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TECHNICAL PAPER

Design and performance analysis of double cantilever type capacitive shunt RF MEMS switch

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Abstract

This paper presents a novel structure of capacitance shunt type RF switch for 5G applications. The proposed RF MEMS switch is having Cantilever type designed with optimized dimensions to operate in V-band applications. The electromechanical analysis is done by using the COMSOL tool. The actuation voltage of the proposed switch is 10.5 V with the air gap of 1 μm and gold as a beam material. The proposed switch with the meanders and perforations show the scattering parameters in HFSS software such as insertion loss (S_{12}) of − 0.033 dB and return loss (S_{11}) less than − 48 dB and the isolation (S_{21}) calculated in off-state as − 62 dB at 50 GHz.

1 Introduction

In the present scenario, the demand for internet of things (IOT) is enormous. It appears every day various industries provide new IoT enabled devices. The IOT applications rank in the order of smart houses, wearables, smart cities, smart grids, internet, for industries, smart car, and smart agriculture, etc. 5G makes a benefit for the IoT because of its performance targets high data rate and massive device connectivity (Ijaz et al. 2016; Sharma and Tiwari 2016; Iannacci 2017a). 5G uses the high frequencies, above 24 GHz in millimeter waves range. For the IOT frame of reference, the 5G mobile devices are expected to receive a wide scope of wireless connections to increase the appearing applications such as device to device (Iannacci et al. 2016a; Akpakwu et al. 2018). The solution for these challenges is RF-MEMS technology which demands higher operation frequencies. It possesses large reconfigurability while decreasing the hardware redundancy and power consumption (Brown 1998; Iannacci 2017b).

Intense research on the MEMS Switches operating in the radio frequencies is a major challenge in industries. RF-MEMS is a microelectromechanical system comprises of Sub-millimetre sized parts which provide radio frequency Functionality with electronic components. RF MEMS switches can classified based on the actuation method, i.e., electrostatic and electromagnetic (Rebeiz and Muldavin 2001; Kim and Chun 2007). Based on the circuit configuration classified into series and shunt switches. Based on clamp configuration they are divided into cantilever and fixed–fixed type. Because of low power dissipation, low power consumption, and high isolation, low insertion loss, and low return losses, less cost and low weight made the MEMS switches utilized rather than the gallium arsenide switches, FET (field impact transistors) and the photo injection diode switches (Mafinejad et al. 2017). In this aspects, the forthcoming field of 5G (Iannacci et al. 2016b) seems to be the fitting application area for this type of technology to completely express its potential. But there are few challenges which should be reduced in order to increase the performance and efficiency, they are the pull-in voltage, switching time and losses such as the insertion loss, the return loss, and the isolation loss.

From the literature survey, we observed that, RF MEMS switch are having 45 V of pull-in-voltage. The RF loss of insertion loss as − 1.43 dB and return loss as − 15 dB at 50 GHz frequency (Iannacci et al. 2016b). RF MEMS

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switch silicon contact at 50–110 GHz using dual axis movement for high isolation of − 42.2 dB (Lee et al. 2010). RF MEMS switch with micro strip t-line instead of CPW having isolation loss of − 35.75 dB at 40 GHz frequency (Ziko and Koel 2018). We also observe a low isolation at a 45–70 GHz frequency, to avoid this problem we optimize a proposed double cantilever type switch. In this paper, we designed and simulated the RF MEMS switch by using electromechanical analysis and observed by reducing the pull-in-voltage, fast switching time, stress analysis and different scattering parameters such as isolation, insertion loss and return loss for V-band applications.

The organization of the paper; in Sect. 2 follows the design and dimensions of a proposed switch which is having perforations and meanders. Section 3 follows, the results and discussions of a proposed switch and finally, the conclusion is given in Sect. 4.

