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Multi Parametric Extraction and Validation of Series DC Contact RF MEMS Switches for Low-Frequency Wireless Communication Applications

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Abstract- *In this paper, we have designed and analyzed different MEMS structures suitable for series DC contact RF MEMS switches. To validate the proposed switch, we have extracted the multiple parameters at the simulation level. Overall, we have analyzed three structures, i.e., fixed-fixed, crab leg, and folded. Compared to other structures, the folded structure is offering a good performance. So, the folded structure-based series DC contact RF MEMS switch requires an actuation voltage of 4.5 V, eigenfrequency 6640 Hz, isolation loss - 40 dB, and insertion loss - 0.2 dB. The switch performance is analyzed within frequency band 0.2-20 GHz; after observing the behavior of the switch, it is clear that the switch is suitable for low-frequency wireless communication applications like Bluetooth, Wi-Fi, and WiMax.*

Index Terms- *Series switch, MEMS, actuation voltage, material science, perforation, micromechanical structures, electrostatic actuation.*

I. Introduction

Now a day's MEMS is the trending technology that is offering many miniaturized devices like switches, varactors, and filters in radio frequency communication applications. Many researchers already demonstrated that MEMS technology-based RF MEMS switches play a vital role in offering high performance in terms of high isolation and low power consumption. Because of their great potential, RF MEMS switches have become significant in future wireless communication applications like reconfigurable antennas and microwave testing equipment. Based on the circuit configuration, RF MEMS switches are classified as series and shunt. In this paper, we have demonstrated the design and performance analysis aspects in electrostatically actuated series DC contact RF MEMS switches. Achieving low actuation voltage, high switching speed, and low switch resistance are the major research challenges in series DC contact RF MEMS switches[1-3]. Low spring constant offering mechanical membranes offer low actuation voltage [4]. Incorporation of the holes into the membrane helps to improve the switching time [5-6]. By using low sheet resistance metal thin film as contact material, we can reduce the RF losses [7-9].

This paper is organized as follows: in Section II, we have reviewed the previous work related to series DC contact RF MEMS switches. In Section III, we have described the problem statement. Series RF MEMS switches performance analysis, and parametric extraction is discussed in Section IV. A performance improved RF MEMS switch with folded flexure is presented in Section V and followed by Conclusions in Section VI.

II. Related Work

RF MEMS technology has great potential, and it is already proved in terms of linearity, power consumption, and reliability when compared with solid-state technologies. And RF MEMS switches are essential for future wireless communication applications. This is one of the major motivating points for many researchers to choose RF MEMS switches as a major research domain.

The paper [10] discusses the bidirectional actuated ohmic RF MEMS switches with dual contact. The authors primarily concentrated on the reliability of the switch. The proposed switch is offering a very low contact resistance of 0.3 Ω.

The paper [11] presents a study of broadband Cryogenic DC-Contact RF MEMS Switches. The switch is offering an isolation loss of -20 dB and insertion loss of -0.6 dB. The authors additionally described the temperature effects on RF MEMS switches reliability.

The authors in [12] demonstrated multiple timescales in cantilever-based DC contact RF MEMS switches. A parametric study was performed to investigate the effect of system parameters on switch bounce.

The paper [13] presents a low actuation voltage RF MEMS switch that can integrate with CMOS technologies. Experimental measurement results indicate a pull-in voltage of 0.5 V for 1.5 μm displacement. The measured return loss is -20 dB and insertion loss - 0.1 dB over the frequency range of 3 kHz to 3 GHz. The switching time is 0.22 ms.

The paper [14] demonstrated a comprehensive study on contact material selection for DC contact RF MEMS switches. The authors concluded that gold as a contact material helps to reduce contact resistance by 16%. Ashby's material selection approach is incorporated in the process of material selection. HfO_2 is used as a dielectric material.

After a close review of series DC contact RF MEMS switches, we have noticed few research gaps and identified the scope of research. The major research challenges in DC contact RF MEMS switches are reducing the actuation voltage, reducing the switching time, and improving the radio frequency properties.

