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STRUCTURAL AND MATERIAL BASED COMPREHENSIVE PERFORMANCE ANALYSIS ON SHUNT CAPACITIVE RF MEMS SWITCH

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Abstract

In this paper, we have presented the structural and material based comprehensive analysis on shunt capacitive RF MEMS switches. The switches properties are analysed by considering two structures, i.e., clamped-clamped and serpentine structure. The material analysis is done on different thin films like substrate, dielectric, and membrane. With the comprehensive analysis, it is clear that the serpentine structure is offering extraordinary features in the form of pull-in voltage and switching time. The material analysis is revealed that silicon, HfO_2, and Aluminium (Al) are the best material for substrate, dielectric, and membrane thin films. Finally, we designed a switch with improved performance, the switch offering an actuation voltage of 3.68 V, insertion losses of -0.55 dB, and isolation losses of -51 dB. The designed switch is suitable for K and Ka-band applications like radar and satellite applications.

Keywords: Material science, MEMS technology, Microstructure, RF switches, Thin films.

1. Introduction

Radio Frequency (RF) switches are very needy devices in future high-frequency mobile communication applications. Especially in the design of transceivers, the RF switches are primarily used for frequency tuning and frequency reconfigurability. Low power consumption is the potential research challenge in RF switches, which extremely influences the battery lifetime. Solid state technology and the MEMS technology offers fine performance RF switches.

However, the MEMS technology is the rapidly growing technology with great potential which offers low power consumption, high linearity, and high reliability. The solid-state technology RF switches, i.e., PiN diodes performance is not up to the level of requirement of 5G communication. But the MEMS centred RF switches are offering the finest performance when matched with solid state technology-based RF switches. Not only RF switches, MEMS technology proved its ability in the design of filters, varactors which are essential devices in mobile communication applications [1].

The RF MEMS switches are adopted by high-frequency potential applications because of offering great performance in terms of low power consumption, high isolation, and high linearity. Despite these features, the RF MEMS switches have some potential research challenges, i.e., high actuation voltage(20-80 V), high switching time (1-300 µs), and low isolation. Prior performance analysis helps to advance the switches performance in mechanical, electrical and radio frequency multi-physics. These basically are classified as series and shunt. However, shunt type switches are appropriate for high frequency and series type switches are appropriate for low frequency applications.

K-band, and Ka-band covers the frequency in the range of 18-27 GHz, and 27-40 GHz respectively, which have some potential millimetre-wave applications like vehicle speed detection, satellite communication, satellite television, and radar astronomical observation and microwave communication [2].

With the motivation of research challenges of RF MEMS switches, in this paper, we have analysed and improved the performance of switches by doing simulations using FEM tools which are suitable for K-band, and K-band applications. Curiously and dedicatedly many researchers have proposed different shunt switches with different materials and membrane structures [3]. Cantilever, clamped-clamped, folded, and serpentine structures are adopted by many researchers. Proper selection of thin-films, i.e., substrate, dielectric, and membrane for the design of these switch helps to advance the switch performance [4-9]. In this paper, we analysed and enhance the performance of shunt capacitive switch with proper performance analysis, i.e., structural and material analysis.

2.Related Work

Several investigations advanced the research on micro electromechanical switches [10]. Improving the performance of these switch is a potential research aspect, so researchers curiously advanced the research on shunt switches. But because of the requirements in high-frequency communication applications, still these switches have few research challenges like low actuation voltage, high isolation, and low insertion.

Dubuc et al. [10] primarily described the parameters influencing the reliability of these switches, like dielectric chagrining. Bridge type micromechanical structure is incorporated in these switches. The authors proposed RF MEMS switches for future 5G communication applications.

Badia et al. [11] mainly demonstrated the shunt capacitive switch. The role of dielectric material on the performance is analysed. Si_3N_4 and AlN dielectric material are taken into consideration in the performance analysis. The switch with AlN as a dielectric material offering up-capacitance of 98.67 fF, and the down-capacitance of 1.295 pF.

Laxma and Shanmuganantham [12] proposed a novel shunt capacitive switch with AlN dielectric thin film for high capacitance ratio. The switch is offering an actuation voltage of 5 V for 1 µm gap, insertion of -0.5 dB, and isolation of -55 dB.

Table 1. Comprehensive study on shunt capacitive RF MEMS switches.

Ref.	Description	Limitations
[13]	Together with the analytical measurement tests, a numerical technique is provided to determine the release time of the gold cantilever switch which is thermally curled in micrometre size. Beam dimension is 400×200×2 µm, frequency range 0.1-40 GHz, and input power is 0-10 W.	Actuation voltage is very high. Material analysis no performed.
[14]	A lateral-capacitive transition was actuated electro thermally processed built and assembled using bulk micromachining. In because of this turn, the HfO_2 was used as a dielectric substance which offers excellent legal and electric characteristics. Actuation voltage 40-80 V, spring constant 42 N/m, mass flow rate is 9.8×10^{-6} kg/s.	Switching time of the switch is not discussed.
[15]	Shunt capacitive switches with K-band control were built using GaAs III-V manufacturing method completely compliant with normal MMIC output.	Actuation voltage analysis is not performed.
[16]	A simplifies and coherent model of study using yang power simulation model was introduces perforated shunt turn considering fringing area impact attributable to scale of finite board, thickness of beam and each space.	Radio Frequency analysis is not performed.
[17]	It has been shown that a low cost and unorthodox imaging technique is effective for the optional characterisation of the capacitive switches suspended double-clamped bridge in switches. Capacitance ratio is in the range of 12-16.	Switching time of the switch is not discussed.
[18]	The FEM tool level analysis of a tunable antenna equipped with CPW stub, on which these switches are mounted. Air gap (d) 3 µm, C_{up} is 39.65 fF, and C_{down} is 2.2 pF.	Material analysis no performed.
[19]	SiN_x's electrical properties with embedded CNT's by chance bunches arranged or vertically positioned, and Au nanorods were investigated. The electric properties are considered to be important affected by both embedded and directed nano filter. Actuation voltage 30 V, air gap 3 µm.	Actuation voltage analysis is not performed.