2 Details of the proposed RF MEMS switch

The switch is initially ON-state condition i.e., the air gap is present in between the beam and dielectric. When the voltage is applied the beam gets contact with the dielectric layer i.e., OFF-state condition. This ON-state and OFF-state positions are observed in Figs. 1 and 2.

The shunt type cantilever switch consists of two beams, a substrate, a dielectric layer, and CPW. The proposed switch is designed with different dimensions as shown in Table 1. The CPW (coplanar waveguide) consists of two ground planes and signal line which is made up of aluminium. The dielectric layer made up of Si_3N_4 and it is fixed between beam and transmission line. Gold is considered as beam material which is located above the dielectric layer and consists of two supportive blocks (Rao et al. 2018a). By using meanders and perforations we have observed that the low pull-in-voltage is reduced to 10.5 V.

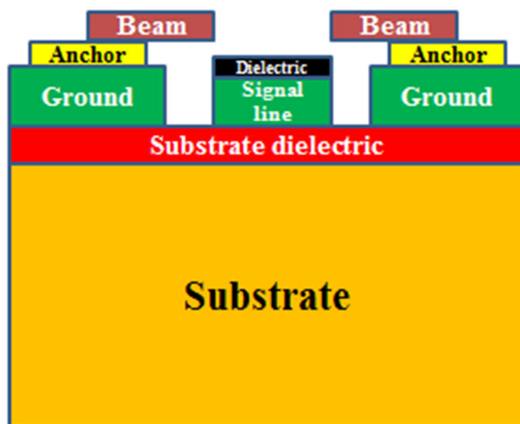

Fig. 1 Shunt type cantilever type up state switch

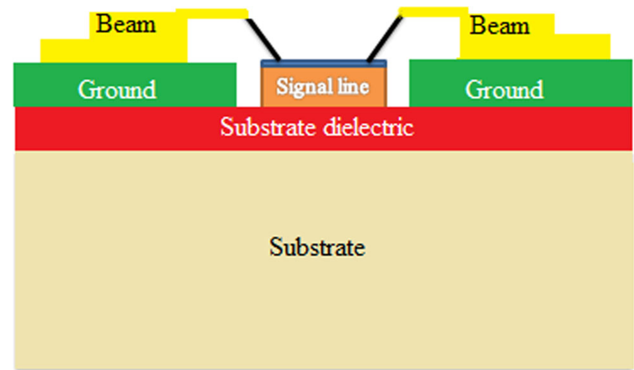

Fig. 2 Shunt type cantilever type down state switch

The top view of proposed shunt type cantilever switch is as shown in Fig. 3.

The proposed switch is designed with this optimized dimension to work with in “V” band applications (Girija Sravani et al. 2018).

3 Results and discussions

3.1 Electromechanical analysis

All the switching characteristics of the proposed switch is analyzed by using COMSOL tool and electromagnetic analysis by HFSS software. In this analysis, we are mainly focusing on the spring constant and pull-in-voltage.

3.1.1 Spring constant

Spring constant depends upon the stiffness of the material, the thickness of the beam and the residual stress. For the proposed switch the gold material is considered for the beam to calculate the spring constant.

The spring constant value for both the cantilevers is 12.4 N/m.

The spring constant is calculated by using formula is given by

$$k = \frac{Ewt^3}{l^3} \tag{1}$$

where w and l are width and length of the beam, E is Young’s modulus of the gold material and ‘t’ is the thickness of the beam.

3.1.2 Pull-in-voltage

It is defined as minimum voltage desire to pull-down a membrane switch of a RF switch.

