



Design, optimization and analysis of reconfigurable antenna using RF MEMS switch

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Abstract

This paper presents the design, optimization and analysis of a novel radio-frequency micro electromechanical system (RF MEMS) switch for reconfigurable antenna. The proposed antenna operates at frequency band from 4.5 to 12.5 GHz. The antenna is created by reconfiguring its size using a rectangular patch and an inverted U shaped patch via RF MEMS switch. A series metal to metal contact RF MEMS switch is designed and optimized for low actuation voltage with adequate switching speed and excellent RF characteristics. The design of RF MEMS switch is simulated using CoventorWare and RF analysis is performed on Ansys HFSS software. Pull in voltage obtained for the switch is 5.7 V with switching time of 38.7 μ s. The isolation obtained is better than -20 dB for DC to 25 GHz. Insertion loss is less than -0.4 dB for DC to 60 GHz and return loss is also better than -23 dB for DC to 60 GHz. Further the designed reconfigurable antenna is simulated using Ansys HFSS software. The antenna is reconfigurable at 4.5 GHz, 8.6 GHz, 9 GHz, 12.3 GHz, 12.4 GHz and 12.5 GHz for different switch positions.

1 Introduction

With the advancements in electronics and wireless communication, the demand for miniaturization of wireless devices is increasing. This miniaturization can be achieved by reducing the number of antennas in the device by using reconfigurable antennas. A reconfigurable antenna can change its properties by altering the radiated fields of effective aperture based on the purposeful rearrangement of antenna currents or reconfiguration of radiating edges (Christodoulou et al. 2012; Costantine et al. 2015). Reconfigurability in an antenna can be achieved in terms of frequency of operation, radiation pattern, polarization behavior, or a combination of any of these properties (Christodoulou et al. 2012). It causes significant reduction in size when compared to a multi antenna system and maximizes the antenna performance to satisfy changing operating requirements.

Frequency and radiation pattern reconfigurability in antenna is usually achieved electrically by using RF MEMS switch or PIN diode to redirect their surface currents. PIN diode based switch can control large RF signals using low dc voltage. They have high switching speed and are reliable due to absence of mechanical parts. However, they have relatively high power consumption and poor RF characteristics like insertion loss and isolation above 1 GHz (Rebeiz 2003; Balaraman et al. 2002; Sravani et al. 2018; Ehmke et al. 2000). On the other hand, RF MEMS switch offer substantially better performance than PIN diode as they offer very low insertion loss, high isolation and low power consumption. They are very compact and light weight as compared to PIN diodes.

RF MEMS switches have experienced immense growth in past two decades due to their immense potential in defense, telecommunication and satellite communication. RF MEMS switches are an excellent choice for reconfigurable implementations due to their exceptional RF characteristics. In an RF MEMS switch, the mechanical movement can be achieved using four different actuation techniques—electrostatic, piezoelectric, magnetostatic and thermal actuation. Electrostatic actuation method is most prevalent due to virtually zero power consumption, small size and relatively short switching time (Rebeiz 2003). The mechanical movement of switch can be vertical or lateral.

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The vertical movement typically results in small size devices while lateral movement results in large size devices. Apart from reconfigurable antennas, these RF MEMS switches are also useful for other microsystems like phase shifters, tunable filters and matching networks. (Rebeiz 2003; Ehmke, et al. 2000).

RF MEMS switch can have metal to metal contact or capacitive contact either in series or shunt configuration. A metal to metal contact switch consists of a cantilever beam suspended over a gap between transmission lines. A metal to metal direct contact is achieved between the conductive cantilever beam and transmission lines due to the electrostatic potential developed between the actuation electrode and cantilever beam. They exhibit low insertion loss during ON state and high isolation during OFF state of the switch. These switches are capable of maintaining excellent electrical contact while maintaining minimum parasitic capacitive coupling and low contact resistance. They are suitable for applications in the frequency range of DC – 60 GHz (Rebeiz 2003). A capacitive coupled switch uses a metal bridge over the dielectric layer connecting two transmission lines. When the bridge is in up position, the capacitance is low creating a high impedance path driving the switch in OFF state. When an appropriate DC voltage is applied, the electrostatic force pulls down the metal bridge on the dielectric layer. The bridge gets capacitive coupled with the transmission lines making a high capacitance and low impedance path allowing the high frequency RF signal to pass and driving the switch to ON state. Capacitive coupled RF MEMS switch are suitable for applications in the frequency range of 10–120 GHz (Rebeiz 2003). Therefore, a metal to metal contact RF MEMS switch is more suitable for low frequency applications.

In spite of the advantages like small size, low weight, low power consumption, low insertion loss and high isolation, RF MEMS switch suffer from problems like high actuation voltage and slow switching speed. Electrostatic actuation needs high pull down voltage of 20–80 V which is impractical for reconfigurable antennas (Rebeiz and Muldavin 2001). Thus, it is important to optimize the design of RF MEMS switches for low actuation voltage.