III. Problem Statement

Series DC contact RF MEMS are suitable for low-frequency communication applications. So many researchers are advanced the related work and improved the performance, but because of the demand for the low power consumed, RF switches are creating new research challenges on DC contact RF MEMS switches. In this paper, primarily, we have concentrated on the reduction of spring constant, reducing the actuation voltage, improving the switching time and RF properties.

A. Reduction of spring constant

Low spring constant helps to reduce the required actuation voltage. Doing prior structural and material analysis helps to identify the low spring constant micromechanical structure.

B. Reduction of the actuation voltage

Electrostatically actuated RF MEMS switches performance depends on the required actuation voltage. Achieving low actuation voltage is the major research challenge in RF MEMS switches.

C. Improving reliability

Compared with solid-state technology-based RF switches, MEMS technology-based RF switches reliability is very low. Improving the reliability of RF-MEMS also switches a major research challenge in RF MEMS technology.

D. Improving radio frequency (RF) performance

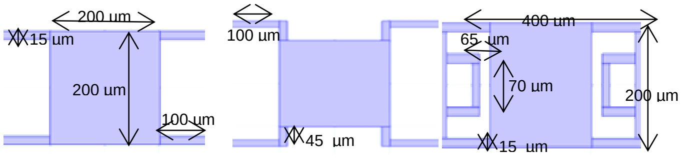
DC contact RF MEMS switches, radio frequency properties like isolation losses and insertion losses depend on the gap in the transmission line and the contact material, respectively.

IV. Performance Analysis and Parametric Extraction

In this paper, we have analyzed the performance of electrostatically actuated series DC contact RF MEMS switches. In the process of the performance analysis, we have considered criteria like structure, perforation, material, and thickness. To validate the switch, we have extracted most of the performance deciding parameters in the electrical, mechanical, and RF category.

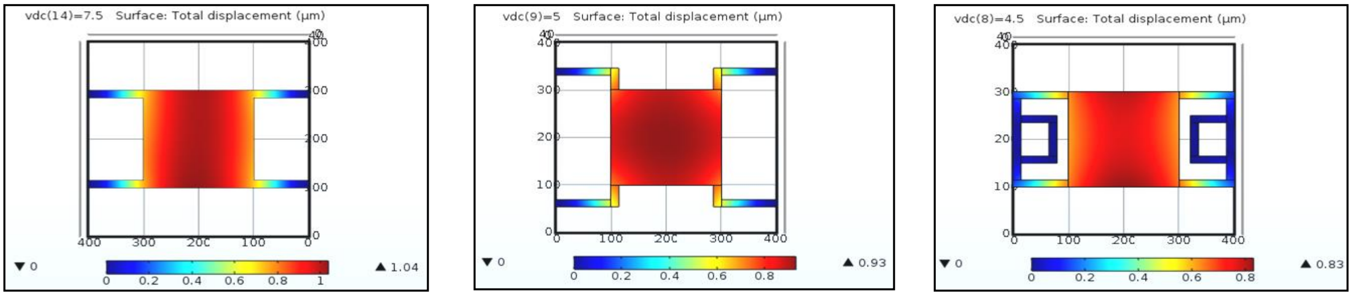
A. structural analysis

Reliability is one of the research challenges in RF MEMS switches, so doing the prior structural analysis helps to improve the reliability of the switch. Overall we have analyzed the three micromechanical structures, i.e., fixed-fixed, crab-leg, and folded structures, as shown in Figure 1. The three structures are actuated electrostatically by using the FEM tool. In the primary analysis, we have simulated the structures with gold material of 1 µm thickness.



(a) (b) (c)

Figure 1. Micro mechanical structures, a) fixed-fixed, b) crab leg, c) folded.



(a) (b) (c)

Figure 2. Electrostatic Actuation, a) fixed-fixed, b) crab leg, c) folded.

B. Perforation analysis

Holes or perforation to the membrane helps to reduce the required actuation voltage, as well as it helps load uniform distribution. Because of the uniform distribution of loading, the reliability of the switch will improve. Here, we have perforated the membranes with 15 µm x 15 µm size holes. Because of this perforation, the pull-in voltage is reduced significantly as shown in Table 1. From the structural and perforation analysis, it is clear that the folded flexure-based micromechanical structure is offering low actuation voltage when compared with fixed-fixed flexure and crab leg flexure.

