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Design and Analysis of Resistive Series RF MEMS Switches Based Fractal U-Slot Reconfigurable Antenna

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Abstract The performance improvement of the reconfigurable antennas have potential impact on today's advance wireless communication networks. The design aspects and analysis of resistive RF MEMS series switch based fractal U-slot reconfigurable antenna are presented in the paper. For achieving the optimum performance of the switch in antenna, the low insertion loss and high isolation plays the vital role. Moreover, for the series RF MEMS based switches cantilever length, thickness and a gap space between the electrodes decides the pull-in voltage. The optimization of resistive RF MEMS series switch is carried out by Taguchi method using statistical analysis software. This statistical analysis provided the insight into the parameters that are critical to the design of switch. This optimum switch design is subsequently useful for superior performance of the antenna. The switch is designed and electromagnetic characteristics are analysed. The integration of resistive RF MEMS switches in U-slot fractal antenna is done using simulation tool. The performance of antenna has improved in terms of radiation efficiency and gain while sustaining omni directional radiation characteristics in X–Z plane. The multiband and wide band characteristics are obtained that makes it suitable for Wi-Fi, Wi-Max, UMTS & GSM applications.

Keywords Reconfigurable antenna · Fractal · Koch curve · RF MEMS switch · Resistive RF MEMS switch · Taguchi method

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1 Introduction

RF switches plays important role for obtaining reconfigurability in antenna system. The task of designing front end antenna system is a great challenging one in the area of reconfigurable antenna fields. The various researchers have tried to obtain the reconfigurability by PIN diodes, varactors, variable MEMS capacitors, RFMEMS switches etc. [1, 2]. As compared to other RF switches such as PIN diode MEMS based switches have extremely useful from last decade for telecommunication application due their characteristics such as low insertion loss, excellent isolation, low power consumption and linearity. PIN diodes possess comparatively better capability of power handling, low driving voltage and very low cost [1]. The PIN diodes have high reliability because of non moving parts. But this kind of diode consumes a relatively high amount of dc power because of requirement of large dc bias current in their ON state. As RF MEMS switches are actuated by built up static charges and biased by large dc voltage no current is drawn by these type of switches and they consume negligible amount of power. More over these switches offer relatively high linearity, low insertion loss, high isolation and very wide bandwidth. The MEMS miniature feature reduces the weights and sizes of the integrated devices due to which driving-power consumption is also reduced [1–3].

Basically depending on contact mechanism RF MEMS switches are classified as, metal-to-metal (ohmic or resistive) contact and a capacitive contact [4]. The DC-contact switches with low off-state capacitances i.e. open circuit can operate from 100 MHz to 40 GHz or higher. In the on-state position i.e. short-circuit, the DC-contact switches operates like a series resistor depending on the contact metal used and possess the value of a series resistance (Rs) of 0.5–2 Ω. But the direct contact series switch has a drawback of lower lifetime of contact area compared to the capacitive switches. On the other hand the capacitive contact switches are analysed by the capacitance ratio of the off-state and on-state positions and this is in the range of 80–160 with respect to design. The on-state capacitance is typically 2–3 pF operates on the range 8–100 GHz [5]. Practically, it is difficult to build a large ON-state capacitance using nitride or oxide material layers, hence capacitive switch cannot work for the low-frequency operation [4, 5]. The criteria for the selection of the best kind of resistive RF MEMS series switch with reference to antenna application is the compatibility with the micro strip lines, the simplicity, the long term robustness and reliability since the switch has to be able to perform billions of switching cycles [6].

During integration of switch on antenna platform the impedance mismatch due to packaging and assembling is major problem in hybrid mode. Therefore to sustains the good performance of the antenna with hybrid mode the additional adapting circuitry are used which will also suppress the undesirable RF signal reflection. For the monolithic or integrated mode it is cost effective as the process of fabrication requires single level of packaging process for overall design. The monolithic type of integration of the switches with antenna structure on the lower value of permittivity substrates, especially on the PCB boards will results in compact design. But the failure of one switch will lead to wastage of whole structure. It is reported that high resistive lines are required to bias the switches as metallic lines may perturbed the radiation pattern. [7, 8].

Here in this paper we have designed the fractal U-slot antenna and for obtaining the reconfigurability. We have used the resistive RF MEMS switches, by controlling the ON-OFF positions of the switches reconfigurability in terms of frequency is obtained which is discussed in the paper. The paper is organised as per this sequence-the design outline of the overall work is mentioned in Sect. 2 and the fractal U-slot reconfigurable antenna is under Sect. 3. The design and analysis of the switch is discussed in Sect. 4. The resistive series RF MEMS based antenna design is discussed in Sect. 5.