In this paper, a low actuation series metal to metal contact RF MEMS switch with adequate switching speed and excellent RF characteristics is presented for reconfigurable antenna. This paper is organized as follows. Section 2 discusses the design parameters of RF MEMS switch. Section 3 presents the techniques used for optimization of switch parameters and analysis of optimized switch. Section 4 discusses the design of reconfigurable antenna using RF MEMS switch and RF analysis of the designed antenna. Section 5 concludes the paper.

2 Design of RF MEMS switch

The switch presented in this paper is a series metal to metal contact RF MEMS switch with electrostatic actuation and vertical movement as shown in Fig. 1. The switch consists of bottom substrate made of silicon. The cantilever beam of size $225 \mu\text{m} \times 100 \mu\text{m}$ is fixed at one end while the other end having contact dimple of $45 \mu\text{m} \times 100 \mu\text{m}$ is layered with conducting material for connecting the two transmission lines of $45 \mu\text{m} \times 25 \mu\text{m}$ with $50 \mu\text{m}$ horizontal gap between them. A conducting layer is also placed in the centre of the cantilever beam to induce electrostatic actuation. The simulation of the design of RF MEMS switch is performed on Coventorware, as shown in Fig. 2. In OFF state, the cantilever beam suspends over a vertical gap of $1.5 \mu\text{m}$ above the transmission lines providing good isolation. When sufficient voltage is applied between the actuation electrode ($100 \mu\text{m} \times 100 \mu\text{m}$ in size) and cantilever beam, a metal to metal direct contact is achieved between the conductive cantilever beam and transmission lines driving the switch to ON state. As soon as the applied voltage is removed, the cantilever beam regains its original shape due to its stiffness driving the switch back to OFF state.

In design process of an RF MEMS switch, actuation voltage is a critical parameter that enables the switch to toggle from OFF to ON state and vice versa. When a voltage is applied between the cantilever beam and actuation electrode, the electrostatic force induced on the beam is similar to the electrostatic force that exists on the plates of a capacitor. On equating the applied electrostatic force with the mechanical restoring force due to stiffness of the cantilever beam, the actuation voltage can be expressed as (Rebeiz 2003):

$$V = \sqrt{\frac{2k}{\epsilon_0 W w} g^2 (g_0 - g)} \quad (1)$$

where k = spring constant of the cantilever beam, ϵ_0 = permittivity of free air, w = width of the beam, W = width of actuation electrode, g = height of beam above the transmission line under electrostatic force, g_0 = height of beam above the transmission line without any electrostatic force. The actuation voltage becomes maximum when:

$$\frac{dV}{dg} = 0 \Rightarrow g = \frac{2}{3} g_0 \quad (2)$$

This means that electrostatic force overcomes the spring restoring force when the distance between the cantilever beam and transmission lines becomes $2/3$ of the un-actuated height. So, the pull in voltage can be expressed as (Rebeiz 2003):

Fig. 1 Schematic view of series metal to metal contact RF MEMS switch **a** side view, **b** front view

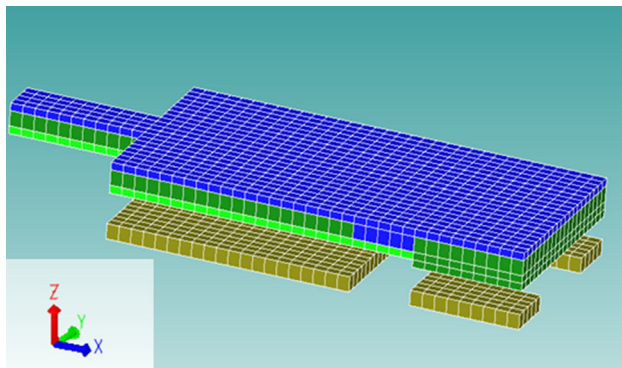
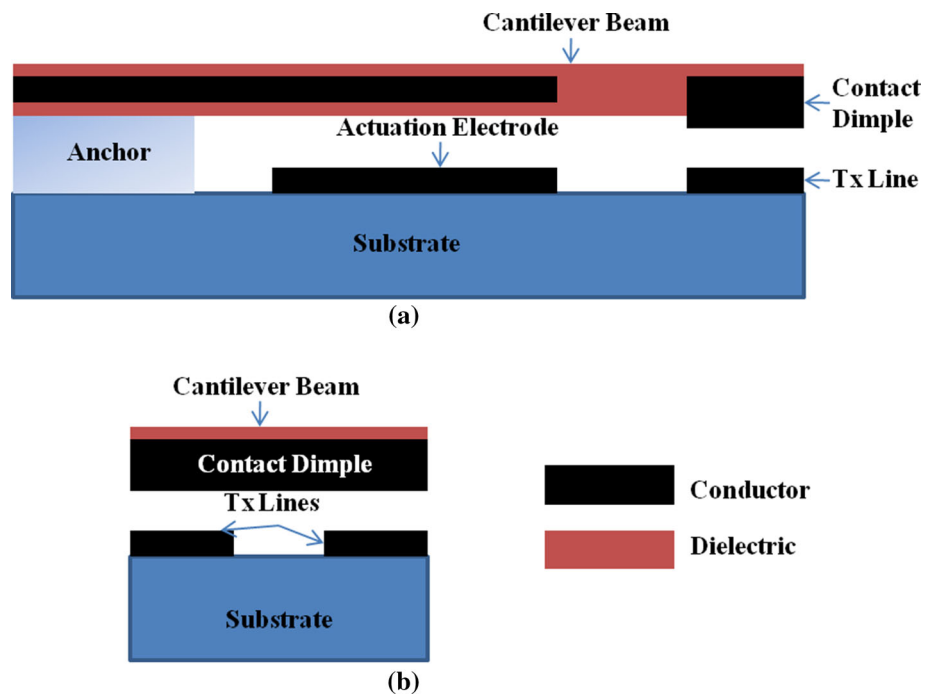


