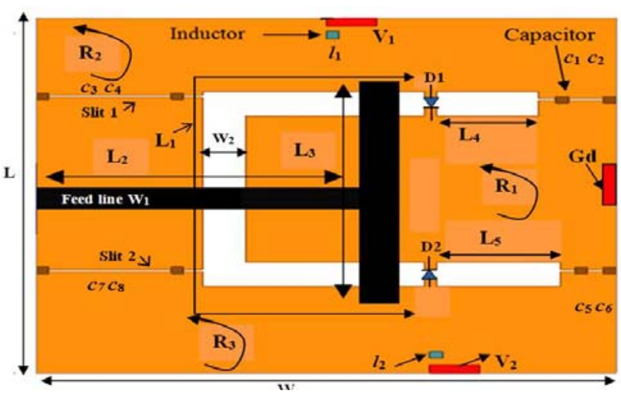


Figure 1. Layout of reconfigurable U-slot antenna A-I.

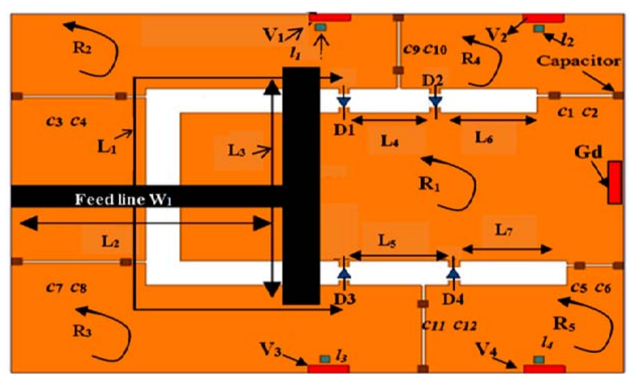


Figure 2. Layout of reconfigurable U-slot antenna A-II.

In antenna A-I, two PIN diodes (D_1, D_2) are placed in between the arms of U-slot as shown in Fig. 1 to change the effective length of slot, thus, producing controllable frequency shifts. The complete biasing circuit of PIN diode consists of two choke coils (l_1, l_2), four pairs of DC block capacitors (C_1C_2, C_3C_4, C_5C_6, C_7C_8) and two DC voltage pads V_1 and V_2. Two small slits of width 0.3 mm are introduced in the antenna plane, which separate the antenna in three isolated regions (R_1, R_2, R_3) and ensure DC isolation between V_1, V_2 and ground signal. These small slits are used for the biasing of PIN diode D_1, D_2 independently, without affecting the antenna performance. Surface mount device (SMD) RF capacitors, each with 30 pF value, are placed across these thin slits to maintain RF continuity and DC isolation. An inductor of 0.3 µH is placed near DC pad so that there is very low leakage towards DC. In antenna A-II, four PIN diodes are placed in the slot to control the frequency shifts. Six small slits of width 0.3 mm are introduced to separate the ground plane in five isolated regions R_1, R_2, R_3, R_4, and R_5 for biasing the all diodes, independently. The complete biasing circuit contains four DC voltage pads (V_1, V_2, V_3, and V_4), six pairs of SMD capacitors, and four inductors (l_1, l_2, l_3, and l_4).

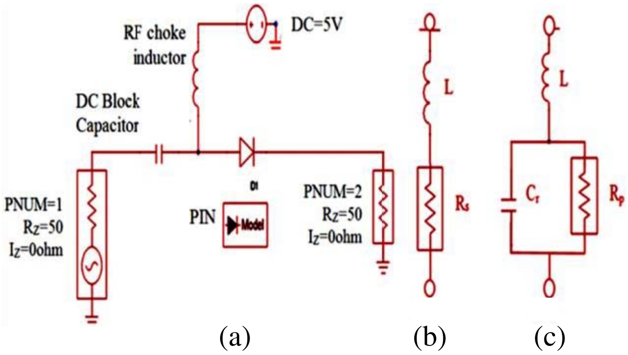


Figure 3. (a) The biasing circuit of PIN diode; (b) equivalent circuit in ON state; (c) OFF state.

