



Design and Analysis of a Serpentine Type RF MEMS Shunt Switch with Low Pull-in-Voltage

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Abstract

This paper presents the design and simulation of the RF MEMS capacitive shunt switch, using FEM and HFSS tools. Here, we have done electromechanical and electromagnetic analysis by varying the materials, thickness, of the beam, gap between the membrane and the dielectric. The Meanders are used to vary the spring constant, which supports changes in pull-in voltage, which is obtained as 6.92 V for gold beam material and the thickness is taken as 0.5 μm , and the switch has a good switching time as 4.9 μs . The up capacitance and stress analysis are obtained as 9.16 fF, 2.69 MPa. The RF performance analysis such as return, insertion loss are analyzed using HFSS software and are obtained as -26.48 dB and -0.60 dB at 60 GHz frequency. The maximum isolation of switch is -41.88 dB at 54.1 GHz, the overall proposed design shows good RF-performance at 45–70 GHz frequency range. Finally, the proposed switch is applicable for high-frequency applications.

Keywords Pull-in voltage · Non-uniform meanders · RF performance

1 Introduction

Micro-electro-mechanical systems (MEMS) devices are used in many applications. These devices are under development for several decades. Many devices in the micrometer range that have some sort of mechanical movement are made using this technology. There are four major components in MEMS devices. They are Micro-sensors [1, 2], Micro-actuators, Microelectronics, microstructures [3]. Some of the applications of this technology include, pressure and temperature sensors, and many advanced applications in the biomedical field and portable personal devices demanded development in miniaturized RF MEMS devices [4]. RF MEMS can be said to, designing and fabricating MEMS for radio frequency (RF) integrated circuits. These devices are either used for actuation or adjustments of components like filters, switches, and variable capacitors. When RF MEMS switches are considered, these switches are of two types metal–insulator–metal(fixed–fixed) capacitive shunt switch [5] and metal–metal resistive series(cantilever) switch [6].

Shunt switches are extensively preferred due to their low power consumption and fast switching time [7] and can be used for high.

Frequency applications [8]. RF MEMS switches have widely become a very speedy movement and started multiple applications in wireless communications and space systems. RF MEMS switches are dominating semiconductors like GaAs, FET, and p-i-n diode switches in RF and microwave systems due to their insignificant power consumption, good isolation, miniaturized and better performance. These switches are extensively designed by using surface micromachining and bulk micromachining methods [9–11].

MEMS switches are the fastest growing technology due to their low pull-in-voltage, low insertion loss, and high isolation loss. They consume less power and are in the size of the micro range. RF MEMS switches are the basic building blocks of the communication systems which include satellite communications [12–15] and mobile phones. The device design is mainly concentrated on high frequency, low scale configurations with more advanced applications.

In this literature survey, the RF-performance return loss and insertion loss are observed as -16 dB, -0.44 dB and isolation -20 dB, the performance of the switch can be used in X, Ku band applications [16].

The capacitive shunt MEMS switch with a different number of meanders was designed and simulated. The return

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loss as -60 dB, insertion loss - 0.2 dB and isolation loss - 14 dB at 20 GHz frequency [17]. From this state of art we have observed some limitations to avoid these limitations at 25–70 GHz frequency observe best results.

In this paper, we have proposed a serpentine structure that has non-uniform meanders with perforations, which results in low spring constant and pull-in-voltage. The main objective is to reduce the pull-in-voltage and maintain high isolation and low return and insertion losses by using electromagnetic, electromechanical, stress, switching time RF performance analysis on this proposed switch are observed such as isolation, insertion loss, and return loss.

The paper is as follows, Sect. 2 follows, design and specifications of the proposed structure with dimensions and the working principle. Section 3 follows with results and discussion of the proposed switch and finally concluded in Sect. 4.

2 Switch Design and its Specifications

The proposed switch is designed using a non-uniform meander technique as shown below in Fig. 1. The meanders reduce the spring constant of the switch which results in reduced pull-in voltage of the switch. The beam is suspended over the Co-planar waveguide (CPW) line. Both ends of the switch are fixed to the anchor leaving a gap for a switch to activate between the ground plates and the beam. The structure has a signal line width of 120 μm and a gap of 80 μm between the ground and the signal line. A 1.5 μm thick coplanar waveguide (CPW) transmission line is subjected over an insulating layer of 1 μm thickness. This insulating layer is spread over a substrate of thickness 450 μm. The schematic of beam with meanders are shown in Fig. 2.