Fig. 2 Simulated design of RF MEMS switch in CoventorWare

$$V_P = \sqrt{\frac{8k}{27\epsilon_0 W w} g_0^3} \tag{3}$$

As the cantilever beam is fixed at only one end and free at the other end, there will not be any residual stress component in the spring constant. So, the spring constant for the cantilever beam depends on the material characteristics and can be expressed as (Bansal et al. 2019):

$$k = \frac{E w t^3}{4 l^3} \tag{4}$$

where E = Young’s Modulus of the beam, w = width of the beam, t = thickness of the beam, l = length of the beam.

The switching time (t_s) for a cantilever RF MEMS switch can be approximated as (Rebeiz 2003):

$$t_s \simeq 3.67 \frac{V_P}{V_S \omega_0} \tag{5}$$

where V_P = pull in voltage, V_S = applied voltage, ω_0 = resonant frequency of the cantilever beam. The switching time strongly depends on the applied voltage. Higher is the voltage applied, the better is the switching speed. Thus, the applied voltage is fixed at 1.4 times of the pull in voltage to get a switch with low switching time at a reasonable voltage level (Sharma and Gupta 2013; Xu et al. 2018). At $V_S = 1.4V_P$ & $\omega_0 = \sqrt{\frac{k}{m_e}}$, (5) can be re-written as:

$$t_s \simeq 2.62 \sqrt{\frac{m_e}{k}} \tag{6}$$

where m_e = effective mass of the cantilever beam.

3 Optimization and analysis of designed RF MEMS switch

This paper emphasizes on designing a low actuation voltage RF MEMS switch with adequate switching speed and excellent RF characteristics. This section explains the ways adopted to design an RF MEMS switch with desired characteristics.

3.1 Material selection

This section discusses the selection of dielectric material for a low actuation cantilever based RF MEMS switch. In

this work, the dielectric materials such as silicon nitride (Si_3N_4), silicon oxide (SiO_2), zirconium oxide (ZrO_2), aluminium oxide (Al_2O_3) and hafnium oxide (HfO_2) have been considered for investigation (Vu et al. 2012; Bonthu and Sharma 2018; Kaur et al. 2013). Simulations have been carried out in CoventorWare to evaluate their performance in terms of pull in voltage. All other design parameters have been kept constant while investigating different dielectric materials for RF MEMS switch. Aluminium is chosen as conductor material for simulations (Nafde and Pande 2017; Sharma and Gupta 2012). Table 1 shows the properties like dielectric constant, young's modulus, poisson's ratio and simulated pull in voltage for considered dielectric materials. From the table, it is clear that HfO_2 shows the minimum pull in voltage and thus, it is best suited dielectric material for the designed RF MEMS switch.

3.2 Wing shaped cantilever beam and perforations

In the above section, HfO_2 and aluminium have been selected as dielectric and conductor material respectively with a pull in voltage of 7.1 V. To further reduce the pull in voltage, the following changes have been made in the cantilever beam.

From (3), it is clear that pull in voltage can be reduced by increasing the width of cantilever beam. So, the part of cantilever beam exactly above the actuation electrode has been extended horizontally on both sides by $25\ \mu\text{m}$ resulting in a wing shaped structure as shown in Fig. 3. This increase in width of the beam above the actuation electrode increases the effective area of actuation which increases the electrostatic force between cantilever beam and actuation electrode. Thus, it reduces the pull in voltage required to bring the switch to down state.