2 Design Outline

The rapid expansion in the high density wireless network create a need for reconfigurable multiband antennas. Keeping this in view the reconfigurable U-slot koch fractal antenna has been designed and analysed. The performance of the same is enhanced by inserting the resistive series RF MEMS switches. The target frequency range for the antenna design is 1–8 GHz which will be suitable for GSM, Wi-Fi & Wi-Max applications. The following design outline is implemented for meeting the goal:

1. Design of fractal U-slot reconfigurable antenna.
2. Obtaining reconfigurabilty in terms of frequency using fractal and ideal equivalent model of RF MEMS switches.
3. Design and optimization of resistive RF MEMS series switch for the reconfigurable multiband wideband antenna.
4. Integration of optimized switches with antenna for obtaining the re-configurability in terms of frequency for the overall performance improvement.
5. Fabrication and testing of antenna prototype using equivalent model of switch.

3 Design of Reconfigurable Antenna

Microstrip patch along with the fractal antennas forms a family of small size antennas which offers the advantages of a conformal nature & also the capability of integration with printed circuitry of the communication systems. Here the Koch curve fractal geometry is used in the U-slot and patch to enhance the antennas electrical length with which the resonance occur at lower frequency without changing the actual dimensions of the antenna [9].

FR4-epoxy substrate of 4.4 dielectric constants and 1.6 mm of thickness is used here. The copper patch is (22.4 × 18.8) mm. This is a monopole structure and partial ground plane is used over here with feed line having zigzag edges. A trapezoidal shape of matching section is used which joins the feed line to the rectangular patch antenna with U-slot Koch geometry [10]. The dimensions used for the antenna are mentioned in the antenna geometry as shown in Fig. 1. The details of the antenna design is reported in our previous work [3, 11]. This is the expansion of our previous work and here design and optimization of resistive RF MEMS series switch is carried out. The integration of resistive RFMEMS switches in antenna are also done to further enhance the performance.

3.1 Placement of Switches in the Slot

The reconfigurability can be achieved by placing the RF switches on the antenna's radiating structure. In this case to minimise the impedance matching process the switches are placed in the U-slots [10, 12]. For deciding the placement of switches analysis for current density distribution is carried out which is as shown in Fig. 2.