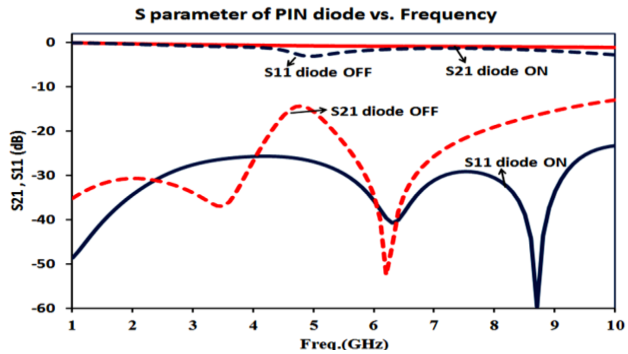


Figure 4. S parameter of PIN diode in OFF and ON condition.

3. BIASING OF PIN DIODE

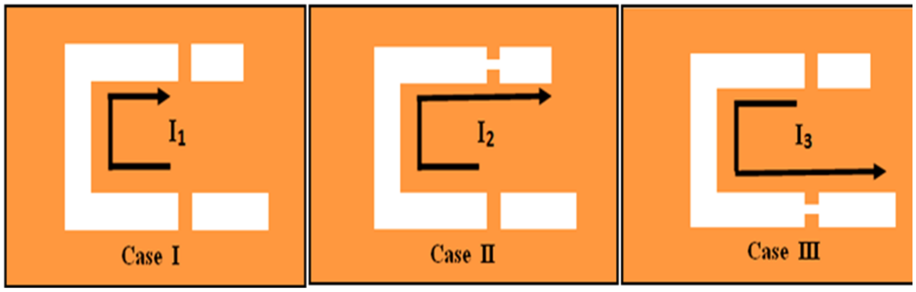
In the design of reconfigurable U-slot microstrip antennas, Infineon BAR6402 PIN diodes are used. Working of PIN diode can be easily explained by Fig. 3(a). In forward bias diode is modeled with a forward resistance of 2.1 ohm and a inductance of 0.6 μH as shown in Fig. 3(b), and in reverse bias it is modeled as a reverse parallel resistance = 3 kΩ, capacitance = 0.17 pF and inductance = 0.6 μH as shown in Fig. 3(c). In Ansoft HFSS simulation, PIN diodes are modeled using lumped RLC boundary to add and analyse the effect of actual PIN diodes. Simulated results in Fig. 4 show that in ON condition, insertion loss is 0.1 dB from 1 GHz to 10 GHz, hence diode will offer low impedance and acts as short circuit for RF signal. When PIN diode is OFF, insertion loss is below −18 dB as shown in Fig. 4, hence it exhibits high impedance, so there is no propagation of power from source to load terminal.

4. DESIGN STRATEGY OF U-SLOT ANTENNA

The resonant frequency of the U-slot is inversely proportional to the slot length [16]. Alternatively, frequency reconfiguration is achieved by positioning the PIN diodes (BAR64-02) such that the antenna resonates at the desired frequency of operation. One can see from Table 1 that the proposed antenna structures operate at different useful frequencies (just by the proper selecting proper number of PIN diodes) having application for GSM, Bluetooth, PHS, etc. Hence, these antennas can prove their significance especially for SDR applications. Using the same strategy, the basic design of antenna A-I is extended to antenna A-II for five different frequencies by increasing the number of slots/PIN diodes to four. Further increase in number of frequency shifts is limited by the antenna performance due to increase in antenna loss by PIN diode, lumped components and DC power supply. Diode D_1 is forward biased when $+5V$ is applied to DC pad V_1 placed in region R_2 and ground signal in region R_1. Similarly, diode D_2 is forward biased when $+5V$ is applied to DC pad V_2 placed in region R_3 and ground signal in region R_1.

Table 1. Different diode condition for antenna design A-I and A-II.