The dimensions of the proposed switch are tabulated below in Table 1.

A thin layer of dielectric material of thickness 0.2 μm is spread over the signal line and below the beam to develop a capacitance between the beam and the signal line. The

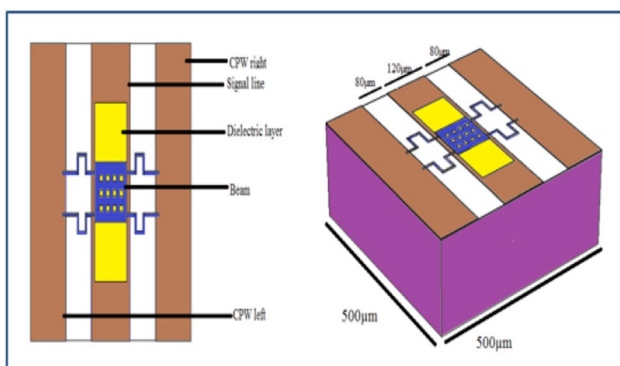


Fig. 1 Top view and 3D view of proposed switch

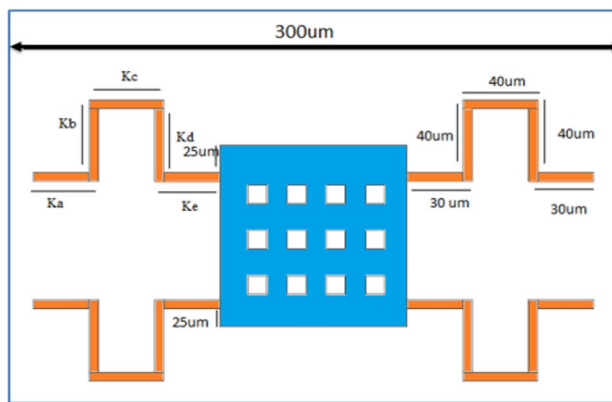


Fig. 2 The schematic view of central beam, meanders and its dimensions

beam is suspended over the dielectric with gaps of 1 μm, 1.5 μm, and 2 μm and analyzed to achieve low pull-in voltage. When the RF signal is passed through the signal line the beam moves towards the electrode below (signal line). The meanders placed help in the effective movement of the beam towards the bottom electrode. This process is called electrostatic actuation. This actuation stops the signal from reaching the output terminal. The performance of the switch is mainly depending on the effective contact area of the beam and dielectric (100 μm X 100 μm) and the spring constant of the meanders. To reduce the spring constant, meanders are introduced to the switch. The material selected for the beam also plays an important role in the performance of the switch. Various materials are taken to the beam to obtain the optimal displacement of the beam, the performance of the switch also depends on the gap between the dielectric and beam. These meanders are anchored to the ground so that the beam acts as a ground terminal to provide electrostatic actuation between the central beam and lower electrodes.

2.1 Working Principle

Initially, the shunt switch is in ON condition like as upstate with some air gap between the beam and dielectric, when voltage is applied the switch displaces towards the dielectric

Table 1 The dimensions of proposed device

Parameter	Length (μm)	Width (μm)	Thickness (μm)
Substrate	500	500	450
Insulator (Oxide)	500	500	1
CPW left and right	140	500	1.5
Signal line	12	500	1.5
Dielectric Layer	100	300	0.2
Beam	300	100	0.5