Table 1. MEMS structure Perforation analysis

Structure	Actuation voltage (V)	Displacement (µm)	
		Without perforation	With perforation
fixed-fixed	7.5	1.04	1.06
crab leg	5	0.93	1.03
folded	4.5	0.83	0.98

From the above analysis, it is clear that because of the incorporation of perforation, the pull-in voltage is reduced significantly. The folded flexure-based micromechanical structure is offering a 1 µm displacement for 4.5 V.

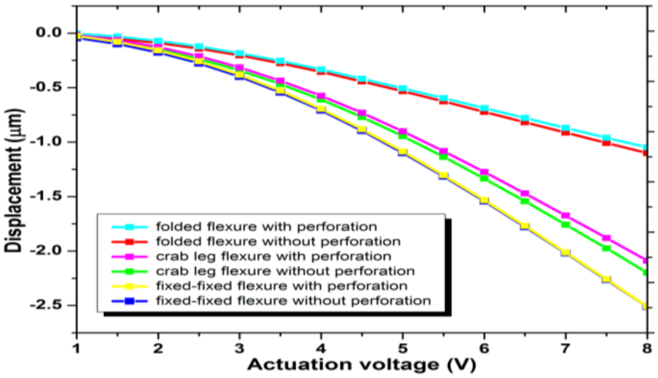
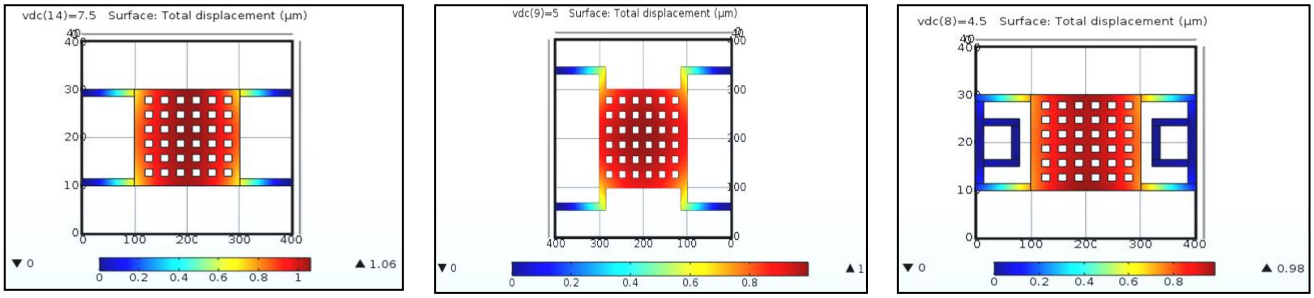


Figure 3. Analysis on actuation voltage (vs) displacement.



(a) (b) (c)

Figure 4. Micro mechanical structures with perforation, a) fixed-fixed, b) crab leg, c) folded.

C. Eigen frequencies

The eigenfrequency (or) natural frequency (or) resonance frequency of micromechanical structure helps to analyze the switching time of the switch. If the eigenfrequency is very high, it means the micromechanical structure will take more Time to settle after applying the actuation voltage. In an eigenfrequency analysis, as shown in Figure 5, we have observed that compared to other structures, folded structure eigenfrequency is very low it indicating that the folded structure will offer low settling time and squeeze thin-film damping.