3. Problem Statement

RF MEMS is the emerging technology which is adopted the high frequency mobile communication applications. RF MEMS switches are already proved their ability in offering high performance with low power consumption. Exploratory findings and the advancements observed from the related work, we have identified a few potential research challenges of shunt capacitive switches for k-band and Ka-band applications. RF MEMS technology deals with different multi-physics, i.e., electrostatic, electromechanical, and electromechanical. Pull-in voltage is related to electrostatic, and these switches require more actuation voltage compared with solid-state technology switches.

The switching mechanism in switches primarily depends on the electromechanical deformation of the membrane. The switching time of the switches is in the range of the millisecond, but the IC technology demands the communication devices using high switching speed in nanoseconds. The radio frequency properties of MEMS switches primarily depend on the dielectric material and the membrane structure, proper selection of the membrane, and the materials help to accelerate the performance. In this paper, we have primarily elevated the factors which majorly influences the performance of electrostatic ally actuated shunt capacitive RF MEMS switches, i.e., actuation voltage, switching time, and RF losses.

Table 2. Problem statement.

Multi-physics	Parameter	Solution
Electrostatic	Actuation voltage	Proper structural analysis helps to reduce the actuation voltage.
Electromechanical	Switching time	Low spring constant structures will offer high switching speed.
Electromagnetic	Insertion and isolation losses	The material analysis for the different thin films significantly improves the insertion and isolation properties.

4. Performance Analysis

In this paper, especially we have analysed two structures, i.e., clamped-clamped and serpentine structure. The performance of electrostatically actuated shunt capacitive these switches is analysed by considering the role of membrane structure and thin-film materials.

4.1. Theoretical analysis

The overall mass (m) of the micromechanical structure can be measure with m = ρ × l × w × t, where ρ - material density, l - length, w - width, t - thickness. Spring constant will vary from flexure to flexure, for the clamped-clamped flexure the spring constant (k) can be expressed as [13, 14],

$$k = 4Ew\left(\frac{t}{l}\right)^3 \quad (1)$$

For the serpentine flexure with material young's modulus (E), the spring constant can be expressed as,

$$\frac{1}{K} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} + \frac{1}{K_4} \quad (2)$$

where,

$$K_{(1,2,3,4)} = \frac{Ewt^3}{l^3}$$

The switching time is one of the primary parameters which decides the switch performance, the switching time can be formulate with the help of resonant frequency. The free body analysis, as shown in Fig. 1, we can extract the expression for the resonant frequency, i.e.,

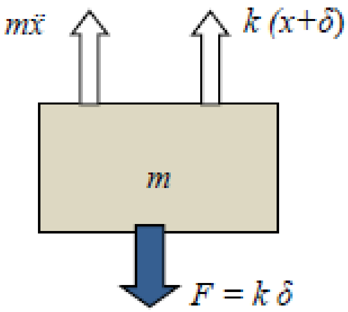


Fig. 1. Free body analysis.

$$m\ddot{x} + k(x+\delta) - F = 0 \quad (3)$$

$$m\ddot{x} + kx + k\delta - k\delta = 0$$

$$\ddot{x} + (k/m)x = 0$$

By comparing above equation with simple harmonic motion, i.e.,

$$\ddot{x} + \omega^2 x = 0 \quad (4)$$

Therefore,

$$\omega^2 = k/m$$

$$\omega = \sqrt{\frac{K}{m}}$$

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \quad (5)$$

The switching time (t_s) of the clamped-clamped and serpentine flexure is expressed as,

$$t_s = 3.67\frac{V_p}{V_s\omega_0} \quad (6)$$

The electrostatically actuated switch parameters mainly rely on the pull-in voltage, it can be expressed as,

$$V_{pull-in} = \sqrt{\frac{8kg^3}{27A\varepsilon_0}} \quad (7)$$

Compared to series DC contact switches, shunt capacitive switches offer best performance at high frequency applications. The shunt capacitive switch upstate capacitance (C_{up}) and downstate capacitance (C_{down})can be expressed as,

$$C_{up} = \frac{\varepsilon_0 A}{g+\frac{t_d}{\varepsilon_r}} + C_f \quad (8)$$

$$C_{down} = \frac{\varepsilon_0 \varepsilon_r A}{t_d} \tag{9}$$

where g - air gap, A - cross sectional area, ε_r - relative permittivity, t_d - dielectric thickness.

4.2. Structural Analysis

The parameters of the switch primarily be contingent on the micro mechanical structure incorporated. The actuation voltage is majorly influenced by the spring content of the micro mechanical structure.