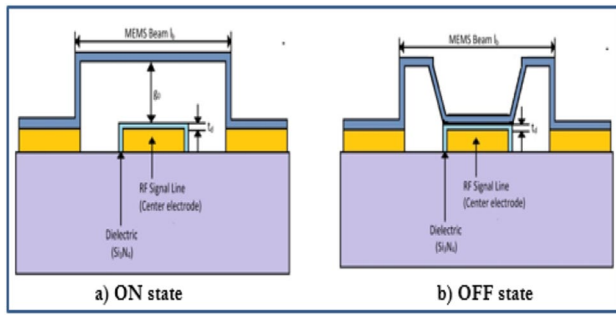


Fig. 3 ON and OFF state positions of a shunt type switch

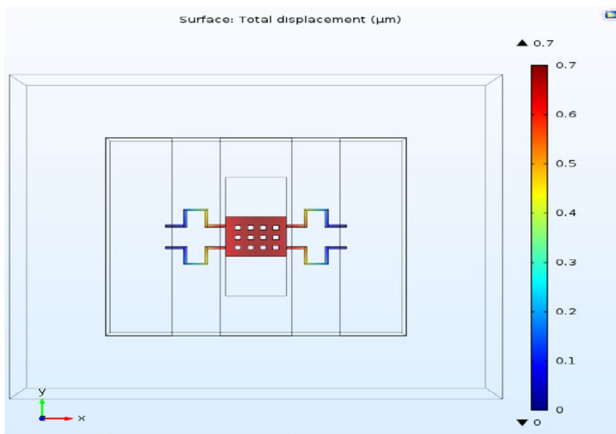


Fig. 4 Simulation of proposed switch by using displacement

when the gap between dielectric and beam reaches 2/3rd of the gap, the electrostatic forces between beam and dielectric become unstable and beam falls on the dielectric this is called downstate as OFF state of the switch as shown in below Fig. 3.

Beam and dielectric are separated by a certain gap, it is nothing but an air gap. When the switch is supplied with the pull-in voltage, the beam undergoes a certain displacement towards dielectric due to electrostatic attraction between the beam and dielectric layer.

There are four meanders to the switch in which each meander gives the restoring force which is developed by the firmness of each meander and this firmness is called the spring constant *K*. These four meanders are connected to the beam which helps the beam to suspend freely so that it has a good contact area with the dielectric which results in the good switching time. The pull-in voltage simulation of proposed switch is shown in Fig. 4.

2.2 Pull-in Voltage and Spring Constant

The electrostatic force is applied on the beam it will be pulled down the top electrode is called pull-in voltage it is calculated by [18],

$$V_p = \sqrt{\frac{8Kg_0^3}{27\epsilon_o A}} \tag{1}$$

where ‘*K*’ is effective the spring constant of *k_a*, *k_b*, *k_c*, *k_d*, *k_e*, ‘*g₀*’ is the air gap between the dielectric layer and the beam, ‘*ε_o*’ is the relative permittivity and ‘*A*’ is an area of the overlap.

2.3 Capacitive Analysis

The performance of the switch is depending on the up and down state capacitance, it is given by [19],

$$C_u = \frac{\epsilon_o A}{g_o + \frac{t_d}{\epsilon_r}} \tag{2}$$

where ‘*t_d*’ is the thickness of the dielectric, ‘*g₀*’ is the air gap between dielectric layer and the membrane, ‘*ε_r*’ is the relative permittivity of the dielectric material, and ‘*A*’ is the area of beam.

The capacitance of down state is given by

$$C_d = \frac{\epsilon_o \epsilon_r A}{t_d} \tag{3}$$

The capacitance ratio is given by

$$C_r = \frac{C_d}{C_u} \tag{4}$$

where ‘*C_u*’ and ‘*C_d*’ are the up and downstate capacitance, it is mainly dependent on the gap, materials of a beam, and dielectric. The capacitive analysis is seen by different relative permittivity materials of beam and dielectric.

2.4 Stress Analysis

The study of the effect of loads on structural components and evaluating the effect of loads of the switch. For evaluating stress solid mechanics was taken as physics and the stress analysis is evaluated by giving the force to the beam. The formula for the force is given by

$$F = \frac{\epsilon_o \epsilon_r S V^2}{2d^2} \tag{5}$$

where ‘*d*’ is the airgap between the beam and signal line, ‘*V*’ is the pull-in voltage, ‘*S*’ is an area of the beam, and ‘*ε₀*’ is the relative permittivity of free space.

2.5 Switching Time

The time taken by the switch to activate from the beam plate to signal line the switching time is given by [20],

$$t_s = 3.67 \frac{V_p}{V_s \omega_0} \tag{6}$$

where ‘Vp’ is the pull-in voltage, ‘Vs’ is the supply voltage, and ‘ω₀’ is the angular frequency of the given switch.

3 Results and Discussions

The proposed RF MEMS switch has non-uniform meanders and serpentine structured meanders. In this work, we have done various analysis like electromechanical and electromagnetic analysis are analyzed.