Case	Antenna I			Antenna II		
	D_1D_2	Active length	f_r GHz	$D_1D_2D_3D_4$	Active length	f_r GHz
I	11	L_1	2.38	1111	L_1	2.28
II	01	$L_1 + L_4$	1.91	0111	$L_1 + L_4$	1.91
III	10	$L_1 + L_5$	1.85	1101	$L_1 + L_5$	1.80
IV	- - -	- - -	- - -	0011	$L_1 + L_4 + L_6$	1.607
V	- - -	- - -	- - -	1100	$L_1 + L_4 + L_7$	1.51



(a) (b) (c)

Figure 5. Induced current distribution during switching in U slot antenna A-I in (a) case I, (b) case II, (c) case III.

4.1. Antenna A-I

When diodes D_1, D_2 are ON {case I-(11)} as given in Table 1, induced current I_1 will flow in length L_1 resulting in different resonating frequencies as shown in Fig. 5(a). When diode D_2 is ON {case II-(01)}, effective length is $L_1 + L_4$ as shown in Fig. 5(b), and induced current I_2 flows in this arm. When diode D_1 is ON {case III-(10)}, induced current I_3 will flow in active length $L_1 + L_5$ giving rise different resonant frequency in different cases.

4.2. Antenna A-II

In case-I when all the diodes (D_1, D_2, D_3 and D_4) are ON (logic 1, 1, 1, 1), effective length of slot is L_1. In case-II, diode D_1 is OFF and other diodes D_1, D_2, D_3 and D_4 are in (logic 0, 1, 1, 1) conditions, resulting effective slot length is $L_1 + L_4$. In case-III, when diode D_3 is OFF and other diodes D_1, D_2, D_3 and D_4 are in (logic 1, 1, 0, 1) state, the effective length of slot is $L_1 + L_5$. In case-IV, when diodes are in logic (0, 0, 1, 1), effective length is $L_1 + L_4 + L_6$. In case-V, switching diodes are in logic (1, 1, 0, 0) state and effective slot length becomes $L_1 + L_5 + L_7$. Some cases for diode combination are not reported in Table 1 because resonating frequency in those case coincides with the reported one with lower return loss so they are left out.

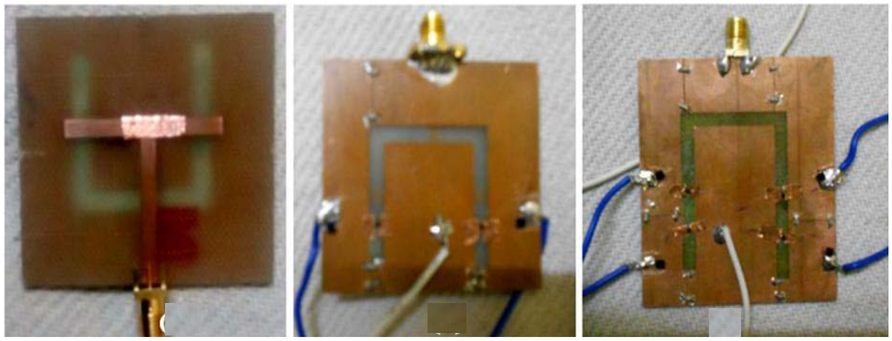
5. FABRICATION AND MEASUREMENT

Fabrication of both the prototypes are done using MITS PCB Prototyping Machine. Photographs of the resultant fabricated antenna are shown in Fig. 6. Both the antennas are fed using T-shaped line as shown in Fig. 6(a). The antennas are composed of a U-shaped radiating slot patch on the other side of substrate as can be seen from Figs. 6(b)–6(c). Fig. 6(b) shows the U-slot patch side of antenna A-I, and Fig. 6(c) shows the U-slot patch side of antenna A-II. For measurement Agilent Technologies VNA model No. N5222A is used.