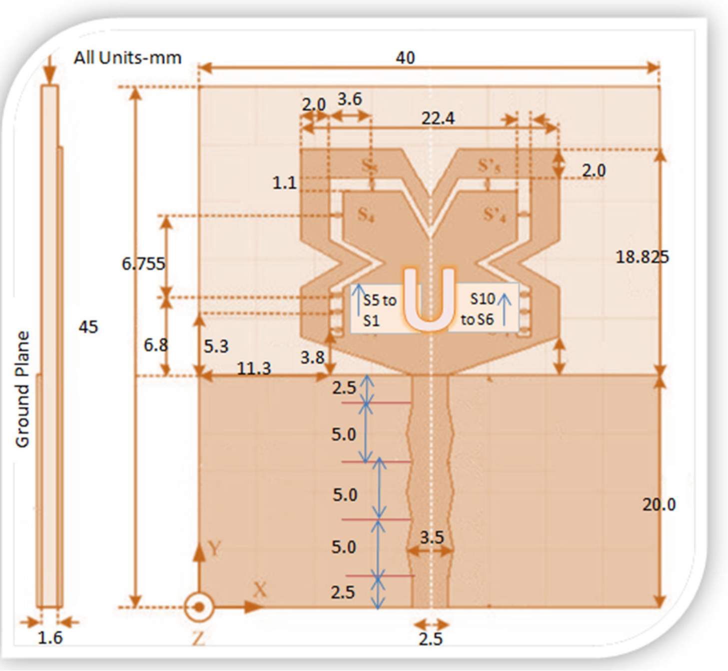


Fig. 1 Antenna geometry

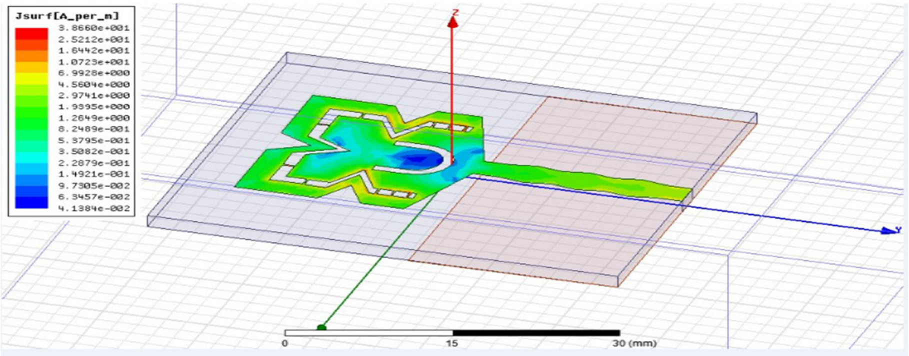


Fig. 2 Surface current density distribution

Analysis regarding the optimum number of switches required is carried out. Looking towards the distribution, multiband and wideband characteristics the ten switches are placed. The locations of the switches are determined in order to achieve the optimum gain at the desired frequency. Scientifically, with the switches incorporation in the radiating slot, the slot length varies which results in frequency shifts or multiple resonant frequencies. The radiation efficiency and gain also varies due the same. The four different case studies are considered in Table 1 for the analysis.

Table 1 Switching conditions [11]

Case	(*S*1, *S*6)	(*S*2, *S7*)	(*S*3, *S8*)	(*S*4, *S9*)	(*S*5, *S10*)
I	OFF	OFF	OFF	OFF	OFF
II	ON	OFF	OFF	OFF	OFF
III	OFF	ON	OFF	OFF	OFF
IV	ON	ON	ON	ON	ON

Table 2 Analysis of the antenna performance

Case	I	II	III	IV
Freq. band I	1.75–1.99 GHZ (BW-240 M Hz) fc-1.87 GHz S11-(−19.62) dB	1.88–1.98 GHz (BW-100 M Hz) fc-1.92 GHz S11-(−19.78) dB	1.96–2.17 GHz (BW-210 M Hz) fc −2.05 GHz S11-(−17.56) dB	Wide Band 2.28–6.67 GHz
Freq. band II	Wide Band 2.50–4.50 GHz	Wide band 3.00–5.30 GHZ	Wide band 3.04–5.62 GHz	NA
Freq. band III	6.05–6.79 GHz (BW-740 M Hz) fc −6.3 GHz S11-(−27.47) dB	6.05–6.80 GHz (BW-750 M Hz) fc −6.32 GHz S11-(−29.48) dB	6.32–6.74 GHz (BW-420 MHz) fc −6.32 GHz S11-(−26.24) dB	NA
Gain in dBi at 1.9 GHz	0.68	1.73	2.25	2.55
Gain in dBi at 4 GHz	1.50	3.08	3.3	3.83
Gain in dBi at 6 GHz	1.38	2.01	3.16	3.68
Directivity	1.96	1.88	1.82	1.76
Radiation efficiency at 1.9 GHz	59.4	79.6	90.3	93.9
Radiation efficiency at 4 GHz	62.7	94.2	94	94
Radiation efficiency at 6 GHz	79	81.1	84.2	86.6

The performance analysis to judge the different parameters of antenna in terms of gain, bandwidth, radiation efficiency and directivity is carried out. The results are summarised in Table 2.

The return loss characteristics for all the four cases has been studied and shown in Fig. 3. It has been observed that gain, radiation efficiency are subsequently increased with inserting the RF MEMS equivalent model for the cases II, III, IV. The performance of the Case IV is depicting very good wide band and maximum gain as compared to other cases at all frequencies of analysis. While the case 2 and case 3 are giving good multiband and wideband characteristics with good amount of gain and radiation efficiency. For the

Fig. 3 Return loss characteristics

integration of the resistive RF MEMS series switch in the slot developed on the patch of an antenna switch dimensions are necessary to be optimised which is discussed in next section.

4 Design and Optimization of Resistive RF MEMS Switch

We have used Taguchi method for optimization of the switch design parameters. With the Taguchi method the number of commutations is reduced and hence time required for analysis is also reduced. The overall operation of the switch depends upon various parameters such as pull-in voltage, current density, isolation and return loss etc. Taguchi method uses the orthogonal arrays for properly organising the parameters that are influencing the process and factor levels on which variation in the parameters are to be obtained. Here the ten numbers of control factors and three number of factor levels have been selected for process of optimization [13]. The various input and output design parameters selected for analysis are given below in Table 3.

The three factor levels which are considered for the purpose of analysis are given in Table 4.

The 27 experimental trial run are provided to MINITAB software and the analysis is carried out. The analysis of pull down voltage infers that the width of the cantilever has lesser impact on pull down voltage while the length and thickness have a remarkable impact. The S11 interaction analysis infers the great impact of frequency on its value and isolation analysis infers the effect of frequency and up-state capacitance on its variation.