Electrostatic actuation is mainly used to actuate mechanism in MEMS switches because of compact sizes and

Table 1 Specifications of the device

S. no.	Component	Width (μm)	Depth (μm)	Height (μm)	Material
1	Substrate	280	95	568	Silicon
2	Oxide layer	280	95	10	SiO_2
3	CPW	170	340	10	Al
4	Dielectric	50	35	0.1	Si_3N_4
5	Beam	50	25	0.5	Gold

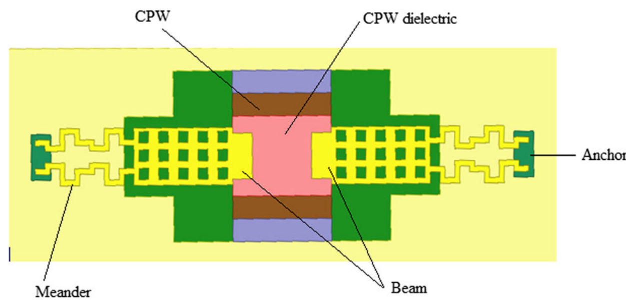

Fig. 3 Top view of proposed shunt cantilever type RF MEMS switch

low power consumption, but low switching speed is the challenge. It overcomes, apply the spring force to pull the beam towards the signal line resulting in capacitive loading on the CPW line. The actuation voltage is mainly depending on spring constant K:

$$V_p = \sqrt{\frac{8kg_0^3}{27\varepsilon_0 A}} \quad (2)$$

where k is spring constant, ε_r is a gap between the beam and CPW dielectric and ε_0 is the permittivity of free space as and A is the area of overlapping of the length and depth of the CPW (Girija Sravani and Srinivasa Rao 2017; Sravani et al. 2018; Hanasi et al. 2014).

Actuation voltage is directly proportional to the spring constant. Here we observed spring constant is low then automatically pull-in-voltage is reduced.

In Fig. 4 we observe the voltage versus displacement of a switch with a constant displacement of 0.76 μm for gold as a beam material, thickness of the beam 0.5 μm and height between the signal line and the beam of 10.5 V.

The beam is displaced two-third of the height between the membrane and the signal line for voltage 10.5 V, observes 0.76 μm in Fig. 5.

3.1.3 Capacitance analysis

The up-state capacitance is calculated by placing the switch in ON-state. The air gap between the dielectric layer and the membrane plays an important role in the upstate capacitance.

The upstate capacitance can be calculated is given by

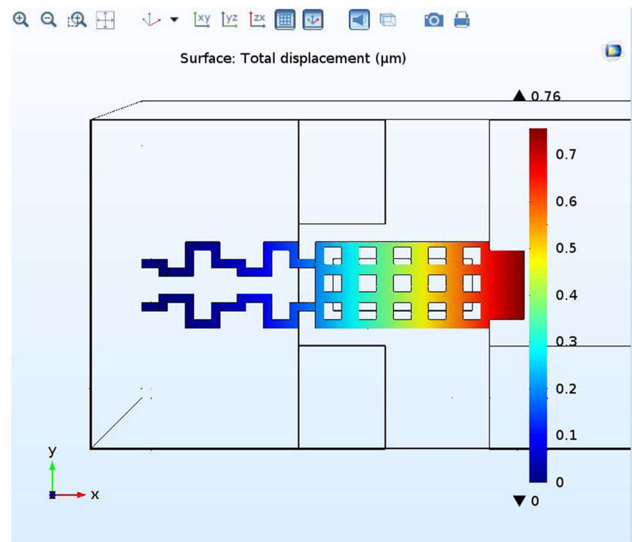

Fig. 4 Electromechanical analysis of a proposed switch

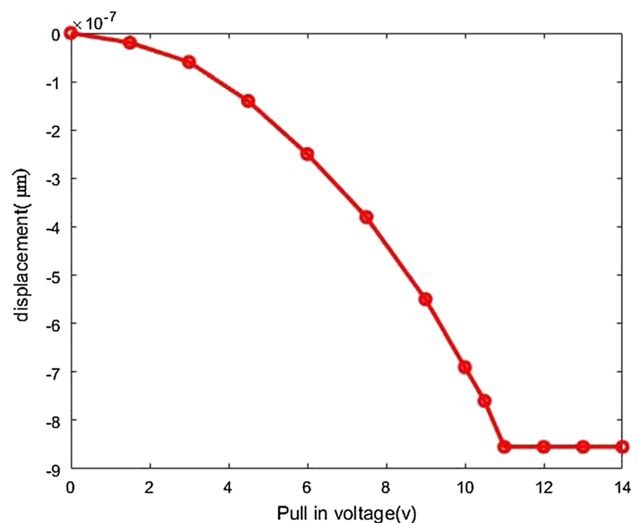

Fig. 5 Voltage vs. displacement of a proposed switch with pull-in-voltage of 10.5 V