6. RESULT AND DISCUSSIONS

6.1. Antenna A-I

The simulated and measured return loss vs. frequency for antenna A-I is shown in Fig. 7. It can be seen that antenna A-I can switch its resonating frequency in three different frequency bands according to the states of two PIN diodes present in the slot as tabulated in Table 2. When both diodes are ON (case-I), antenna resonates at 2.38 GHz with RL 33.75 dB whereas measured RL is 51 dB at 2.41 GHz. In case-II, antenna resonates at 1.91 GHz with RL 23.07 dB, whereas measured RL is 29 dB at 2.02 GHz. In case-III, antenna resonates at 1.85 GHz with RL 21 dB while measured value of RL is found to be 65 dB at 1.82 GHz.



(a) (b) (c)

Figure 6. Photographs of fabricated antenna. (a) Top view design A-I/A-II, (b), (c) bottom view of antenna A-I and A-II.

Table 2. Simulated and measured parameter of antenna A-I.

Case	D_1, D_2	Simulated		Measured	
		Freq. (GHz)	RL (dB)	Freq. (GHz)	RL (dB)
I	11	2.38	33.75	2.41	51
II	01	1.91	23.07	2.02	29
III	10	1.85	21.69	1.82	65

The measured results are satisfactory; however frequency shift w.r.t. simulated results is attributed to the OFF state capacitance of PIN diodes which produce loading effect on the antenna that shifts the resonance frequency [17]. Accordingly, there is no significant variation in frequencies in case-I, as none of the switch is in OFF state, resulting in no loading of OFF state capacitance on antenna and close agreement in measured and simulated frequencies. However, small variation may be due to miss-positioning of diodes and minor fabrication errors. The significant variation in frequencies in case-II, as compared to case-I, is probably due to associated OFF state capacitance of PIN diode in the circuit and miss-positioning of diodes in actual hardware w.r.t. desired position (position of diodes in simulation) in addition to error in fabrication process. The minor shift in simulated and measured resonant frequency in case-III is attributed to miss-positioning of diodes in actual hardware in addition to minor error in fabrication process.

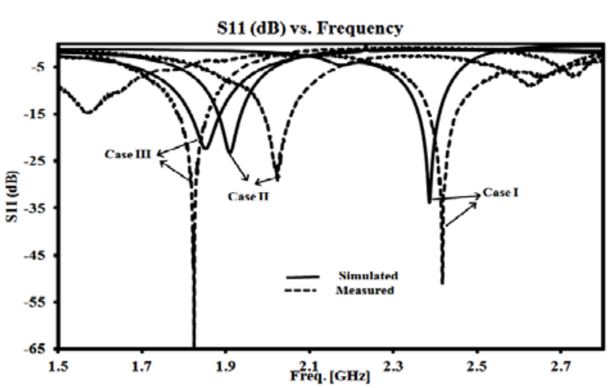


Figure 7. Simulated and measured reflection coefficients vs. frequency for antenna A-I.

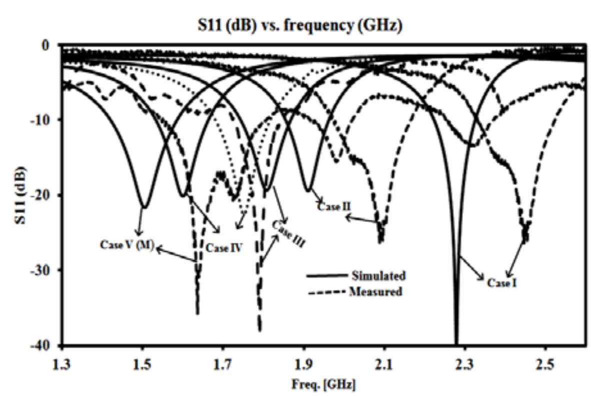


Figure 8. Simulated and measured reflection coefficients vs. frequency for antenna A-II.

Table 3. Simulated and measured parameter of antenna A-II.