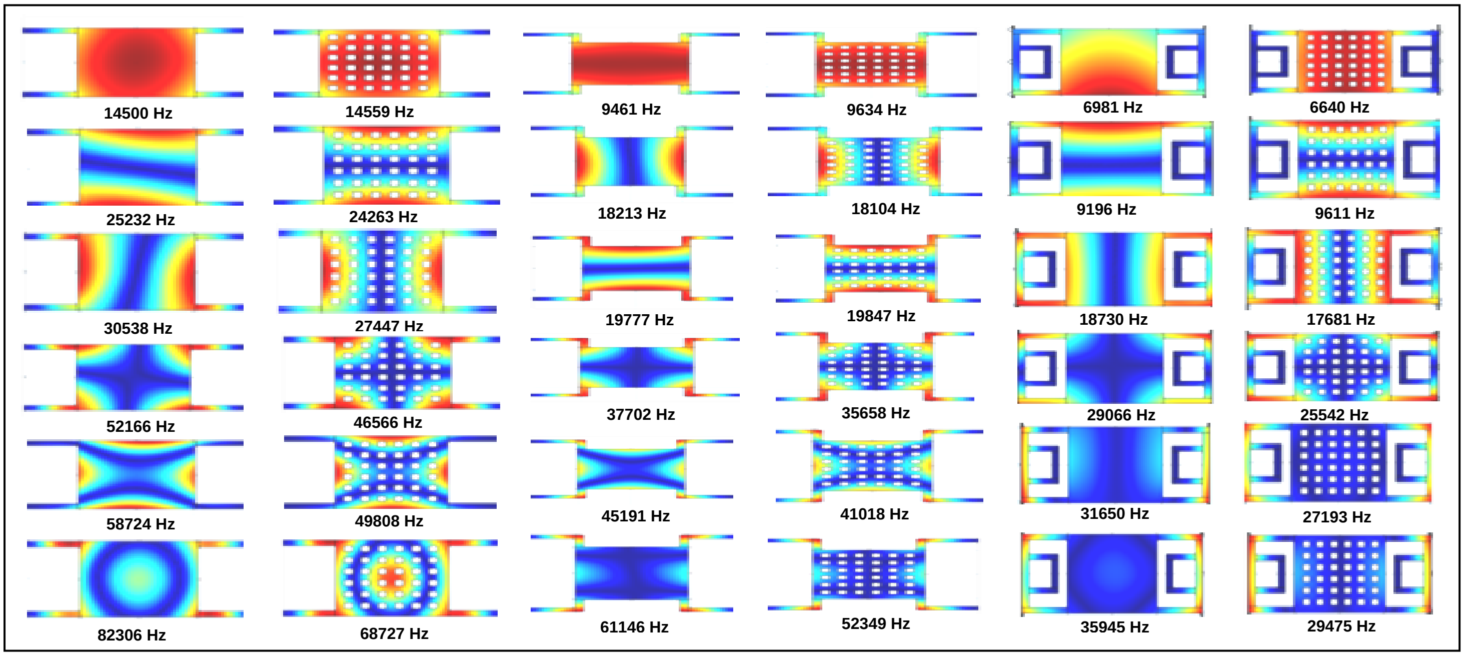
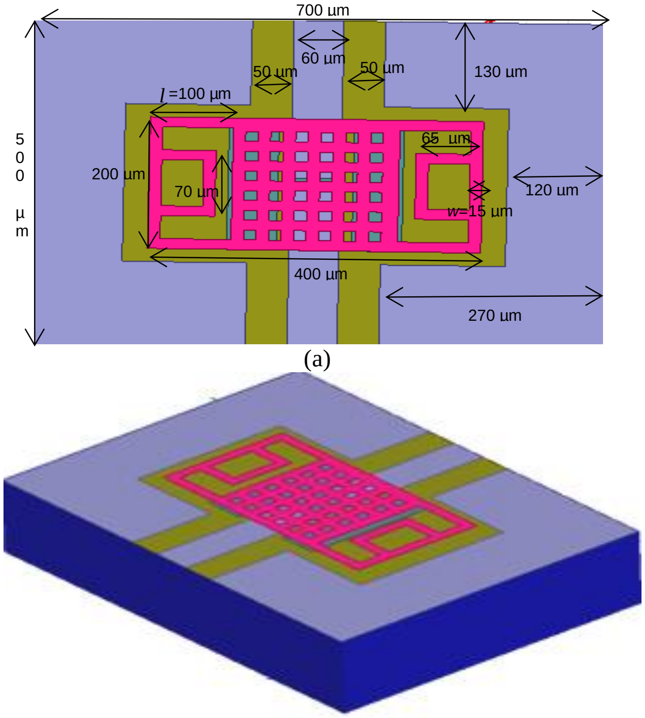


Figure 5. Eigen Frequency-based MEMS structural analysis

V. Proposed series RF MEMS switch

From the analysis in Section IV, it is clear that folded flexure-based micromechanical structure is offering good performance when compared with fixed-fixed and crab leg flexures.