$$C_u = \frac{\varepsilon_0 A}{g + \frac{t_d}{\varepsilon_r}} \quad (3)$$

where ε_0 is permittivity of free space, ε_r is a relative permittivity of the dielectric layer, A is the overlapping area of the signal line length and beam width, t_d is the thickness of

dielectric and gap between the electrodes is g (Lakshmi Narayana et al. 2017; Rao et al. 2018b).

When thickness between the dielectric layer and the beam is considered as 0.5 µm then we observed the upstate capacitance is 4.36 fF (femtofarads) in Fig. 6.

The downstate capacitance is calculated when the switch is in OFF state. In Eq. 4, downstate capacitance is not considered any gap between the dielectric layer and beam. The formula for the downstate capacitance is given as

$$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d}. \tag{4}$$

The formula for the capacitance ratio is given as

$$C_r = \frac{C_d}{C_u}. \tag{5}$$

From the simulated value we observed 75.9 capacitance ratio which is mainly depending on the dielectric thickness From Fig. 7, we observed a downstate capacitance of 0.331 pF (picofarads).

By considering the Fig. 8, we obtained that the simulated value of the switch is 6.89 fF is observed.

3.1.4 Analysis of resonant frequency

The vibrating frequency is pick with resonant frequencies from a vibrate and excitation, essentially in filtering out of an excitation. The resonant frequency is mainly depends on the switching time analysis. This resonant frequency of the switch asserts that the frequency at which displacement of the maximum gap of the switch takes place. This resonant frequency is depends on the spring constant and mass of the materials of the beam.