Table 3 Set of input and output parameters

Set of input parameters		Set of output parameters	
1	Width of the cantilever	1	Pull in voltage
2	Thickness of the cantilever	2	Deflection
3	Length of the cantilever	3	Current density
4	Bottom electrode length	4	Isolation (dB)
5	Bottom electrode width	5	Return loss (dB)
6	Gap or distance between plates		
7	Voltage applied for deflection		
8	Current across strip line		
9	Frequency		
10	Upstate capacitance		

Table 4 Control factors and factor levels

Factor Level	p1-Cantilever width µm	p2-Cantilever thickness µm	p3-Cantilever length µm	p4-BE-length µm	p5-BE-W µm	p6-Gap µm	p7-voltage (V)	p-8 current (mA)	p-9 Freq (GHz)	p-10 Upstate capacitance (Cu) fF
1	150	2	300	80	30	1.5	20	10	1	1
2	180	2.5	350	100	35	1.8	25	15	4	2
3	200	3	400	150	54	2	30	20	8	4

From the Taguchi analysis it has been observed that third factor level is suitable for the further consideration.

4.1 Design of Resistive *RF MEMS* Switch

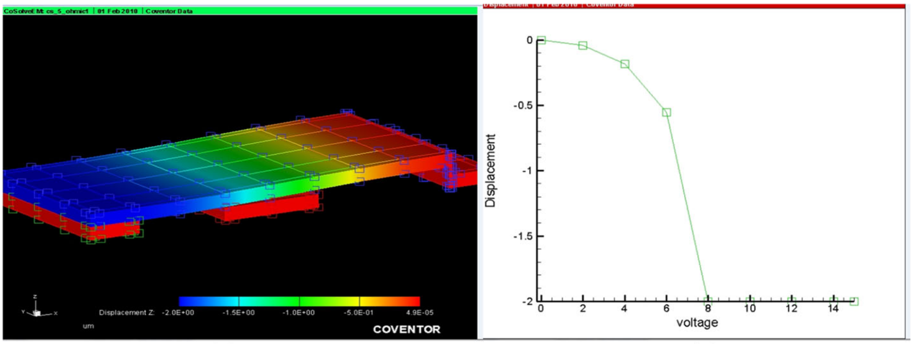
A RF MEMS switch makes the contact between the metals through a cantilever [14, 15]. The cantilever is pulled down by applying the voltage to the pull down electrode which is generally located below the middle section of the cantilever and the tip of the cantilever makes the contact. The most common materials used for the design of switches are copper, aluminium and gold. With respect to the young's modulus, chemical stability the aluminium and gold are best. The aluminium and copper both material study has been done for cantilever and electrodes, anchors design. The model of the switch design is shown in Fig. 4. The pull-in analysis is carried out and results reveal that switch touches the contact area completely at the 8 V.

Ohmic RF MEMS series switch is designed using HFSS. The ON state insertion loss and off state isolation of the switch is obtained using simulation tools. Moreover isolation and insertion loss for the same design considerations were analysed for PIN diode and series RF MEMS for 1–8 GHz which results in the insertion loss of −3.25 dB for PIN diode and −0.1005 dB for the RF MEMS switch. For $R_S = 0.18\ \Omega$ of the switch design the very low insertion loss of −0.018 dB was calculated. It has been reported that the insertion loss for PIN diode for 1–10 GHz is in range of 0.5–2 dB and isolation is less as compared to the RF MEMS switches [4]. The nature of isolation curve in OFF state is as shown in Fig. 5. The values of isolation, insertion loss and S_{11} of switch at three frequencies of operation as given in Table 5 are showing the superiority of RF MEMS switch. Figure 6 shows the surface current density plots for ON–OFF state.

The resistive series RF MEMS integrated antenna design is discussed in next section.

5 Design and Analysis of RF MEMS Integrated Antenna

The simulation of integrated resistive series RF MEMS switch and antenna is done using HFSS. The structure of the antenna design is discussed earlier in Sect. 3. RF MEMS switches placement are done at the same location of the ideal switches. The antenna



(a) (b)