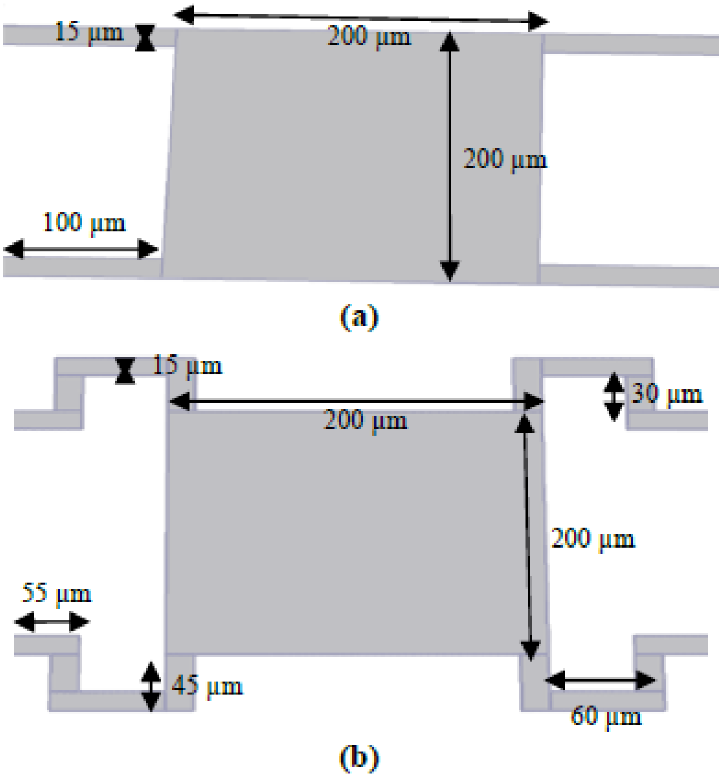
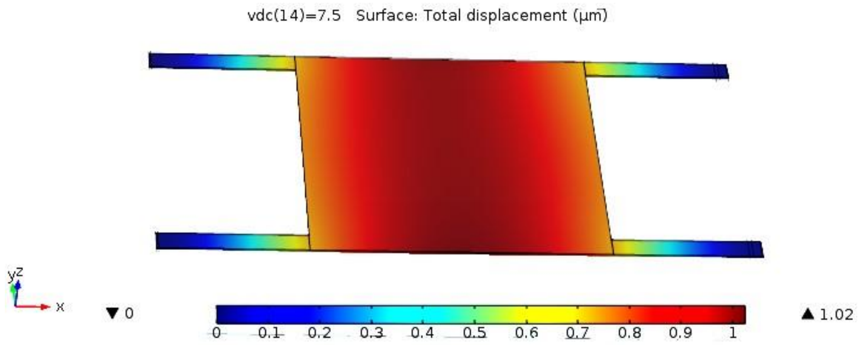


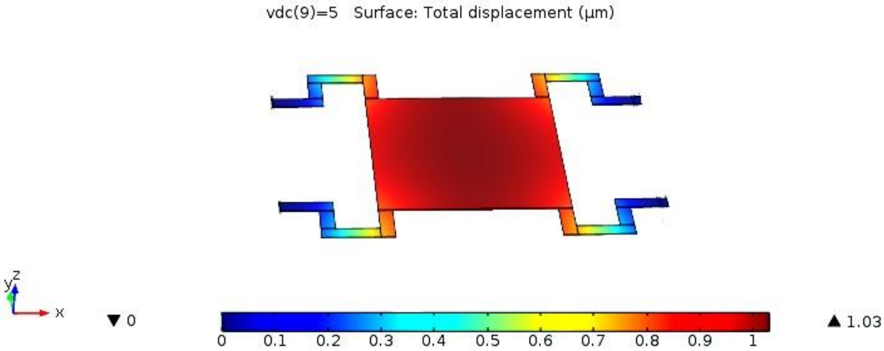
Fig. 2. Structural analysis, (a) clamped-clamped, (b) serpentine flexure with uniform meanders.

The low spring constant structure obviously offers low actuation voltage. Previously there are so many popular structures are proposed by different researchers, here we have taken clamped-clamped structure and serpentine structure shown in Fig. 2, for performance analysis. Gold material with young's modulus (E) of 70 GPa, and density (ρ) of 19300 kg/m^3. The thickness of the structure is taken as 1 µm.

Both micro mechanical structures are designed with gold metal and actuated electrostatically. The actuation voltage of the structure with clamped-clamped flexure is 7.5 V and the structure with serpentine flexure is 5 V for one micrometre displacement as shown in Fig. 3.



(a)

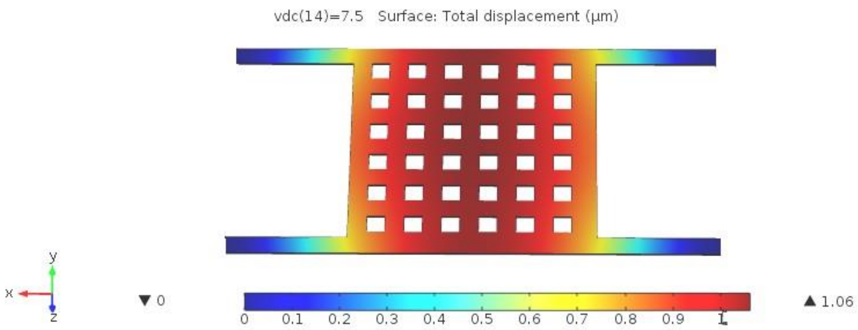


(b)

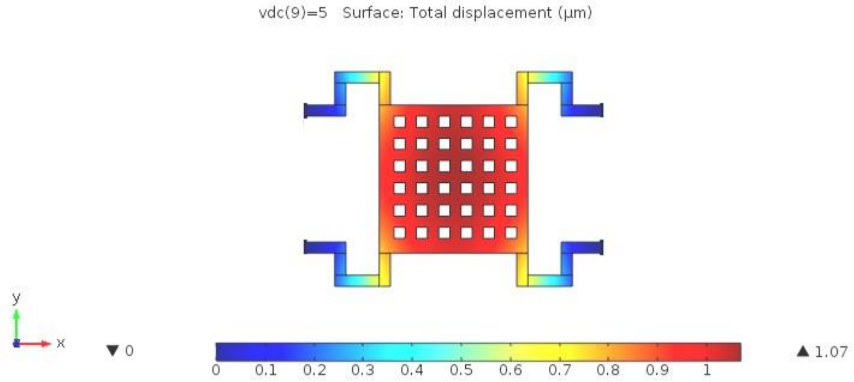
Fig. 3. Electrostatic actuation, (a) clamped-clamped, (b) serpentine structure.