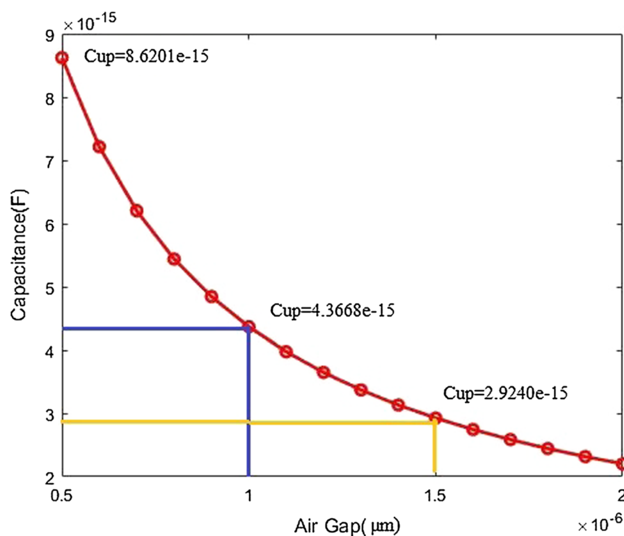

Fig. 6 Airgap vs. capacitance analysis of a proposed switch

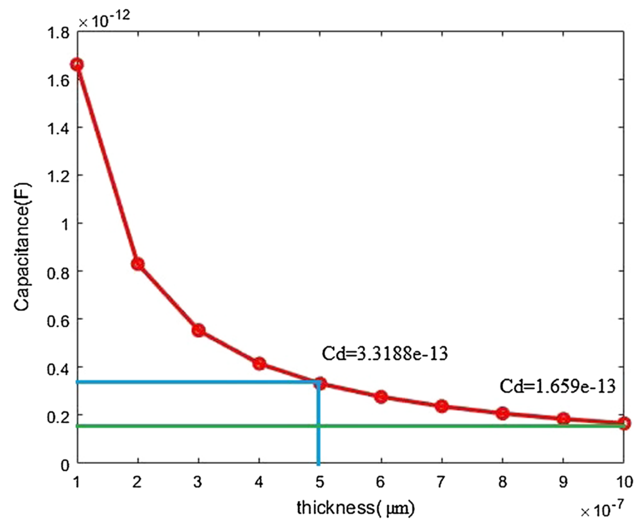

Fig. 7 Dielectric thickness vs. capacitance analysis of a proposed switch

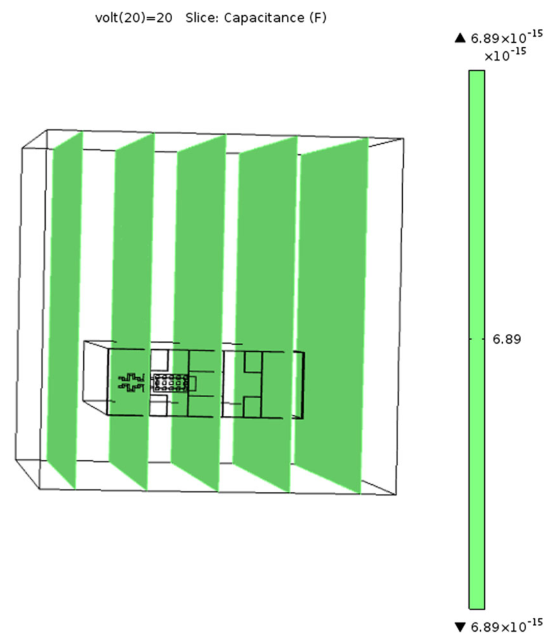

Fig. 8 up state capacitance analysis of the proposed cantilever type RF MEMS switch

The gap between the electrodes in the switch is taken as 0.5 µm subsequently the frequency at which the switch displaces 0.5 µm in sliding direction. The frequency of the switch is acquired by the equation (Chakraborty et al. 2014) is

$$F_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{6}$$

where k is the spring constant and m is the constructive mass of cantilever beam.