3.1 Electromechanical Analysis

3.1.1 Pull-in Voltage/Actuation Voltage

The actuation voltage of the switch mainly depends on the spring constant of the flexures and the air gap between the beam and dielectric. By varying the air gap between the beam and dielectric, beam thickness of 0.2 μm is taken for better actuation voltage for the proposed switch. The pull-in voltage 6.92 V is obtained in COMSOL software where the switch displaces 2/3rd of an air gap.

Figure 5 shows that when a 1 μm gap is given, it has better displacement when compared to 1.5 μm and 2 μm gaps. Therefore, a gap of 1 μm is selected for a proposed switch. Figure 6 shows that gold has better pull-in voltage and has better electrical conductivity and high corrosion resistance than other materials. Therefore, gold is selected as the material of a beam.

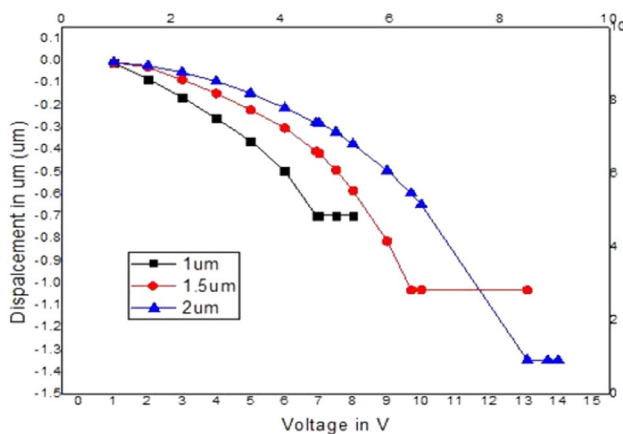


Fig. 5 Voltage vs displacement graph for 1 μm, 1.5 μm, 2 μm, with 0.5 μm beam thickness

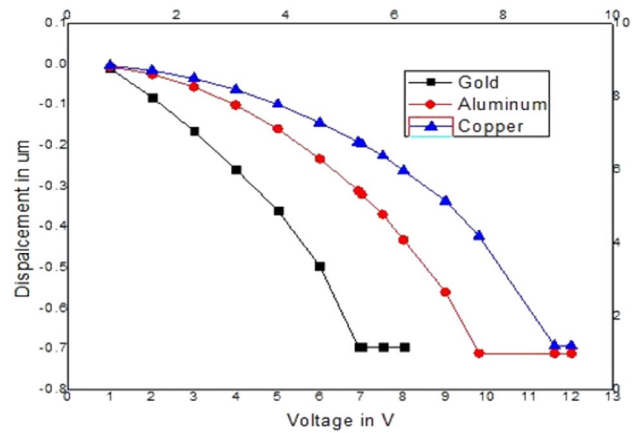


Fig. 6 Voltage vs displacement for various beam materials with 1 μm gap and 0.5 μm beam thickness

3.1.2 Stress Analysis

The COMSOL software is used for stress analysis of RF MEMS switches for applying solid mechanics physics. The stress is uniformly diffused by employing some force on the beam. A calculated force of 1.15 μN is applied on the beam and maximum stress is analyzed in the FEM tool. Figure 7 shows that maximum stress is allowed at the meanders.

3.1.3 Switching Time

The switching time increases with an increase in the pull-in voltage of the switch. It is depending on the pull-in voltage and inversely proportional to the supply voltage. Below Fig. 8 shows the switching time for various beam materials is analyzed. The proposed switch has a switching speed of 4.9 μs at pull-in voltage. In Fig. 9, we have observed