4.3. Perforation analysis

Perforation to the micromechanical structure helps in the process of load distribution and improves the switch reliability. The perforation also helps to reduce the required actuation voltage in electro-statically actuated switches. Here we have perforated the micromechanical structure with holes of dimension 15 µm×15 µm as shown in Fig 4. Because of the perforation the required actuation voltage is reduced for both the structures. Because of the perforation the micromechanical structures displacement is increased an amount of 0.04 µm. It is clear that compared to the clamped-clamped flexure, serpentine flexure is offering low actuation voltage.



(a)



(b)

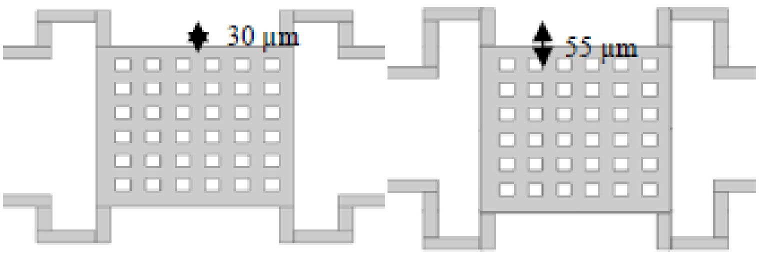
Fig. 4. Effect of perforation, a) clamped-clamped flexure, b) serpentine flexure with uniform meander.

So, further analysis is done on the serpentine structure. From the structural analysis it is clear that serpentine structure is offering low actuation voltage compared with clamped-clamped structure. The stiffness of the serpentine structure is very low when compared with clamped-clamped structure this s the primary reason of offering of low actuation voltage. So further analysis is performed on the serpentine structure.

4.4. Meander Analysis

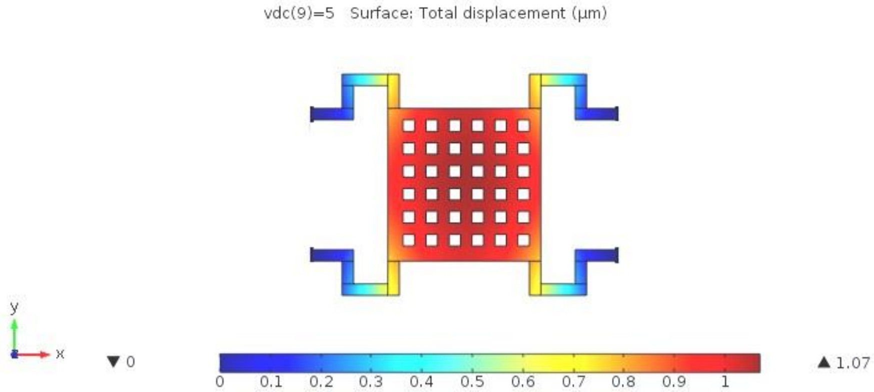
Perfect design of membrane eventually decides the RF MEMS switch performance. From the previous analysis it is clear that the serpentine membrane with uniform meander is offering best performance compared with clamped-clamped structure. In this sub section, we analysed the role of type of meander, i.e., uniform and non-uniform meander of the serpentine membrane on the actuation voltage shown in Fig. 5.

After observing the electrostatic actuation, it is clear that compared to uniform meanders, the non-uniform meander serpentine structure is offering a low actuation voltage. The structure is offering a displacement of 1 µm for 4.5 V shown in Fig. 6. The above analysis is performed by considering the gold (Au) as the membrane material. Perforation to the membrane is an extra added advantage to the switch performance which helps to reduce actuation voltage.

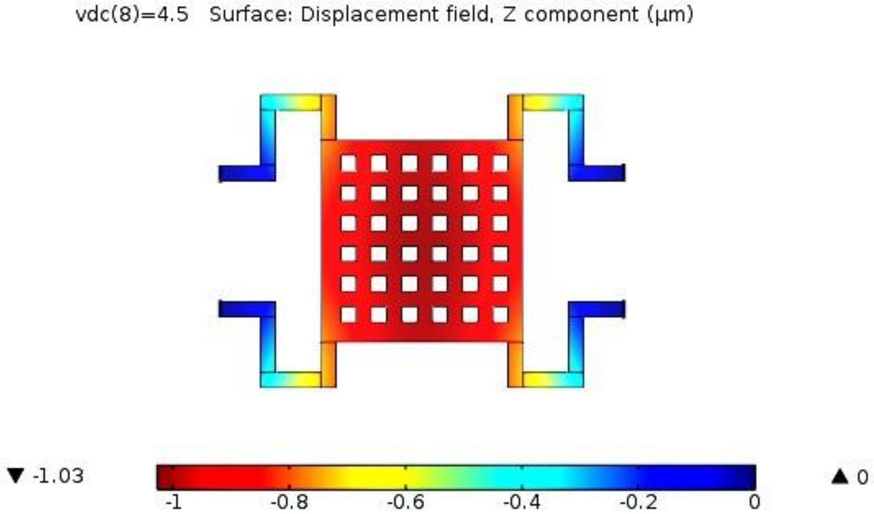


(a) **(b)**

Fig. 5 Serpentine structure meander analysis, (a) uniform meanders, (b) non uniform meanders.



(a)



(b)

Fig. 6. Electrostatic actuation of serpentine flexure with, (a) uniform, (b) non-uniform meanders.