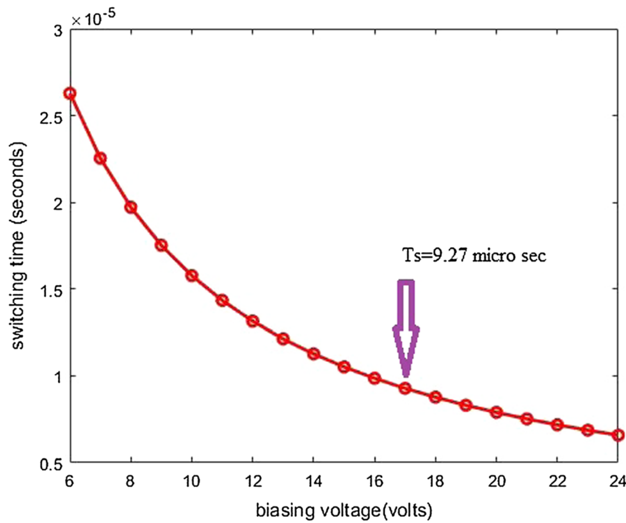

Fig. 9 Switching time analysis with beam thickness 0.5 μm and 1 μm air gap

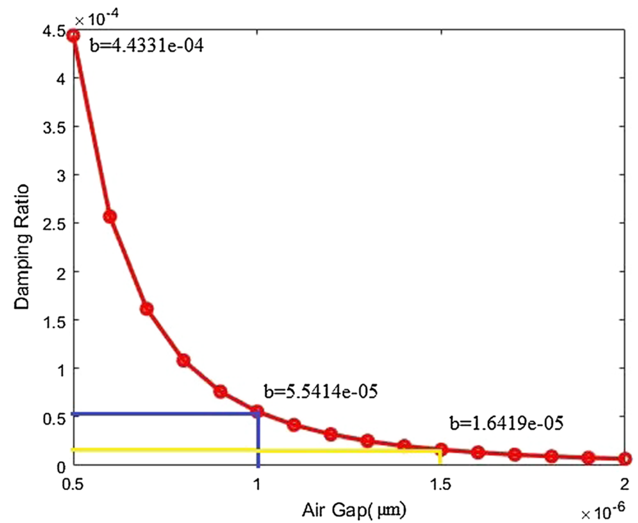

Fig. 10 Air gap vs. damping ratio of a proposed switch

The resonant frequency of switch is acquired from the simulation of the switch in the frequency domain of 50 GHz which is closely related with the theoretical value calculated.

3.1.5 Switching time analysis

The state changing time mainly relies upon the connected voltage since the larger the voltage applied, the powerful the electrostatic forces on the membrane for responding the cantilever beam.

When the electrostatic force is taken at constant and is equal to the initially applied force then the solution for the switching time is given by the equation (Khan and Shanmuganantham 2017):

$$t_s = \frac{3.67V_p}{V_s\omega_0} \tag{7}$$

where V_p is the pull-in voltage of a proposed switch, V_s is actuation voltage ($V_s = 1.4V_p$) and ω_0 is the angular resonant frequency (Fig. 9).

$$\omega_0 = 2\pi F_r \tag{8}$$

3.1.6 Damping coefficient and quality factor

The quality factor can be evaluated by considering the spring constant, resonant frequency, and damping coefficient. It is depending on the membrane and structure of the switch.

The damping coefficient is obtained by equation

$$b = \frac{3}{2\pi}\frac{\mu A^2}{g_0^3} \tag{9}$$

where μ is the viscosity of the air, A is the overlapping area of the signal line length and the beam width and the gap between the electrodes is g. Thus, the quality factor can be determined by the equation

$$Q = \frac{k}{2\pi F_r b} \tag{10}$$

where b is damping coefficient.

In Figs. 10 and 11, we observed the damping coefficient of 5.5414E−5 and quality factor for the proposed switch is 0.49.

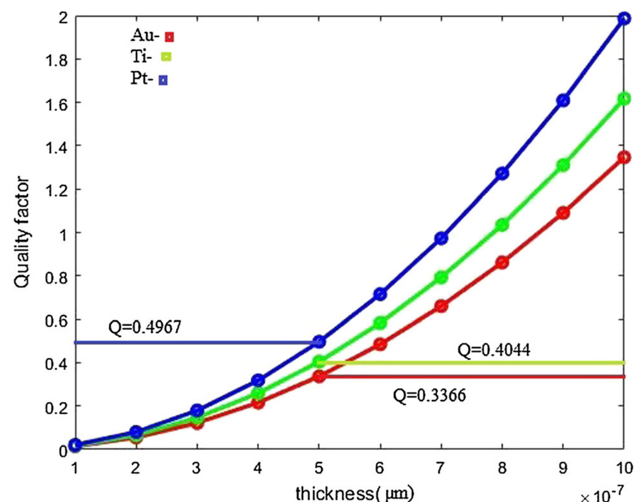

Fig. 11 Thickness vs. quality factor for different materials of a proposed switch