Fig. 4 **a** RF MEMS model. **b** Pull-in analysis

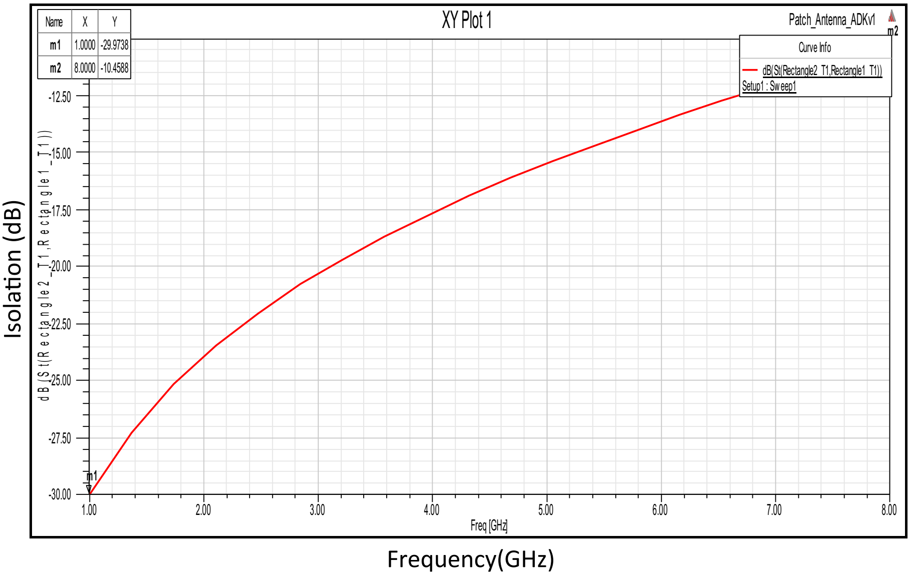


Fig. 5 Isolation OFF state characteristics

Table 5 Isolation, insertion loss and return loss values of switch

Frequency (GHz)	Off-state isolation (dB)	On-state insertion loss (dB)	Return loss values (dB) with RF MEMS Switch Close	Return loss values (dB) with RF MEMS Switch Open
1.9	−23	−0.05	−13	−0.03
4	−17.7	−0.17	−8	−0.05
6	−13.5	−0.19	−5.5	−0.20

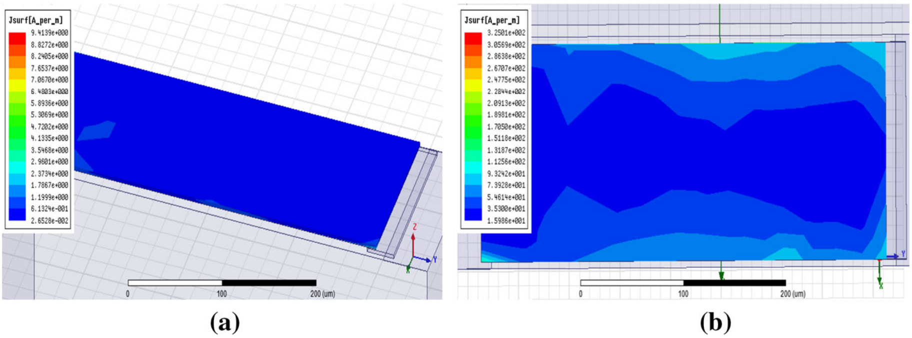


Fig. 6 Surface current density **a** OFF state **b** ON state

structure with MEMS switches is as shown in Fig. 7. Practically, the conductor portion in the antenna is much larger than the metal width in the RF MEMS switch leading to negligible impact of switch impedance on the performance of the antenna. For the best two

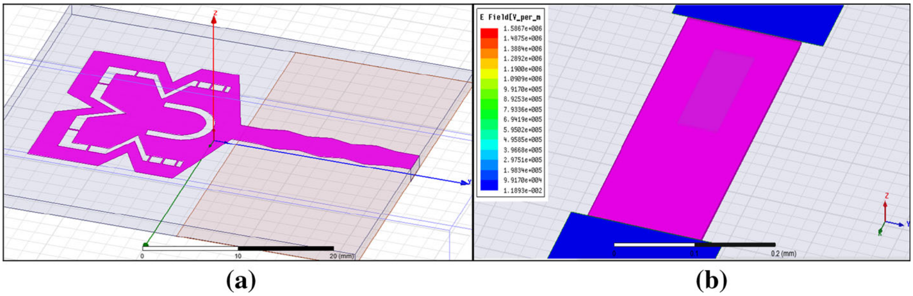
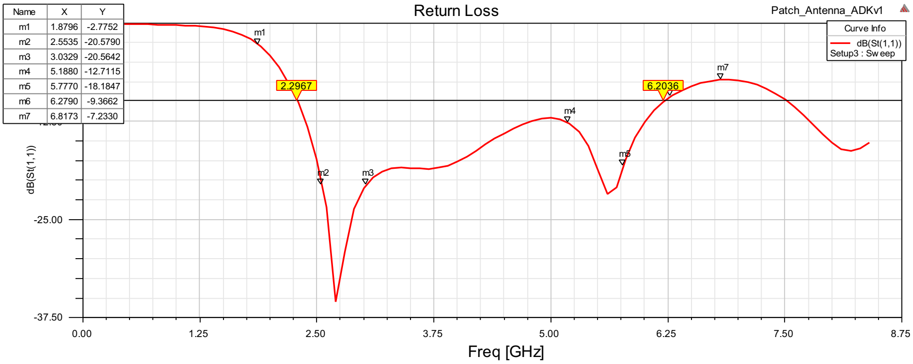


Fig. 7 **a** Model of an RF integrated antenna **b** Cantilever within the slot



Name	X	Y
m1	1.8796	-2.7752
m2	2.5535	-20.5790
m3	3.0329	-20.5642
m4	5.1880	-12.7115
m5	5.7770	-18.1847
m6	6.2790	-9.3662
m7	6.8173	-7.2330

Fig. 8 Return loss characteristics for MEMS integrated antenna when Case IV

cases II & IV, performance analysis are given in details. The return loss characteristic of case IV is given in Fig. 8.