So, here we have designed a series DC contact RF MEMS switch with folded flexure-based micromechanical structure. A CPW transmission line with G/S/G values 50 µm/ 60 µm/50 µm is used to micromachine the switch.



(a)

(b)

Figure 6. Series DC contact RF MEMS switch (a) top view, (b) side view.

Table 2. Series DC contact RF MEMS switch parameters

Parameter	Values (µm) / material
Silicon substrate size	700×500×800
Oxide thickness	1
Membrane material	Gold
Membrane thickness	1
The gap between the membrane and bottom electrodes	1

A. *Mathematics behind folded flexure*

The performance of the RF MEMS switch can be analyzed by extracting the parameters like mass, spring constant, switching time, and RF losses [15-19].

The mass (m) of the membrane will depend on the membrane material whose density (ρ) and the membrane dimensions like length (l), width (w), and thickness (t).

$$membrane\ \ mass(m) = \rho * l * w * t \tag{1}$$

Gold (Au) material, the density (ρ) is 19300 kg/m^3. If l = 200 µm, w = 200 µm, t = 1 µm the then the mass of the membrane is 772 x 10^{-12} Kg.

The spring constant (K) of the micromechanical structure depends on the length, width, and thickness. The actuation voltage of the membrane depends on the spring constant. For folded flexure, the spring constant can be expressed as,

$$spring\ \ cons\tan t(K) \approx 2Ew\left[\frac{t}{l}\right]^3 \tag{2}$$

Gold (Au) material the young's modulus (E) is 70 GPa. If l = 100 µm, w = 15 µm, t = 1 µm the then the mass of the membrane is 2.1 N/m.

The settling time of the RF MEMS switch is the primary performance deciding parameter. The eigenfrequency(ω_o) of the micromechanical structure decides the settling time of the switch, and it can be expressed as,

$$eigenfrequency(f_0) = \frac{1}{2\Pi}\sqrt{\frac{spring\ cons\tan t}{membrane\ mass}} \tag{3}$$

If the micromechanical structure spring constant is 2.1 N/m and the mass is 772 x 10^{-12} Kg, then the eigenfrequency is 8305 Hz.

The voltage required to displace the membrane 2/3 of the gap is known as pull-in voltage. The pull-in voltage of the micromechanical structure can be expressed as,

$$pull-in\ voltage(V_p) = \sqrt{\frac{8K}{27\varepsilon_0 A}g^3} \tag{4}$$

Where A is the cross-sectional area between membrane and bottom electrodes, g is the gap between the bottom electrode and the membrane. If the membrane spring constant (K) is 2.1 N/m, cross-sectional area (A) is 200 µm x 200 µm = 40000 µm^2, air gap (g) is 1 µm, and the free space relative permittivity (ε_0) is 8.854187817 10^{-12} C^2/(N m^2) then the pull-in voltage (V_p) is 1.32 V.

The switching time of the micromechanical structure depends on the pull-in voltage, supply voltage, and the natural or eigenfrequency, and it can be expressed as,

$$switching\ \ time(t_s) \cong 3.67\frac{V_p}{V_s\omega_0} \tag{5}$$

The upstate capacitance of the switch depends on the cross-sectional area between the CPW transmission line strip and the membrane, air gap (g), and the free space relative permittivity (ε_0). And it can be expressed as,

$$upstate\ \ capacitance(C_{up}) = \frac{\varepsilon_0 wW}{g} \tag{6}$$

If the free space relative permittivity (ε_0) is 8.854187817 10^{-12} $C^2/(N\ m^2)$, CPW line strip width (w) 60 µm, membrane width (W) is 200 µm, and the air gap (g) is 1 µm then the upstate capacitance is 106.2 fF.