4.5. Switching time

The switching time (t_s) is generally defined as the time taken by the switch to complete ON and OFF action. The time taken by the membrane to come to down state after applying the appropriate DC voltage is known as the switch ON time represented with t_{ON}, similarly the time required to come to the upstate after applying Zero DC voltage is known as switch OFF time and is represented with t_{OFF}. The total switching time is combination of t_{ON} and t_{OFF}, i.e., $t_s = t_{ON} + t_{OFF}$. The spring constant of the micromechanical structure primarily influences the switching time. If the stiffness of structure low the switching time is low as shown in the Fig. 7. The serpentine structure with meanders is flexible and deforms for low voltages, because of this flexibility the structure is offering low switching time compared with clamped-clamped structure. The switching time of the serpentine structure is 45 µs and the clamped-clamped structure is 80 µs.

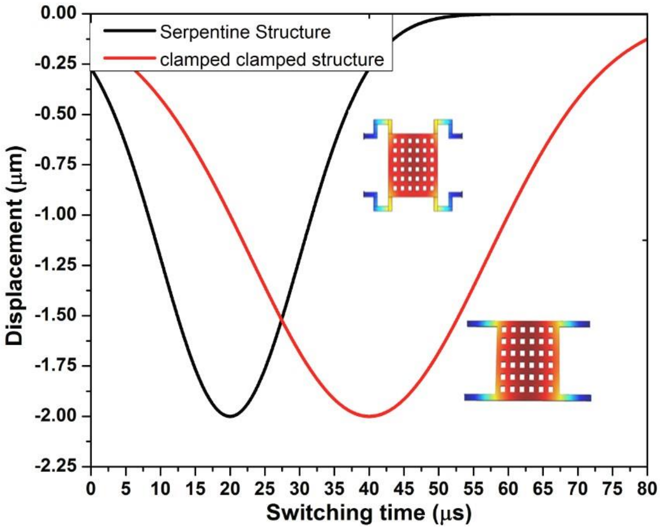


Fig. 7. Switching time (t_s) of the clamped-clamped and serpentine structures.

4.6. Material analysis

The shunt capacitive switch micro machined by deposition of different thin films, i.e., electromagnetic lines, dielectric thin film, membrane thin film on the substrate. The proper selection of the materials for these thin films helps to improve the performance. The serpentine membrane shown in Fig. 6, electrostatic actuation performance is analysed with different membrane materials, i.e., Al, Au, Ag, Cu, Cr, and W.

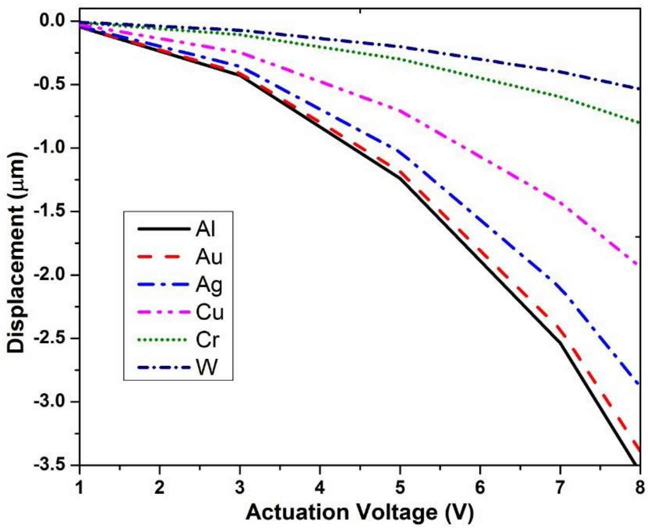
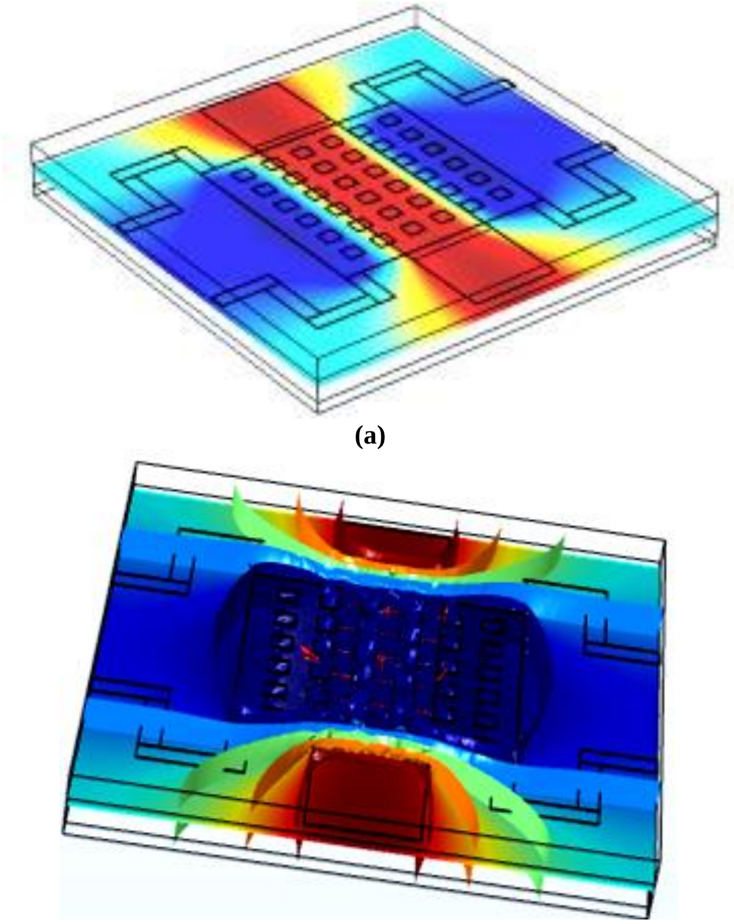


Fig. 8. Serpentine membrane material analysis.