A big hole of size $85\ \mu\text{m} \times 15\ \mu\text{m}$ is defined in the cantilever beam between the wings and the contact dimple. Also, 4×8 (total 32) small holes of size $5\ \mu\text{m} \times 5\ \mu\text{m}$ are defined in the part of cantilever beam just above the transmission lines. These perforations reduce the mass of the cantilever beam which in turn improves the switching

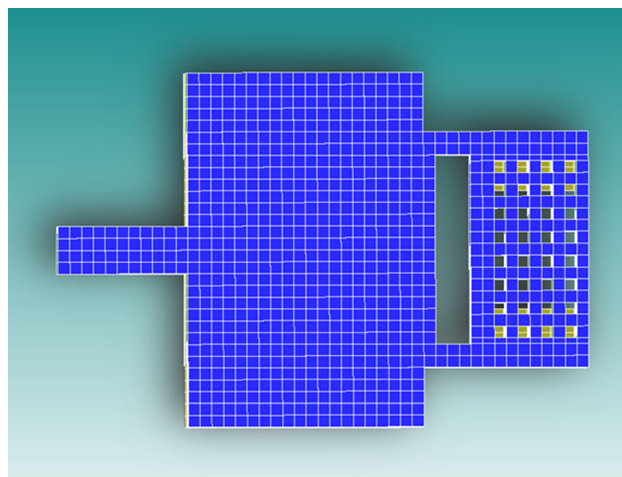


Fig. 3 Optimized RF MEMS switch (top view)

speed. As this part is not above the actuation electrode, it does not affect the actuation area.

After these modifications, the designed RF MEMS switch has been simulated in CoventorWare to evaluate the electromechanical performance of the switch. The pull in voltage is observed as 5.7 V as shown in Fig. 4. From modal analysis, the resonant frequency is observed as 10.791 kHz as shown in Fig. 5. Using (6), the switching time of the switch can be calculated as $38.7\ \mu\text{s}$.

To evaluate the RF performance of the designed RF MEMS switch in terms of isolation, insertion loss and return loss, simulations have been carried out in Ansys HFSS (High Frequency Structure Simulator). Figure 6 shows the isolation characteristics of the designed switch in OFF state. The isolation is better than $-20\ \text{dB}$ for DC – 25 GHz.

Figures 7 and 8 shows the insertion loss and return loss characteristics of the designed RF MEMS switch in ON state respectively. The insertion loss of the switch is less than $-0.4\ \text{dB}$ for DC – 60 GHz. The return loss is also better than $-23\ \text{dB}$ for DC – 60 GHz. So, the designed RF MEMS switch is capable of providing excellent RF characteristics in DC – 25 GHz.

Table 1 Properties and simulated pull in voltage of considered dielectric materials

Dielectric material	Properties			Pull in voltage (V)
	Dielectric constant	Young's modulus (GPa)	Poisson's ratio	
Silicon nitride	8	270	0.27	14.7
Silicon oxide	3.9	71	0.17	8.4
Zirconium oxide	25	200	0.27	12.3
Aluminium oxide	8	383	0.25	17.4
Hafnium oxide	25	57	0.29	7.1