In series DC contact RF MEMS switches, if the membrane is in upstate, the switch is in OFF state, and the input RF signal is getting isolate. Under this condition, the switch isolation losses can be expressed as,

$$isolation\ \ losses = S_{21} = \frac{2j\omega C_{up} Z_0}{1 + 2j\omega C_{up} Z_0} \tag{7}$$

If the actuation voltage is applied, then the membrane will come to the downstate, and the switch is turned into an ON state, then the input RF signal is allowed to the output. Under this condition, the switch insertion losses can be expressed as,

$$insertion\ losses = S_{21} = 1 - \frac{R_s}{2Z_0} \tag{8}$$

Where 'R_s' is the switch resistance which includes DC contact resistance and membrane resistance, in general, the switch resistance (R_s) is in the range of 1-3 Ω.

$$R_s = 2Z_0(1 - 10^{\frac{S_{21} in\ dB}{20}}) \tag{9}$$

With the help of insertion losses (S_{21}), we can write the expression for the return losses of the switch when the switch is ON, i.e.,

$$|S_{11}|^2 = 1 - |S_{21}|^2 \tag{10}$$

B. Results and discussions

The series DC contact RF MEMS switch is micromachined on a CPW transmission line. Silicon is used as a substrate. SiO_2 is used as an insulating layer. CPW and membrane are micromachined by using gold (Au) material. The air gap (g) between the membrane and the bottom electrode is 1 µm. The folded flexure with perforation is used as a membrane.

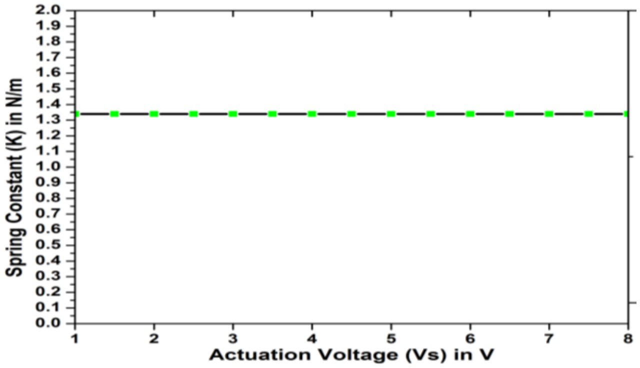


Figure 7. Spring constant.

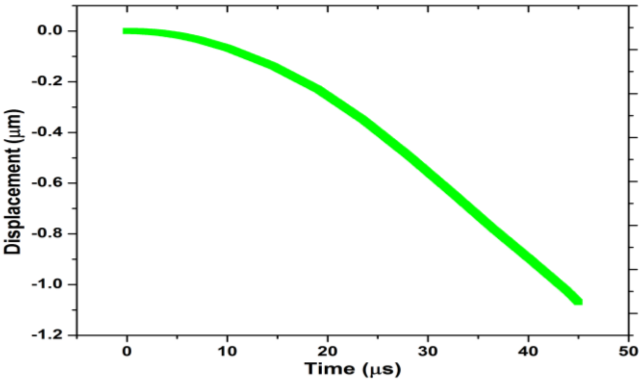


Figure 8. Switching time.

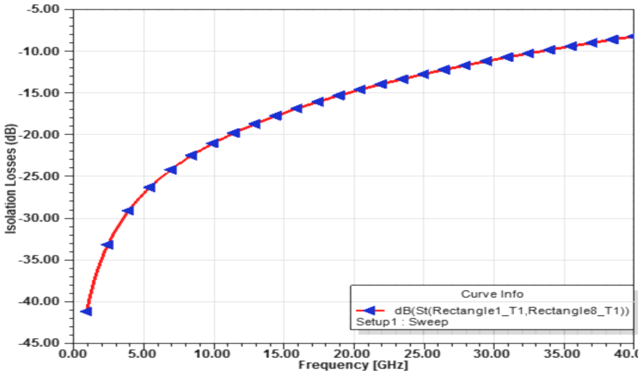


Figure 9. Isolation losses.