Case IV is giving better gain and radiation efficiency as compared to antenna without switches and offers wide bandwidth among all switching cases. This gain can further be improved with Rogers substrates and high dielectric constants will led to compact structures. Performance analysis of case II shows the good multiband and wide band characteristics as shown in Fig. 9 and Table 7 depicts the analysis of all the parameters related to case II.

5.1 Fabrication and Testing of Antenna Prototype

The antenna prototype is fabricated and measurement is carried out by connecting the Copper Strip for ON and disconnecting the switch for OFF state. The Fig. 10 shows the fabricated prototype. The return loss characteristics are shown in Fig. 3 for all switching conditions and measured values for various parameters are reported in Table 2. The Good multiband and wide band characteristics are obtained for the different switching conditions. Tables 2, 6 and 7 also depicts the increase in gain and radiation efficiency with the switches incorporation. The measurement is carried out on Agilent technologies N5230-A network analyser of frequency range of 20 GHz and Fig. 13 shows case II measured return

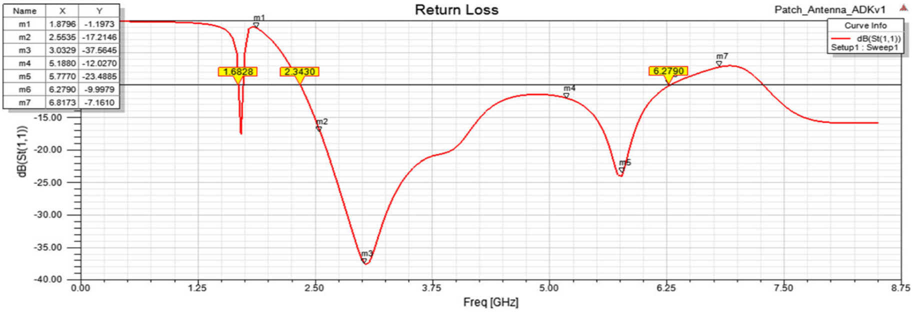


Fig. 9 Return loss characteristics for MEMS integrated antenna for Case II

Fig. 10 Fabricated prototype

Table 6 Performance analysis of the antenna for Case-IV

Frequency (GHz)	Gain comparison			Radiation efficiency comparison		
	Antenna without switches (dB)	Antenna with metal equivalents (dB)	Antenna ohmic RF MEMS switches (dB)	Antenna Without switches (%)	Antenna with metal equivalents (dB) (%)	Antenna with ohmic RF MEMS switches (%)
1.9	0.68	2.55	2.60	59.40	93.90	94.20
4.0	1.50	3.83	3.63	62.70	94.00	93.80
6.0	1.38	3.68	3.95	79	86.60	88.40

Table 7 Performance analysis of the antenna for case-II at resonant frequencies

Parameters	Frequency band I fr1 = 1.7 GHz	Frequency band II fr2 = 3 GHz	Frequency band III fr3 = 5.75 GHz
Return loss	−19 dB	−39 dB	−24 dB
Bandwidth	70 MHz	Wide band 76.3%	109 MHz
Gain	3.9 dB	4.3 dB	4.9 dB
Radiation efficiency	90%	92%	92%

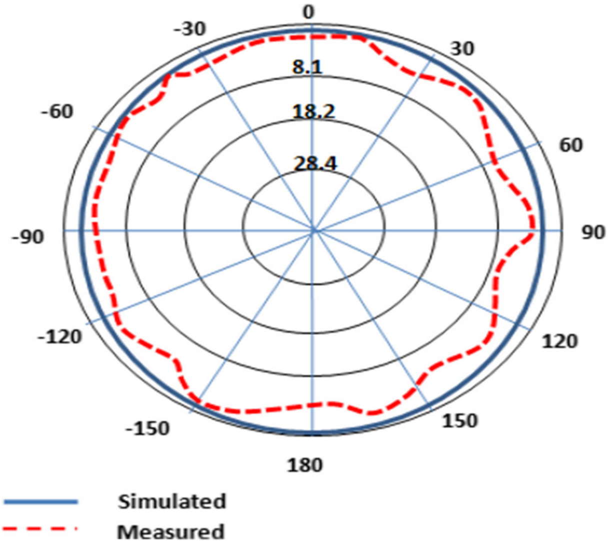


Fig. 11 *X–Z* plane radiation pattern for Case 4 at 1.9 GHz

loss plot. Figure 11 depicts the radiation pattern at 1.9 GHz & Fig. 14 reflects the simulated and measured results of case IV. The good match between measured and simulated result is observed.