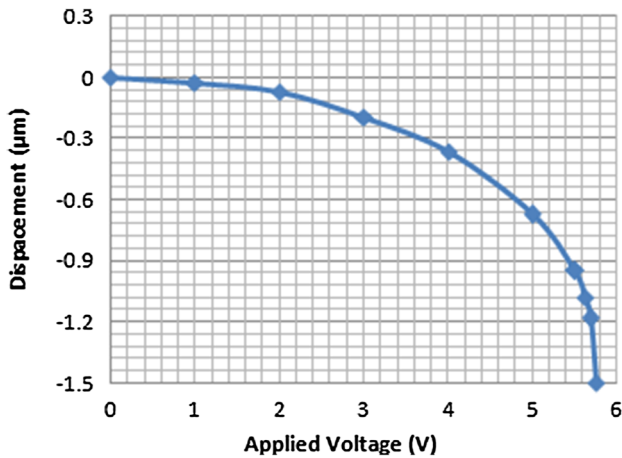


Fig. 4 Pull in voltage analysis of designed RF MEMS switch

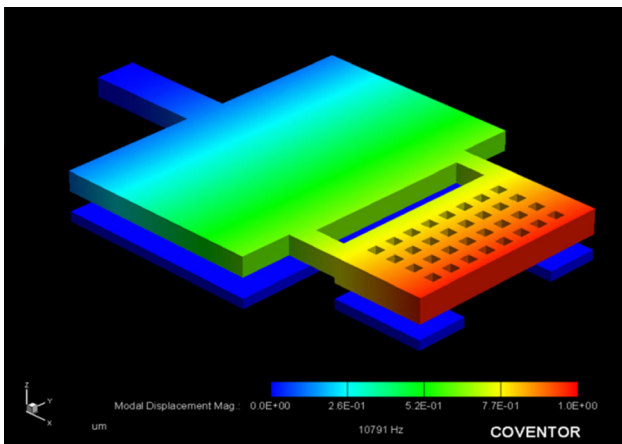


Fig. 5 Modal analysis of designed RF MEMS switch

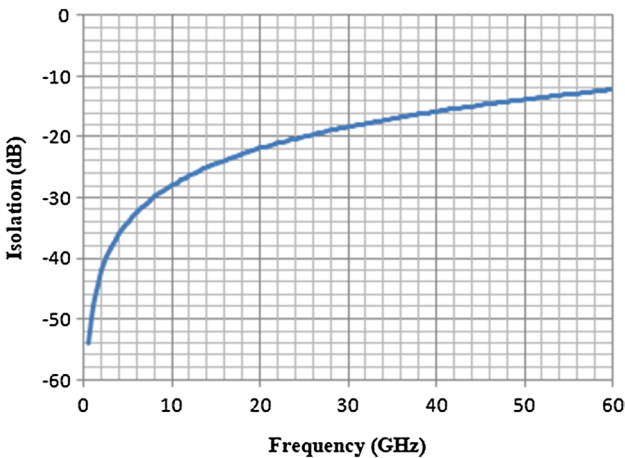


Fig. 6 Isolation characteristics of switch in OFF state

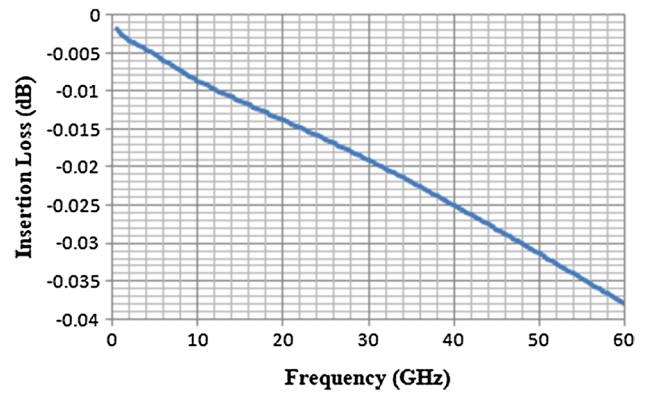


Fig. 7 Insertion loss characteristics of switch in ON state

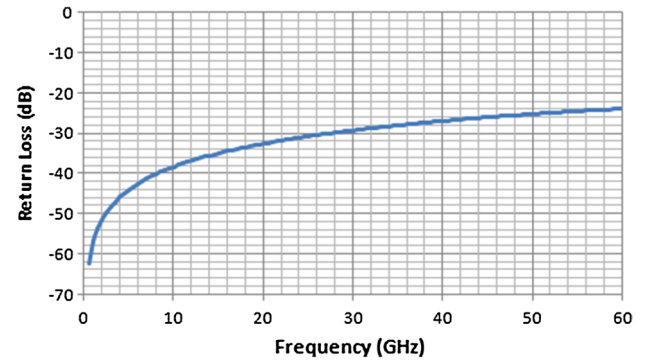


Fig. 8 Return loss characteristics of switch in ON state

4 Design and analysis of reconfigurable antenna

The schematic diagram of proposed reconfigurable antenna using RF MEMS switch is shown in Fig. 9. The antenna is a rectangular patch with an inverted U shaped structure connected by the means of two RF MEMS switches. The substrate used is FR-4 epoxy of size 18 mm × 13 mm × 4 mm with dielectric constant of 4.4.

The proposed reconfigurable antenna has been simulated in Ansys HFSS to evaluate its RF performance in terms of return loss and gain. For simplicity in simulating the structure, the switch has been replaced with a transmission line to represent the ON state and the switch has been considered absent to represent the OFF state.

Figure 10 shows the return loss plot for all four cases of switch positions in the antenna.

Table 2 lists the resonant frequencies for all four cases with corresponding gain and radiation efficiency. In case 1, the antenna can be operated at 8.6 GHz and 12.5 GHz with gain of 3.17 dB and 2.26 dB. In case 2, the antenna can be operated at 9 GHz and 12.4 GHz with gain of 1.87 dB and 2.11 dB respectively. In case 3, the antenna can be operated at 9 GHz and 12.4 GHz with gain of 1.91 dB and 2.32 dB respectively. In case 4, the antenna can be