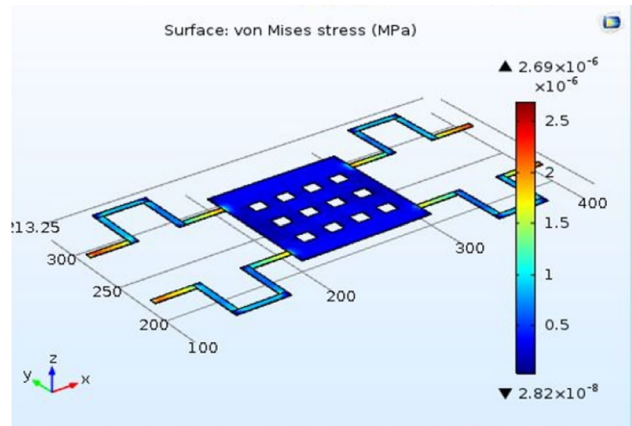


Fig. 7 Von mises stress has maximum stress at 1.15 μm

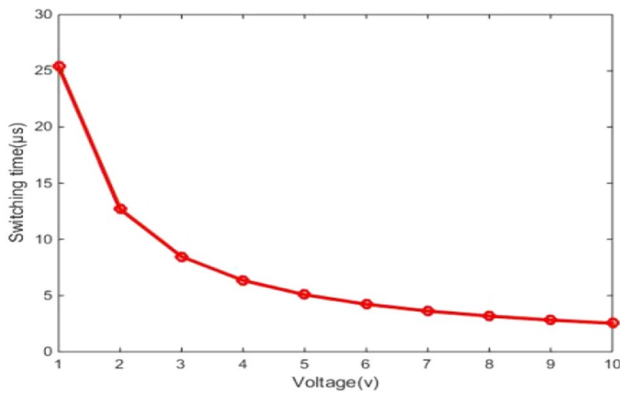


Fig. 8 Switching time analysis when gold is used as a beam material

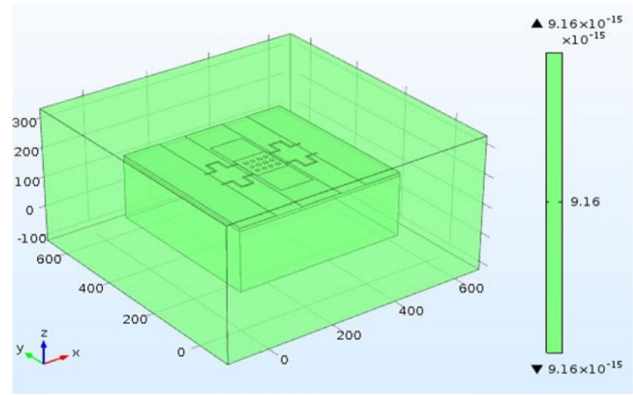


Fig. 10 Capacitance analysis of a RF proposed switch

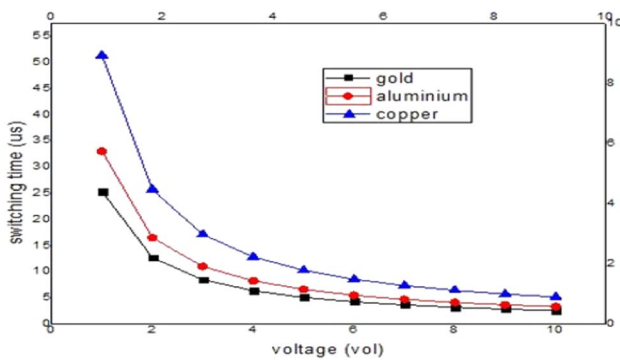


Fig. 9 Switching time analysis for various materials between 1 to 10 V

different beam materials for fast switching time, here, the gold is got good switching time.

3.1.4 Capacitance Analysis

The working of a switch is depending on the overall capacitance analysis. The up-state capacitance of the proposed switch is observed as 9.16 Femtofarads, here we have plotted voltage versus different capacitance values. Figure 10, 11 show the simulated result and graphical representation of the capacitance of the proposed switch.

3.2 RF Performance (Electromagnetic) Analysis

Electromagnetic analysis of the switch is done by using HFSS software. Generally, we have observed isolation in off-state position > -10 dB and observes return loss in on-state position > -10 dB and the insertion loss is observed in < -0.5 dB.