Case	Measured		Simulated			
	Freq. GHz	RL (dB)	Freq. (GHz)	RL (dB)	Eff. %	Gain (dB)
I	2.454	26	2.28	41	68	1.7
II	2.08	25	1.91	19.3	72	2.2
III	1.79	38.5	1.80	19.2	78	2.5
IV	1.75	22	1.60	18.7	76	1.75
V	1.637	36	1.51	20.1	60	1.2

6.2. Antenna A-II

The proposed antenna A-II is capable of operating at five different frequencies in the wide operating frequency range of 1.5 GHz–2.4 GHz. These operating frequencies along with the PIN diodes state are mentioned in Table 1. Simulated and measured return loss vs. frequency for antenna A-II is shown in Fig. 8 and tabulated in Table 3. In case-I, antenna resonates at 2.28 GHz with RL 41 dB, whereas measured value is 26 dB at 2.454 GHz. In case-II, antenna resonates at 1.91 GHz with RL 19.34 dB while measured value of RL is 25 dB at 2.08 GHz. In case-III, antenna resonates at 1.8 GHz with 19.2 dB RL while measured value of RL is 38.5 dB at 1.79 GHz. In case-IV, antenna resonates at 1.60 GHz with RL 18.7 dB. In case-V, antenna return loss is 20.1 dB at 1.51 GHz whereas measured return loss is 36 dB at 1.637 GHz.

The variation in simulated and measured frequencies in case-IV & V, and relatively large shifts are attributed to large OFF state parasitic capacitance associated with two numbers of PIN diodes in the antenna circuits. This shift is small in case-II & III as only one diode is in OFF state and relatively low associated capacitance. The observed value of relatively large shift in resonance frequency in case-II (as compared to case-III) is in accordance with [17], as OFF state diode capacitance is known to have appreciable effect at higher frequencies. The larger shift in case-I is attributed to feed wires, imperfections of the components, miss-positioning of diodes in actual hardware w.r.t. desired position, in addition to error in fabrication process and pronounce effects of parasitic at higher frequencies.

The simulated radiation efficiency and gain for antenna A-II are shown in Fig. 9 and Fig. 10, respectively. Maximum value of gain obtained is 2.5 dB, and maximum value of efficiency is 78% in case III. Efficiency and gain in all the cases is greater than 1.2 dB and 60%. Simulated and measured E and H plane radiation patterns for all switching diodes cases are stable in all cases and close to simulated one as shown in Fig. 11. It can be seen that nearly directive radiation pattern (quasi-doughnut-shaped) is observed for E plane (y-z plane) and H (x-y plane) plane, respectively, which is useful for personal and mobile communications to get higher gain compared to omni directional antenna for increased performance and minimize interference effects from unwanted sources.

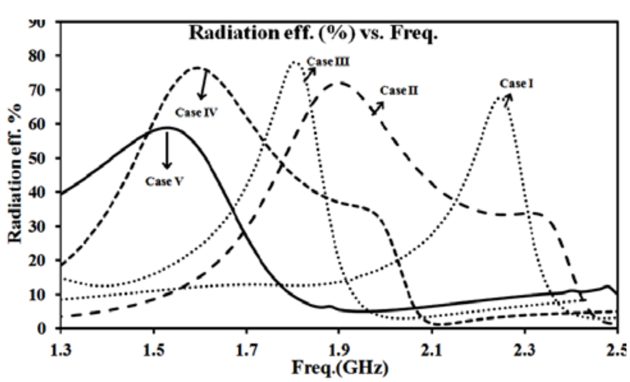


Figure 9. Radiation eff. vs. frequency for U-slot antenna A-II.