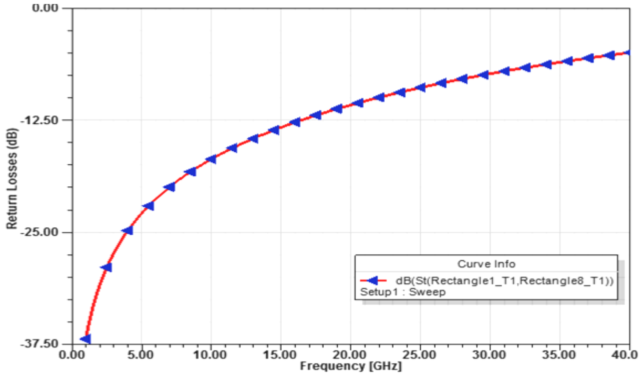


Figure 10. Return losses.

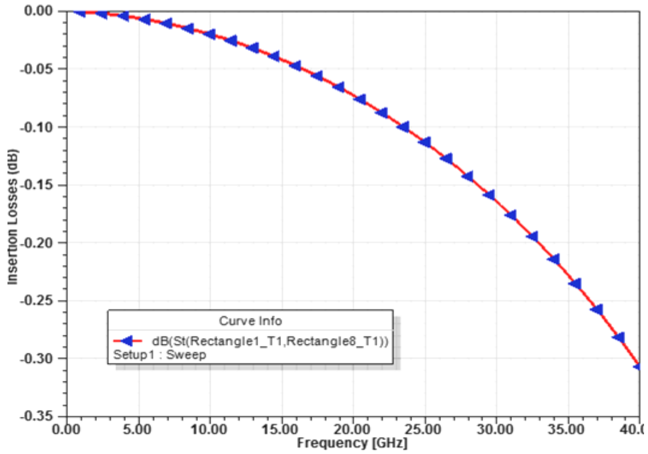


Figure 11. Insertion losses.

Table 3. Folded flexure RF MEMS switch parametric analysis.

Parameter	Theoretical value	Simulation value
Mass	772 x 10^{-12} Kg	772 x 10^{-12} Kg
Spring constant	2.1 N/m	1.34 N/m
Actuation voltage	1.848 V	4.5 V
Eigenfrequency	8305 Hz	6640 Hz
Switching time	44 μs	40 μs
Isolation losses	- 65 dB	- 68 dB
Insertion losses	- 0.18 dB	- 0.2 dB

Table 4. Comparison of present work with existing.

Parameter	Ref. [20]	Ref. [21]	Ref. [22]	Prosed work
Substrate material	Borofloat glass	Silicon	Sapphire	Silicon
Transmission line	CPW	CPW	CPW	CPW
G-S-G	110 μm/ 18 μm/110 μm	---	---	100-70-100
Membrane material (thickness)	Gold (1 μm)	Gold (1 μm)		Gold(1 μm)
Perforation to membrane	No	No	Yes	Yes
Membrane height	1-5 μm	---	1 μm	1 μm
Membrane mass (Kg)	---	---	---	772 x 10^{-12} Kg
Spring constant (N/m)	---	---	---	1.34 N/m
Actuation voltage (V)	24 V	3.75 V	7 V	4.5 V
Eigen frequency (Hz)	---	---	---	6640 Hz
Switching time (μs)	---	69.4 μs	---	40 μs
Isolation losses (dB)	- 20 dB	- 70 dB	- 45 dB	- 68 dB
Return Losses (dB)	---	---	---	-38 dB
Insertion Losses (dB)	- 0.71 dB	- 0.06 dB	- 0.5 dB	- 0.2 dB

VI. Conclusion

Overall, we have analyzed three structures, i.e., fixed-fixed, crab leg, and folded. Compared to other structures, the folded structure is offering a good performance. So, the folded structure with a spring constant of 1.34 N/m, based series DC contact RF MEMS switch requires an actuation voltage 4.5 V, eigenfrequency 6640 Hz, isolation loss - 65 dB, and insertion loss - 0.2 dB. The switch performance is analyzed within frequency band 0.2-20 GHz.

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