These S-parameters are depending on the up and down-state capacitance when the switch is in the ON state, it will

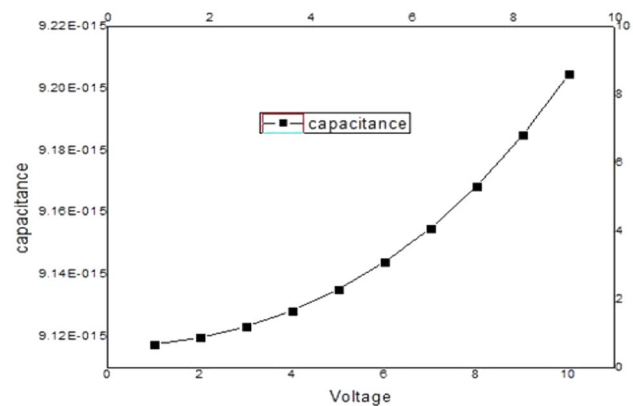


Fig. 11 Capacitance vs Voltage analysis of a proposed switch with meanders

show return and insertion loss, as it is in the OFF state we will measure isolation.

The proposed switch has maximum isolation of -41.88 dB at 54.1 GHz frequency, minimum Insertion loss of -0.60 dB at 60 GHz, and return loss of -26.48 dB at 60 GHz frequency as shown in below Figs. 12, 13, 14. The switch exhibits the best RF characteristics in the frequency range of 45–70 GHz frequency for 5G applications.

4 Conclusion

In this paper, RF MEMS capacitive shunt switch with serpentine meander type structure is designed and simulated. The electromechanical parameters like pull-in voltage, switching time, capacitance, are analyzed by varying thickness, materials, and different gaps, the pull-in voltage is obtained as 6.92 V. The simulated value of the up-state capacitance is 9.16 fF and the switching speed (time) is obtained as 4.9 μ s. The maximum stress is obtained as

Fig. 12 Isolation loss of proposed model at 45–70 GHz frequency

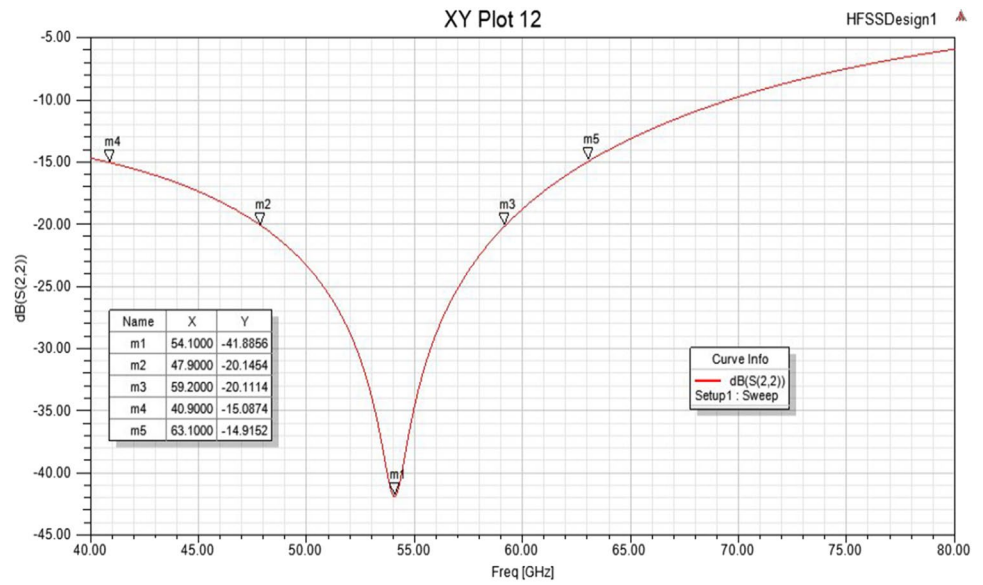
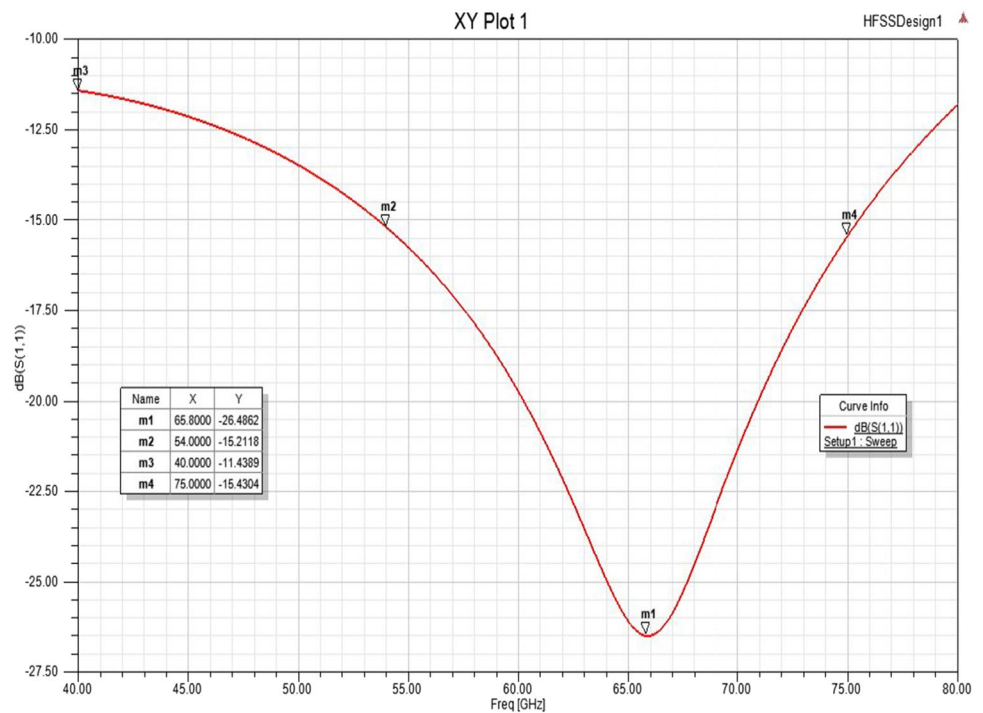