The serpentine membrane material analysis revealed that the Al is offering low actuation voltage compared with the other metals, i.e., Au, Ag, Cu, Cr, and W. Light weight material deforms for less external force, here Al is a lightweight metal compared with the others, so it deformed for low actuation voltage. The shunt capacitive switch performance relies on the capacitance offered by the switch when membrane in up and down state. Here we have performed the capacitance analysis by choosing different dielectric material, i.e., HfO_2, AlN, ZnO, Si_3N_4, Al_2O_3, SiO_2.

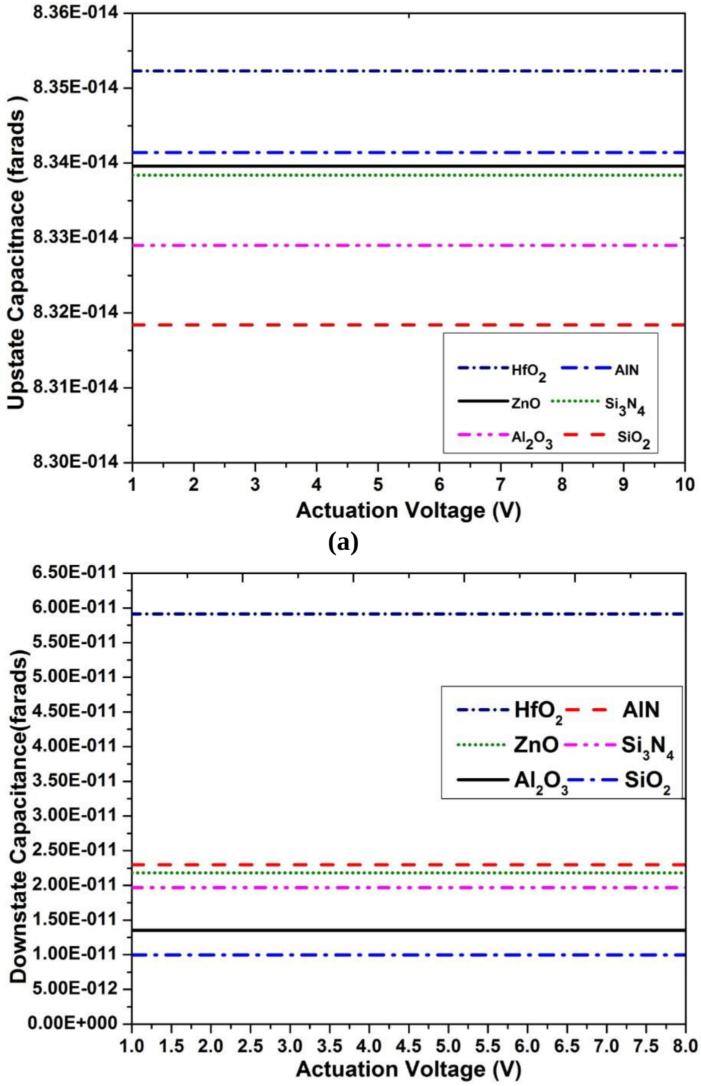


(a)

(b)

Fig. 9.Switch capacitance analysis,
(a) Electrostatic analysis, (b) fringing fields.

When no actuation voltage applied, the micromechanical membrane is in upstate, and the capacitance presented by the switch is known as the upstate capacitance. If the applied actuation voltage is above the pull-in voltage the membrane will deform and come to down state, and the capacitance presented by the switch is known as the downstate capacitance. The Radio Frequency(RF) properties, i.e., insertion losses and the isolation losses are completely depending on the up and down capacitance of the switch. The dielectric material analysis with different materials, i.e., HfO_2, AlN, ZnO, Si_3N_4, Al_2O_3 and SiO_2 revealed that high relative permittivity material offers great performance in terms of capacitance. The relative permittivity of the HfO2 is 25, and the up- capacitance is 83.52 fF and down- capacitance is 60 pF.



(a)

(b)

Fig. 10. Dielectric material capacitance analysis, (a) upstate capacitance, (b) downstate capacitance.

Table 3. Dielectric material capacitance analysis.

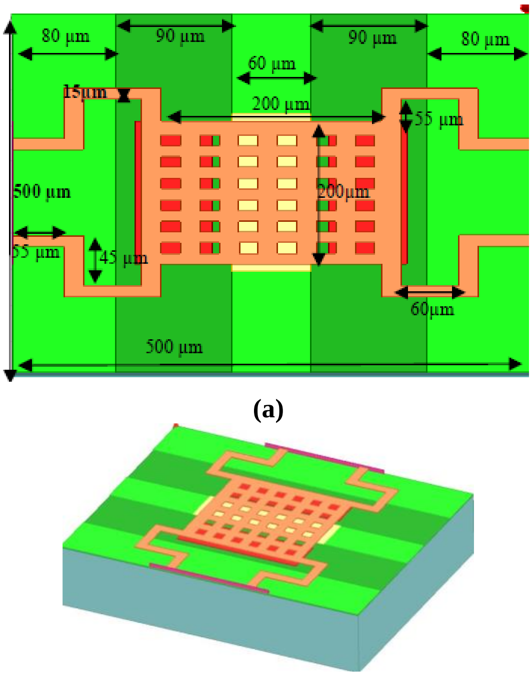
Material	Relative permittivity	Upstate capacitance (farads)	Downstate capacitance (farads)
HfO_2	25	8.35×10^{-14}	5.91×10^{-11}
AlN	9.8	8.342×10^{-14}	2.30×10^{-11}
ZnO	9.7	8.339×10^{-14}	2.18×10^{-11}
Si_3N_4	9.6	8.336×10^{-14}	1.97×10^{-11}
Al_2O_3	5.7	8.33×10^{-14}	1.35×10^{-11}
SiO_2	4.2	8.32×10^{-14}	0.98×10^{-11}

Prior performance analysis on shunt capacitance switch in terms of structure, material is revealed so many techniques, i.e., serpentine structure is offering low actuation voltage when compared with clamped-clamped structure, Al like lightweight materials also helps to improve the actuation voltage and the high relative permittivity material like HfO_2 as dielectric material helps to advance the capacitance ratio. By incorporating these all in the switch defiantly performance of the switch improves.