The analysis of resistive series based Fractal U-slot antenna is implemented for the switching conditions mentioned in Table 1. Gain and radiation efficiency improved for all the cases in line with earlier discussed results of reconfigurable antenna given in Table 2.

The comparison of gain and radiation efficiency is done for both metal equivalent and ohmic RF MEMS switches and findings are given below:

1. With the introduction of resistive series RF MEMS switches there is significant improvement in gain and radiation efficiency. Table 6, 7 depicts the same.
2. With introduction of metal equivalent similar results are obtained. In order to assess the statistical equivalence of data obtained, the test of correlation is done. It is found that the correlation coefficient of metal equivalent and ohmic switches is 0.97 (Correlation coefficient above 0.80 indicates strong correlation). This indicates a

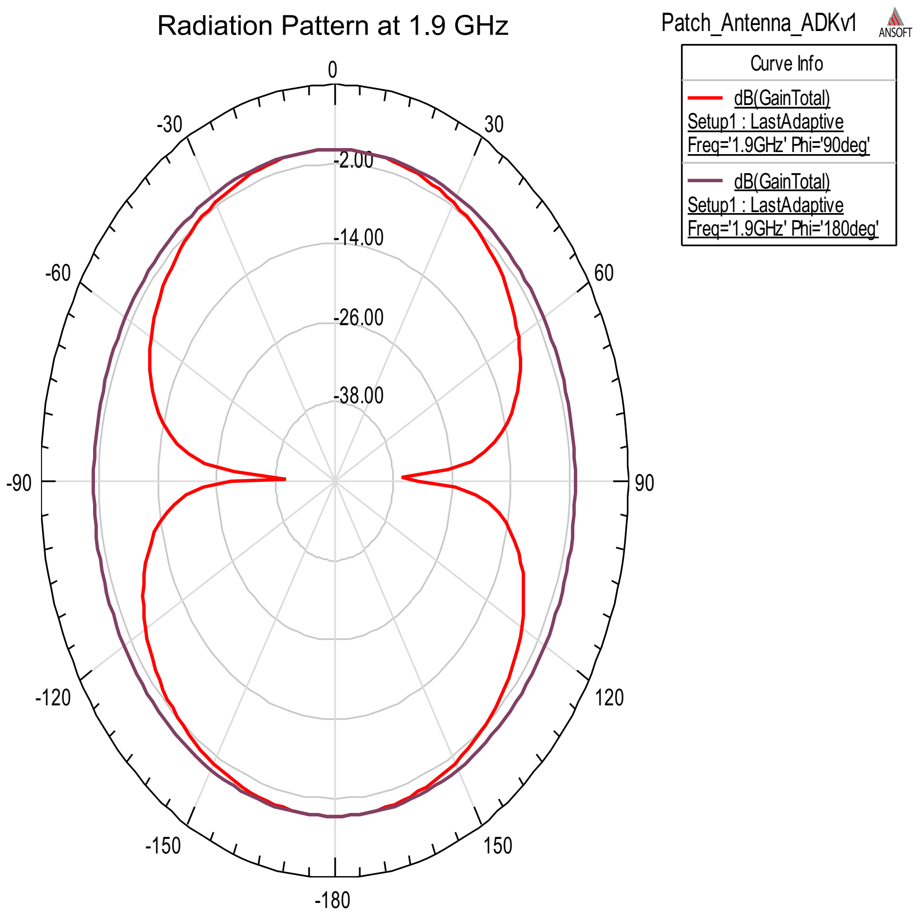
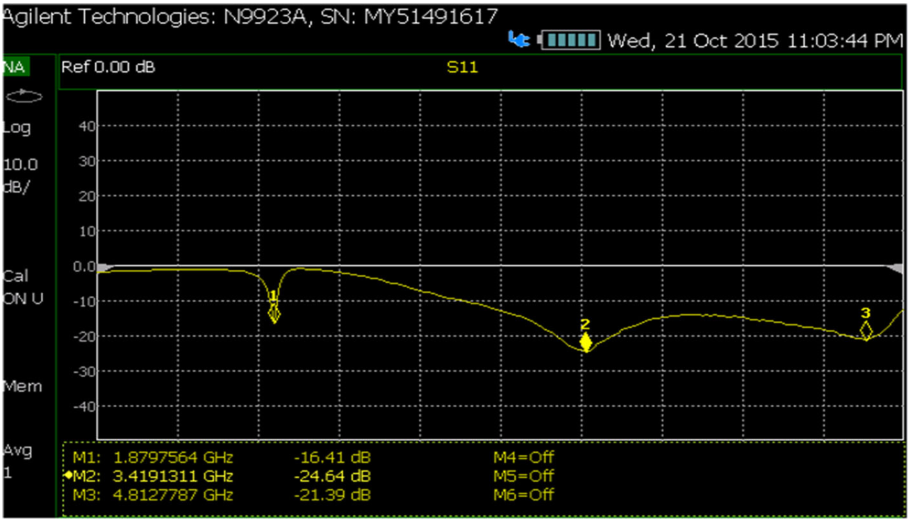