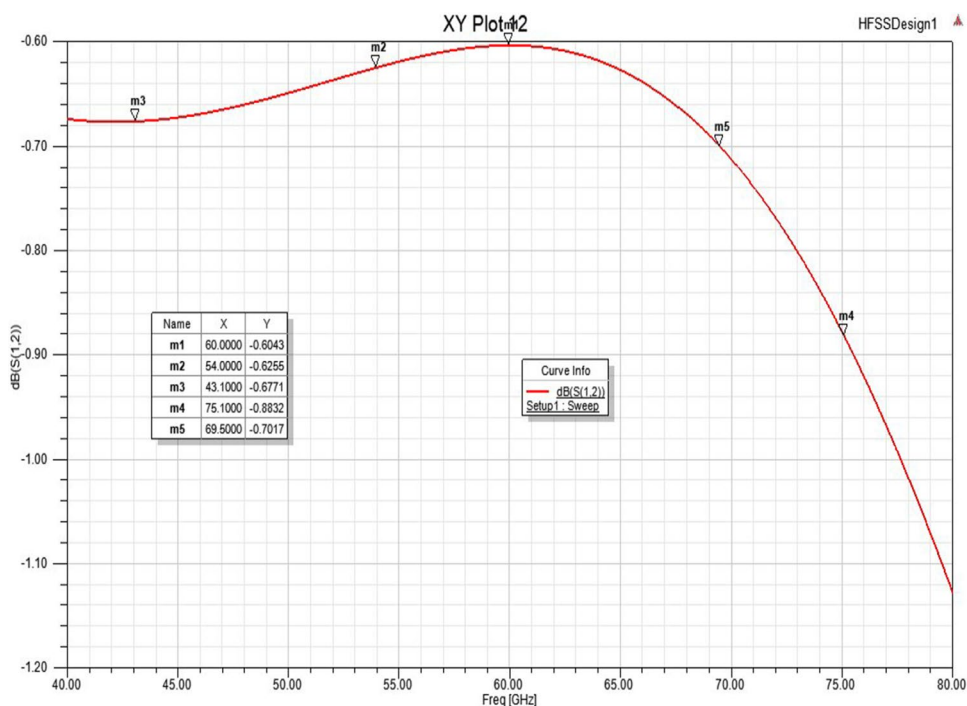
Fig. 13 Return Loss of proposed model at 45–70 GHz frequency



2.69 MPa. The capacitance is a crucial role in performing good magnetic analysis, the proposed switch shows better electromagnetic analysis in the range of 45–70 GHz with good isolation of -41.88 dB at 54.1 GHz and minimum

return and insertion loss of -26.48 dB, -0.60 dB is obtained at 60 GHz frequency. So, the proposed switch can be recommend for 5G applications.

Fig. 14 Insertion Loss of Proposed model at 45–70 GHz frequency



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