Fig. 9 Schematic diagram of designed reconfigurable antenna

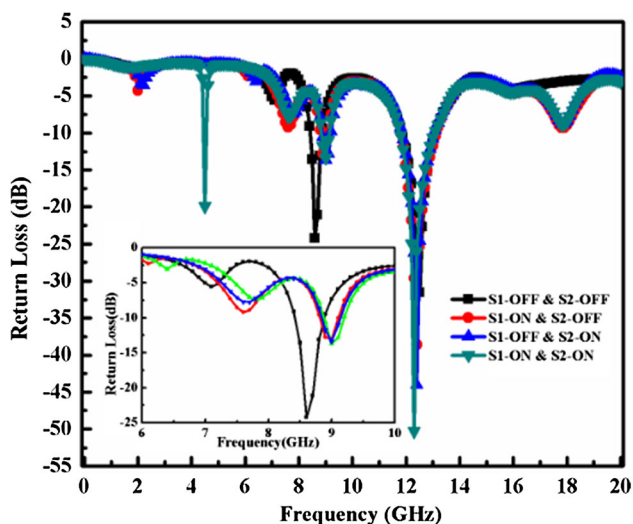
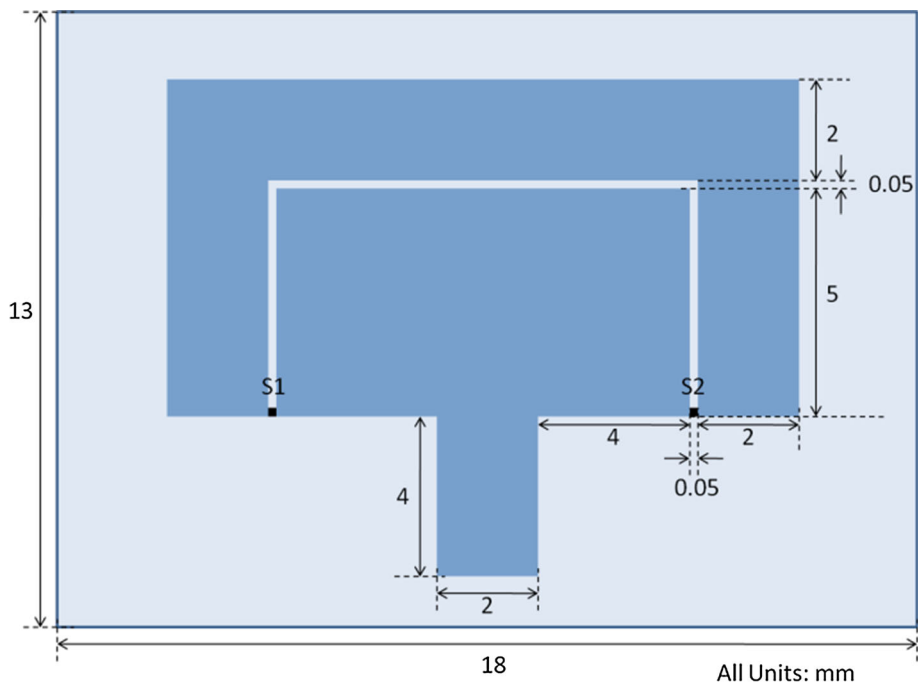


Fig. 10 Return loss characteristics of antenna for different switch positions

Table 2 RF characteristics of antenna for different switch positions

Case	Switch position	Resonant frequency (GHz)	Gain (dB)	Radiation efficiency (%)
1	S1-OFF and S2-OFF	8.6	3.17	76.4
		12.5	2.26	83.6
2	S1-ON and S2-OFF	9	1.87	73.6
		12.4	2.11	82.4
3	S1-OFF and S2-ON	9	1.91	73.8
		12.4	2.32	82.3
4	S1-ON and S2-ON	4.5	0.41	34.5
		9	1.80	74.1
		12.3	1.92	81.3

operated at 4.5 GHz, 9 GHz and 12.3 GHz with gain of 0.41 dB, 1.80 dB and 1.92 dB respectively.

Thus, the designed antenna is frequency reconfigurable at 4.5 GHz, 8.6 GHz, 9 GHz, 12.3 GHz, 12.4 GHz and 12.5 GHz for different switch positions.

The E-plane (x - y) radiation patterns ($\Phi = 90^\circ$) are simulated for different switch positions and are shown in Figs. 11, 12, 13 and 14. Figure 11 shows the E-plane radiation pattern at 8.6 GHz and 12.5 GHz for case 1. Figure 12 shows the E-plane radiation pattern at 9 GHz and 12.4 GHz for case 2. Figure 11 shows the E-plane radiation pattern at 8.6 GHz and 12.4 GHz for case 3. Figure 11 shows the E-plane radiation pattern at 4.5 GHz, 9 GHz and 12.3 GHz for case 4.

From Figs. 11, 12, 13 and 14, it is clear that the designed antenna also shows radiation pattern reconfigurability for different switch positions.