Fig. 12 Radiation pattern 4 GHz, 6 GHz (*Red* Y–Z Plane, *Black* X–Z Plane)

strong correlation and inter-changeability of ideal metal equivalents for verification purpose.

3. As resistive RF MEMS switch offers high isolation and very low insertion loss they have emerged as an excellent choice for reconfigurable antenna.
4. The return loss characteristics in Fig. 8 shows the very good wide band characteristics and improved gain and radiation efficiency as reported in Table 6.
5. The return loss characteristics in Fig. 9 shows the good impedance matching for UBW, GSM, Wi-Fi and Wi-Max frequency range. The bandwidth of 100 MHz and wide bandwidth of 76.2% observed from 2.3 to 6.2 GHz for case II.
6. Almost Similar radiation pattern is obtained for all the operating frequency bands as shown in Fig. 12.

Thus single antenna supports multi band and wide band operation sustaining similar and good radiation characteristics, minimum insertion loss and high isolation with negligible power consumption for multiple switching cases. These characteristics of the antenna design will have a positive impact on wireless communication system.



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Agilent Technologies: N9923A, SN: MY51491617
Wed, 21 Oct 2015 11:03:44 PM
M1:  1.8797564 GHz   -16.41 dB   M4=Off
◆M2: 3.4191311 GHz   -24.64 dB   M5=Off
M3:  4.8127787 GHz   -21.39 dB   M6=Off
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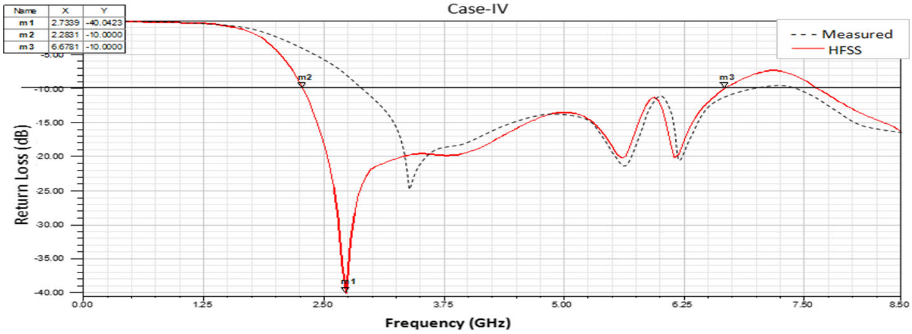
Fig. 13 Measured Return Loss characteristics for case II



Name	X	Y
m1	2.7339	-40.0423
m2	2.2831	-10.0000
m3	6.6781	-10.0000

Fig. 14 Measured and simulated return loss characteristics

6 Conclusions

The design and analysis of resistive RF MEMS series switch has been done and the same is integrated in the U-slot fractal reconfigurable antenna using simulation tool HFSS. The multi band and wide band characteristics are obtained in every switching conditions. The antenna radiates with similar radiation patterns in three frequency bands. The incorporation of switches improves the radiation efficiency and gain of the antenna. Taguchi analysis is used for optimisation of switch design parameters. The high isolation and low insertion loss of RF MEMS switch is obtained. These values are far superior as compared to PIN diode. The fabricated prototype of U-slot fractal antenna has been tested with metal strips i.e. RF MEMS ideal equivalents and excellent results are obtained. The omni directional pattern is obtained in X–Z plane and ‘8’ shaped pattern is obtained in

Y–Z plane. The overall bandwidth in the range of 100–250 MHz and 420–750 MHz is obtained.

This multiband and wide band design with improved gain and radiation efficiency is suitable for Wi-Fi, Wi-Max, GSM, UWB range and also can be used in microwave imaging and satellite communication applications.

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