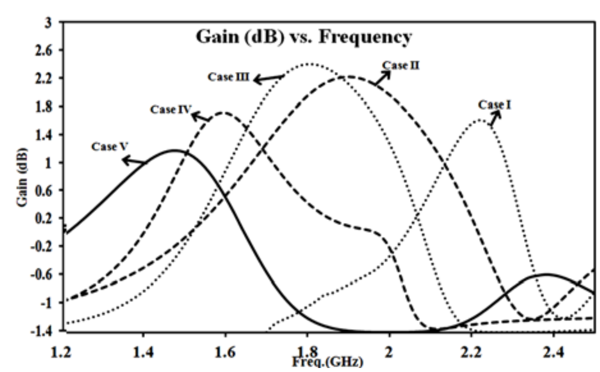
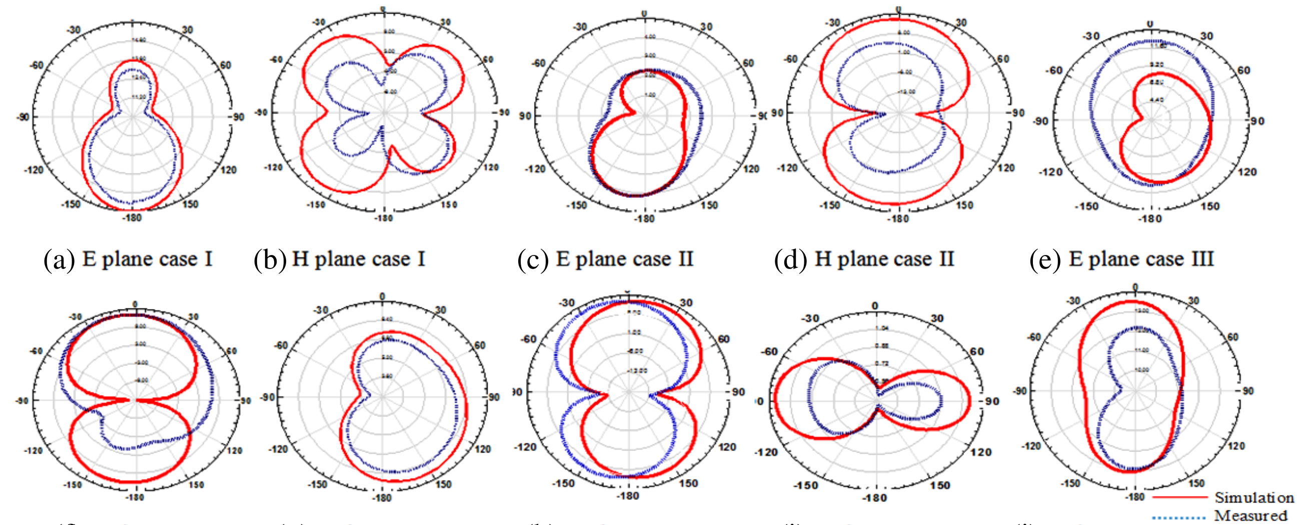


Figure 10. Gain vs. frequency for U-slot antenna A-II.



(a) E plane case I (b) H plane case I (c) E plane case II (d) H plane case II (e) E plane case III

(f) H plane case III (g) E plane case IV (h) H plane case IV (i) E plane case V (j) H plane case V

Figure 11. Simulated and measured radiation pattern of the proposed antenna design A-II in E and H plane.

A novel frequency reconfigurable U-slot microstrip antenna with T-shaped feed line for Software Defined Radio applications has been designed and tested. The present structure is implemented on a low cost FR4 substrate as a proof of concepts; moreover, the antenna size can be further reduced by including defective substrate structure (DSS) or by designing the antenna on low loss dielectric substrates. The paper presents the concept of frequency reconfigurabilty which can be used in software defined radio application so that after sensing antenna can reconfigure its resonating frequency in specified bands.

7. CONCLUSION

Frequency reconfigurable U-slot microstrip antenna with T-shaped feed line for Software Defined Radio application has been designed and implemented successfully. Frequency reconfiguration is achieved by tuning the slot length. By the proper selection of number of PIN diodes (BAR64-02) and their ON/OFF states, effective length of U-slot antenna can be controlled. Fabricated U-slot antenna (A-II) shows tuning frequency range from 2.454 GHz to 1.637 GHz with return loss better than 22 dB in all cases, giving a frequency ratio $f_r = f_h/f_l$ of 1.49 : 1. Simulated and measured results are presented, and performance of the antenna is thoroughly investigated.

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