5. Proposed Model

Eventually we have designed a performance improved shunt capacitive switch on silicon substrate. Serpentine structure with non-uniform meanders designed with Al with 0.7 µm thickness. The membrane is perforated with 15 µm × 15 µm size square holes which helped to reduce the actuation voltage. HfO_2 with relative permittivity (ε_r) of 25 is used as a dielectric material. By incorporation all the techniques revealed in the performance analysis in terms of structure and the material sure the overall performance is improved significantly. The coupled simulation is used in FEM tool with solid-mechanics and the electrostatic multi-physics. The spring constant, and membrane mass parameters are transferred between the physics. Extra fine meshing is used for better accuracy.

The switches design typically involves step by step deposition of different thin films, i.e., substrate, dielectric, and membrane thin film. Unlike previous designs, in this paper we are doing prior material analysis which helps to identify suitable material for different thin films. Completely the switch is micro machined on silicon substrate and 1µm thickness SiO_2 is place in between substrate and CPW lines as an insulating layer.



(a)

(b)

Fig. 11. Serpentine membrane switch, (a) top view, (b) side view.

Table 4. Dielectric material capacitance analysis.

Parameter	Material	Length×width×thickness in μm
Substrate	Si	500×500×800
Insulator	SiO_2	500×500×1
CPW	Au	100×80×100
Dielectric	HfO_2 (ε_r=25)	220×80×0.05
Air Gap	-	2
Membrane	Al	2

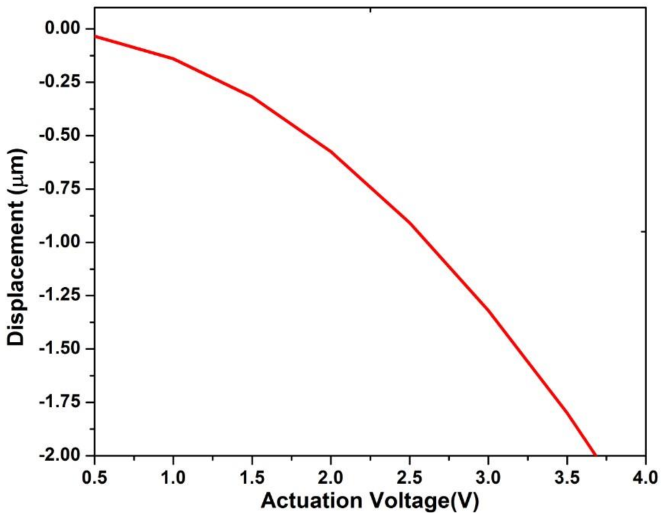


Fig. 12. Al 0.7 μm thickness membrane, actuation voltage (vs) Displacement.

If the applied DC voltage is below the pull-in voltage the micro mechanical membrane is in upstate, the RF signal is completely permitted to the output, so the switch is offering low insertion of -0.55 dB @ 23 GHz as shown in Fig. 13.

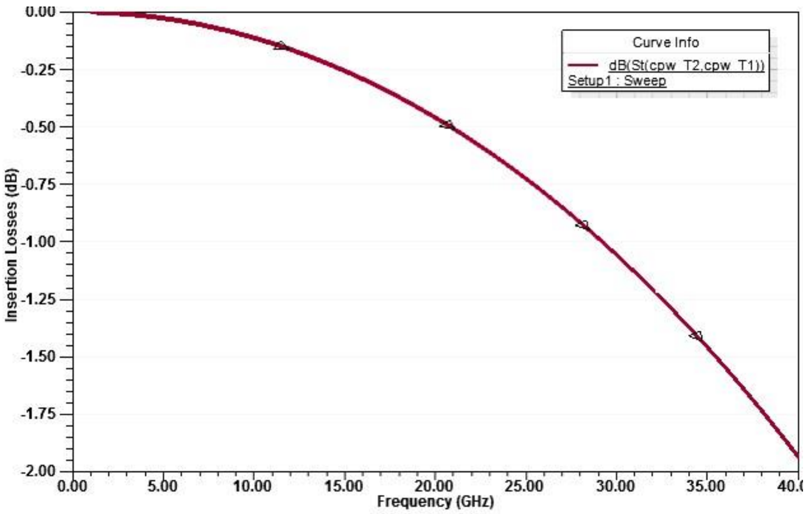


Fig. 13. Insertion Losses (dB).

The perforation to the membrane helps in uniform distribution of electrostatic force as shown in Fig.14. When the applied DC voltage is above the pull-in voltage, the structure will get deform and it will come to downstate as shown in Fig.15.

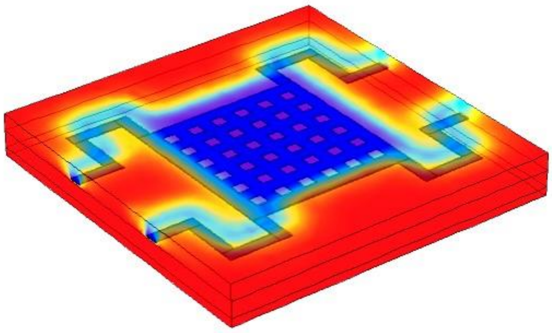


Fig. 14. Load distribution in non-uniform meander serpentine flexures.