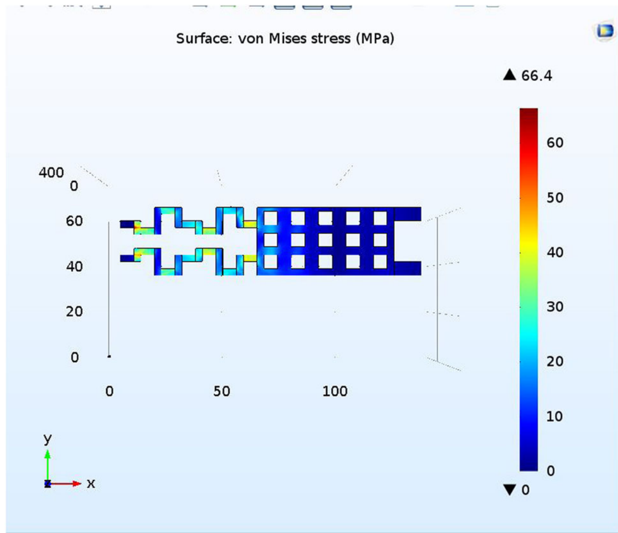

Fig. 12 Maximum stress analysis of a proposed switch

3.1.7 Stress analysis

Mechanical behavior is used to perform in FEM Tool. The pull-in phenomenon and stability of the design is to understand the stress analysis. The deflection of beam due to stress for height is analyzed in von Mises stress. The beam is made up of gold, which is stress is represent in MPa:

$$F = \frac{\varepsilon_r \varepsilon_0 S V^2}{2d^2}. \tag{11}$$

By varying the force we observed the stress that the switch can bear in solid mechanics of COMSOL tool. In Fig. 12, observed the stress applied on the beam is 66.4 MPa.

3.1.8 Radio frequency performance analysis

In the Radio Frequency ranges, the loss of a signal in MEMS switch is sometimes taken as $|S_{21}|^2$, but the decrease in S_{21} does not necessarily indicate the power loss of the switch but it can also be due to increasing in the reflected power from the switch ($|S_{11}|^2$). The power loss owing to the MEMS switch can be explained with the help of S-parameters (Vu et al. 2009; Mafinejad et al. 2009; Vu et al. 2012; Girija Sravani et al. 2019).

3.1.8.1 Insertion loss In insertion loss of the RF MEMS switches changes a RF signal to control the power dissipation in switch at signal transmission line. This loss happens at low frequencies just as at high frequencies. At this low frequency, because of a resistive loss in between a finite resistances of transmission line and also switch membrane contact region, while at microwave frequencies

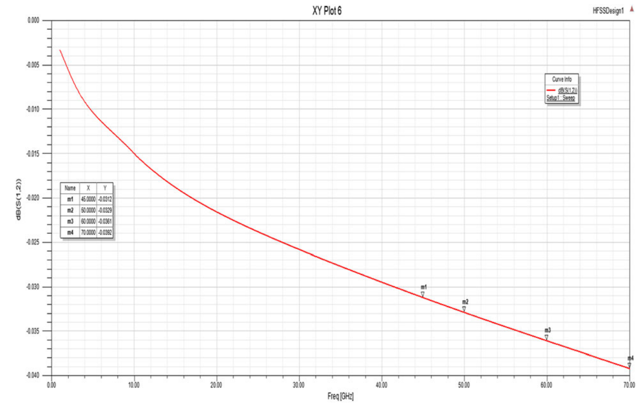

Fig. 13 Insertion loss of the proposed switch

addition misfortune due to skin profundity impact. For the structure aspect, this loss should be minimized for transmission of the signal:

$$S_{21} = \frac{1}{1 + \frac{j\omega C_d Z_0}{2}} \tag{12}$$

where C_d is down state capacitance of a switch, Z_0 is impedance matching.

In Fig. 13 we observes − 0.0397 is observed at 70 GHz frequency

3.1.8.2 Return loss It states that the RF power is reflected by the system/structure at the input signal of a switch with its transmission state. This return loss happens due to mismatching the total impedance between the transmission line and the switch:

$$S_{11} = \frac{-j\omega C_u Z_0}{2 + j\omega C_u Z_0}. \tag{13}$$

In this Fig. 14 we observes − 48.15 dB is observed at 45 GHz frequency.