Fig. 11 E-plane radiation pattern of antenna in case 1

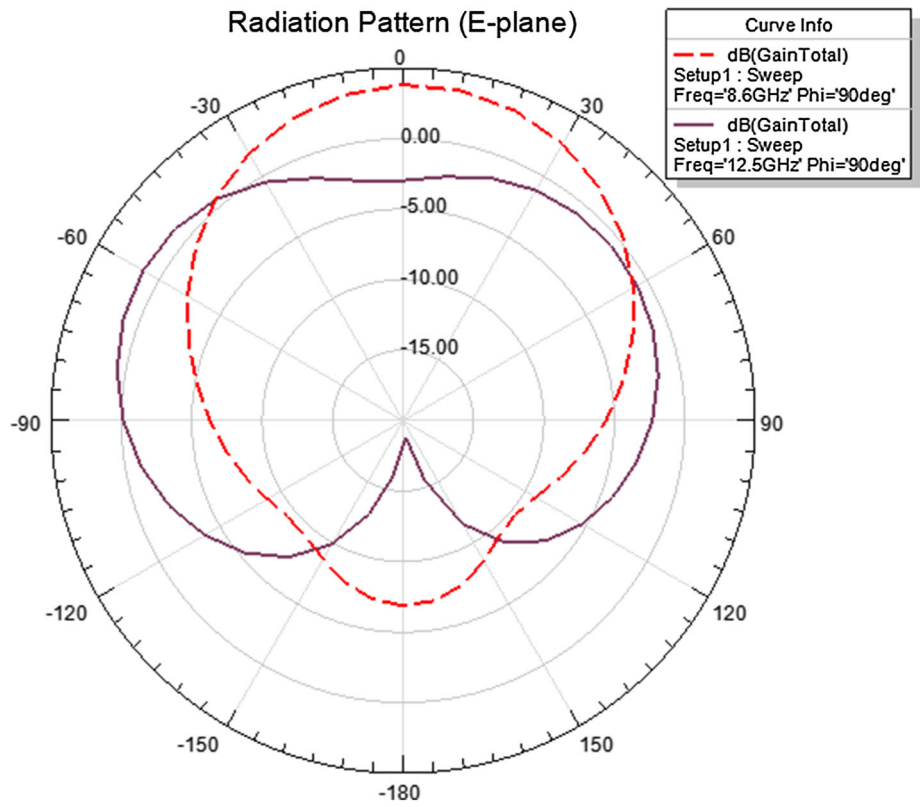


Fig. 12 E-plane radiation pattern of antenna in case 2

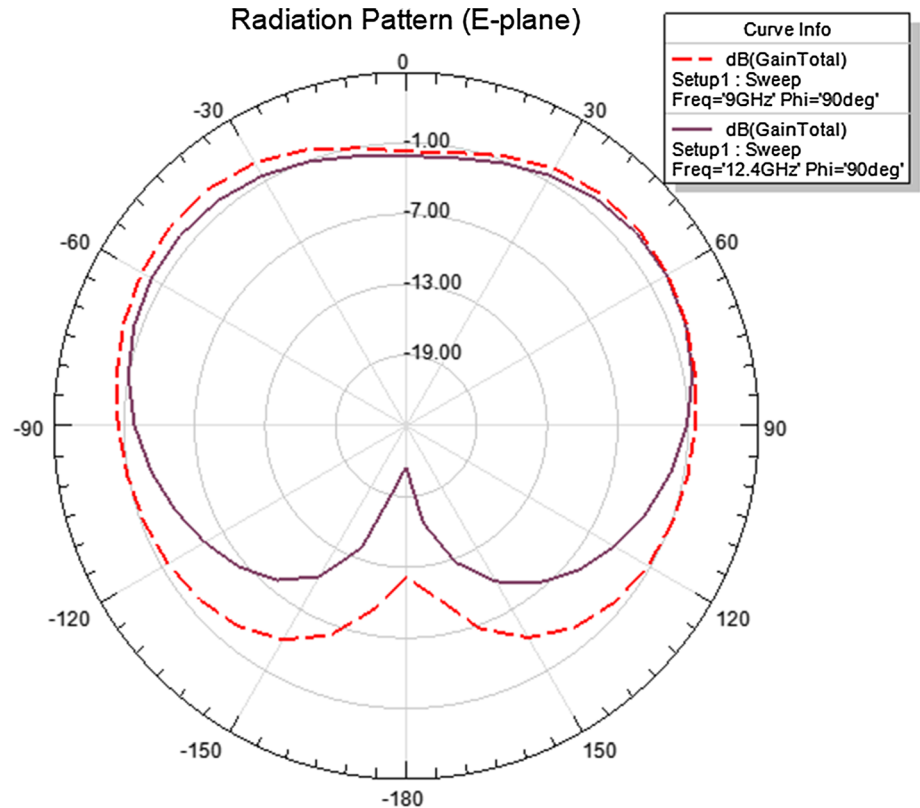


Fig. 13 E-plane radiation pattern of antenna in case 3

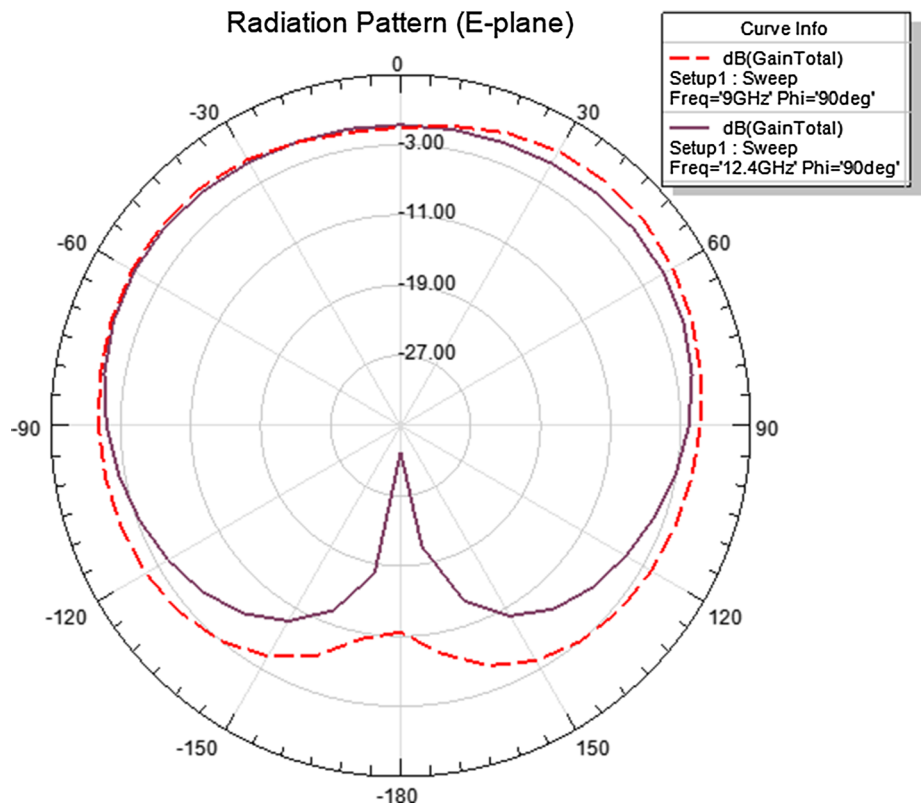
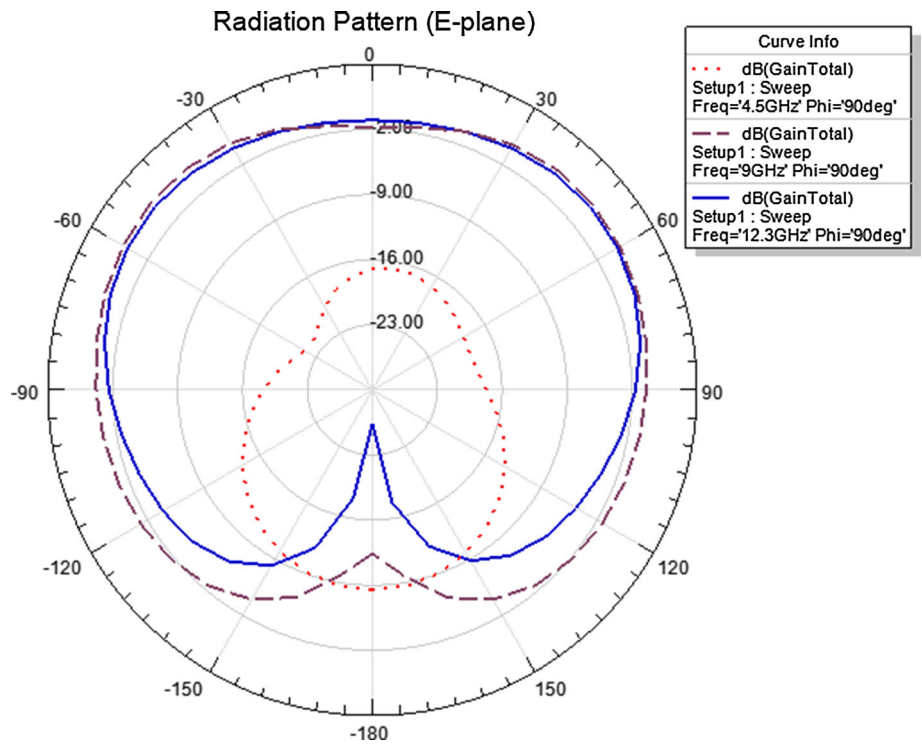


Fig. 14 E-plane radiation pattern of antenna in case 1



5 Conclusion

In this paper, a novel reconfigurable antenna has been designed using RF MEMS switches. Firstly, a metal to metal contact series RF MEMS switch has been designed and optimized to obtain a pull in voltage of 5.7 V and switching time of 38.7 μ s using Coventorware. The optimized switch is then validated for RF performance in DC – 25 GHz using HFSS. The designed reconfigurable antenna is analyzed in HFSS and shows frequency and radiation pattern reconfigurability at 4.5 GHz, 8.6 GHz, 9 GHz, 12.3 GHz, 12.4 GHz and 12.5 GHz for different switch positions.

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