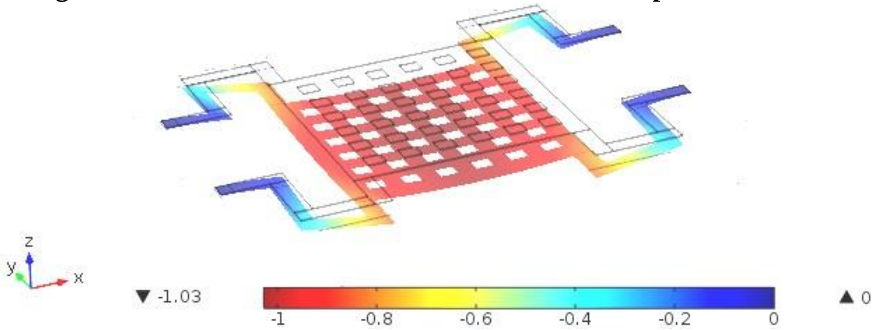


Fig. 15. Membrane is in downstate.

When the micromechanical structure is in down state the switch will offer high isolation of -51dB at 23 GHz. And the switch is offering an up-capacitance of 83.5 fF and the down-capacitance of 59.1 pF.

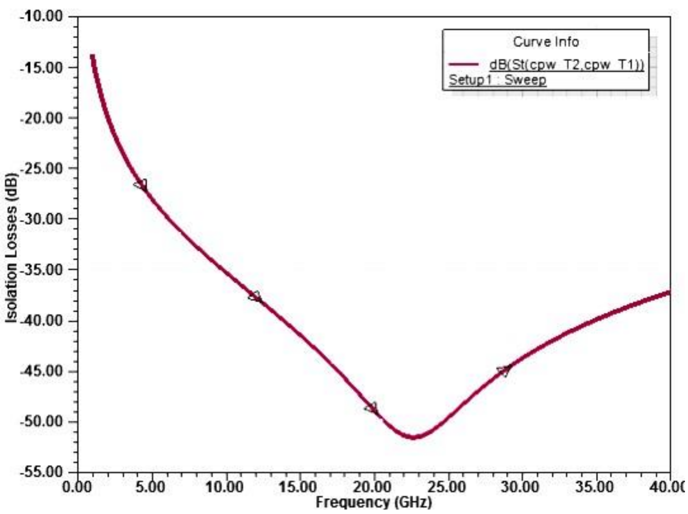


Fig. 16. Isolation losses (dB).

Eventually we have extracted most of the performance deciding parameters of the shunt capacitive switch and try to compare the theoretical and simulated values. Here the simulated results are near to the theoretical values. The mass of the serpentine structure is 783×10^{-12} kg. The serpentine structure with non-uniform meanders offered a low spring constant of 1.79 N/m. The Eigen frequency (or) natural frequency (or) resonant frequency is 7.445 kHz. The switch requires 3.68 V actuation voltage for 2 μm membrane downward deformation which created hope on possibility of integration of switches with IC technology. The novelty in the designed RF MEMS switch is incorporation of non-uniform meander based serpentine structure and high relative permittivity offering dielectric thin films. Because of this incorporation the switch performance is improved significantly.

Table 5. Dielectric material capacitance analysis.

Parameters	**Serpentine with non-uniform meander**	
	Theory	**Simulation**
Mass (m)	783×10^{-12} kg	783×10^{-12} kg
Spring constant (k)	2.07 N/m	1.79 N/m
Resonant frequency (f_r)	7785 Hz	7445 Hz
Actuation (V)	3.95 V	3.68 V
Upstate capacitance(C_{up})	80.39 fF	83.5 fF
Downstate capacitance (C_{down})	56.21 pF	59.1 pF

The major finding of this work is, because of incorporation of Al based serpentine membrane the required actuation voltage is reduced to 3.68 V. HfO_2 dielectric material, with high relative permittivity the switch is offered high capacitance ratio. Because of high capacitance ratio the switch offers high isolation of -51 dB.

Table 6. Dielectric material capacitance analysis.

Parameter	**[20]**	**[21]**	**Our work**
Mass (m)	---	---	783×10^{-12} kg
Spring constant (k)	---	---	1.79 N/m
Resonant frequency (f_r)	---	---	7445 Hz
Actuation Voltage	19.2 V	25.2 V	3.68 V
Upstate capacitance(C_{up})	22 fF	---	83.5 fF
Downstate capacitance(C_{down})	2.21 pF	---	59.1 pF
Insertion Losses (dB)	- 0.05 dB	- 0.1dB	- 0.55 dB
Isolation Losses (dB)	-12dB @ 61.5 GHz	-40 dB @ 11 GHz	-51 dB

6. Conclusions

Prior performance analysis with respect to structure and material definitely helped to improve the performance of switch. The structural analysis is performed on clamped-clamped and serpentine structures, and it is revealed that the serpentine structure is offering low actuation voltage. The material analysis is primarily aimed to select best material for the membrane and the dielectric thin films. The serpentine membrane with Al material of 0.7 μm thickness offers a low actuation voltage of 3.68 V. HfO_2 of 0.05 μm thickness is selected as a dielectric material which offers best up-capacitance of 83.5 fF and the down-capacitance of 59.1 pF. Eventually the switch offers an insertion loss of -0.55 dB and isolation of -51 dB. The designed switch is suitable for K and Ka-band applications.

Nomenclatures

C_{down}	Downstate capacitance
C_{up}	Upstate capacitance
f_r	Resonant frequency
K	Spring constant
m	Membrane mass

Abbreviations

FEM	Finite Element Method

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