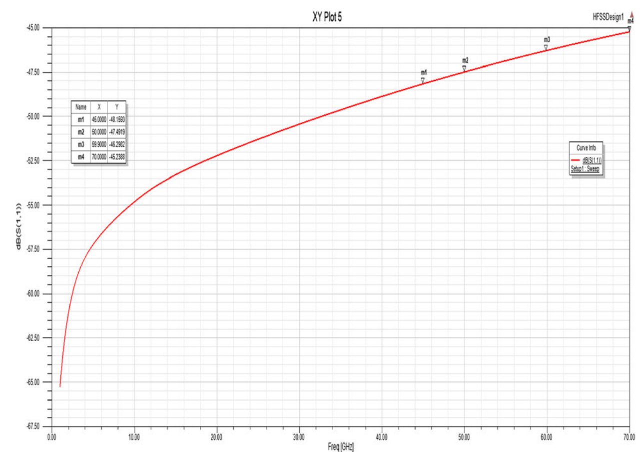

Fig. 14 Return loss of a proposed switch

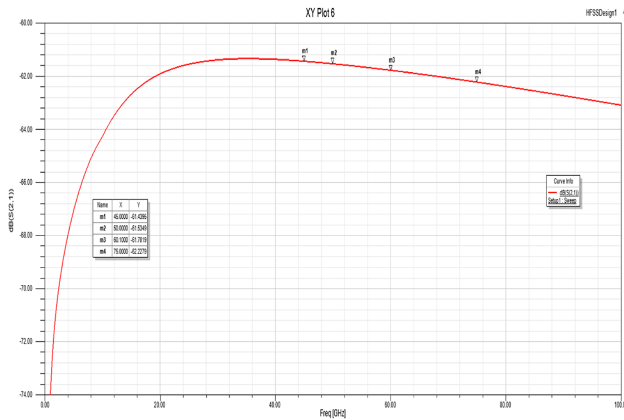

Fig. 15 Isolation of a proposed switch

Table 2 Comparison of the proposed RF MEMS switch with literature works

Parameters	Goldsmith et al. (1998)	Vu et al. (2009)	Proposed design
Pull in voltage (V)	30–50	32	10.5
Capacitance up state (fF)	30–40	9.5	4.3
Capacitance down state (pF)	3.2–3.5	–	0.331
Switching time	–	300 ns	9.27 µs
Insertion loss	< − 0.25 dB at 35 GHz	− 1.94 dB at 60 GHz	− 0.033 dB at 50 GHz
Isolation loss	− 35 dB at 35 GHz	− 14.79 dB at 60 GHz	− 62 dB at 50 GHz
Return loss	− 0.16 dB at 35 GHz	–	− 48 dB at 50 GHz

3.1.8.3 Isolation It states that RF signal present in the isolation between the output and input terminals in this signal state. In decibels a high isolation is indicated with small coupling between the input and output bounding's. Generally, in RF MEMS switches are having high isolation it is one of main advantage.

In this Fig. 15 we observes − 62.22 dB is observed at 70 GHz frequency isolation is calculated when the switch is in OFF-state. Insertion and return losses are calculated by keeping the switch is in ON-state.

From Figs. 13, 14 and 15 the RF performance analysis the insertion loss (S_{12}) for the proposed switch as − 0.033 dB, the return loss as − 48 dB, isolation when both cantilevers are in downstate as − 62 dB at the 50 GHz frequency for V-band applications. The comparison of the proposed RF MEMS Switch with others are presented in Table 2.

4 Conclusions

In this paper, double cantilever type RF MEMS shunt switch is designed with various parameters such as pull-in-voltage, switching time, quality factor, damping ratio, upstate and downstate capacitances are analyzed both theoretically and practically. The pull-in-voltage is observed as 10.5 V. The switching time analysis is performed by varying the beam thickness and air gap between the dielectric layer and beam is observed as 9.3 µs. The electromagnetic analysis such as insertion loss, isolation, and return loss are analyzed that the switch shows good Isolation of − 62 dB at 45–70 GHz frequency for 5G applications of V-band range.

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