Design and Simulation of low actuation voltage Cantilever RF MEMS switches suitable for Reconfigurable antenna applications

RAJI GEORGE, C R S KUMAR, S A GANGAL
Electronics Engineering Department,
Defence Institute of Advanced Technology,
Girinagar, Pune,
India.
rajigeorge2006@gmail.com

Abstract:

This paper presents a novel cantilever based RF MEMS series switch. The cantilever is of a dielectric material to prevent crosstalk and for isolation between the RF and DC signal. This switch has low actuation voltage and good RF performance in the frequency range from 2 to 12 GHz. Low actuation voltages are achieved by varying the spring constant of the beam. The spring constant of the beam can be varied by varying the geometry of the beam. We have introduced geometrical variations in the beam design that have led to low actuation voltage and good RF performance. A meander shaped beam is proposed which gives the least actuation voltage. The meanders in the beam reduce the spring constant without affecting the RF performance of the switch. The proposed design has a very low Pull in voltage of 6.64V. The RF performance of the switch shows that the Return loss is-25.65dB at 9.8GHz.The isolation is about-64.02dB and the insertion loss is about -0.2065dB at 9.7GHz.

Key- words: Reconfigurable Antenna, Cantilever, Pull in voltage, Spring Constant, meander

I. INTRODUCTION:

Antennas are a critical component of all personal electronic devices, microwave and satellite communication systems, radar systems and military surveillance. In many systems there is a requirement to perform various functions across several frequencies. Reconfigurable Antenna has been developed as the new type of Antenna Technology.[1]Reconfigurable Antennas can change their radiation properties like frequency, polarization or radiation pattern by redistributing the RF currents over its surface. Thus, they can be used in communication systems where multiple antennas can be replaced by a single reconfigurable antenna. Reconfiguration can be achieved by physically or electrically modifying the antenna dimensions using RF switches, impedance loading or tunable materials. [2]

The switches that are used for reconfiguration are radio frequency (RF) micro electro mechanical systems (MEMS) switches, FETs or PIN diodes. RF MEMS switches have better switching characteristics like very low insertion loss, very low power requirements and high isolation which cannot be attained by using semiconductor switches.

MEMS is an integration of mechanical elements and electronics on the same substrate using the micro-fabrication technology.[3]The design of the RF MEMS switches depends on their usage as a series or a shunt switch and on its movement lateral or vertical. They could be metal to metal contact or capacitive and could be actuated by electrostatic, magneto-static, piezoelectric or thermal actuation.[4] A MEMS switch is either implemented as fixed- fixed beam or cantilever beam structure.[5] MEMS cantilever switches are popular due to its low cost and easy fabrication. The Cantilever switches suitable for Reconfigurable circuits are generally made of silicon (Si), silicon nitride (SiN) or polymers [6].

In this paper, Cantilever based RF MEMS switches which could be used with Reconfigurable circuits are designed and simulated. The aim of this study is to evaluate the effect of beam geometries on the actuation voltage. A novel design is proposed for the cantilever design which gives the least actuation voltage with good RF characteristics.

II. LITERATURE REVIEW

A. Reconfigurable Antenna:

In this paper, cantilever switches for frequency reconfiguration in antennas are designed. A frequency reconfigurable antenna can dynamically adjust its frequency. Frequency reconfiguration can be achieved by using switches. Switches are an integral part of reconfigurable antennas.Fig.1 shows the structure of a reconfigurable dual patch antenna with RF switch. The structure operates at a frequency of f1 when the switch is OFF and at a frequency of f2 when the switch is ON. Thus, the resonating frequency depends on the length of the patch. Thus the length and size of the patch are determined by the status of the switch.

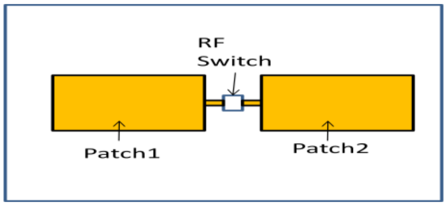


Fig. 1 Frequency Reconfigurable Dual Patch Antenna

B. RF MEMS switch:

RF MEMS switches are an attractive solution to reconfigurable antennas. The remarkable advantages of RF MEMS switches over the semiconductor switches are low loss, high isolation, near zero power consumption, lack of inter-modulation and easy integration. Fig 2 shows the structure of Cantilever based RF MEMS switch.

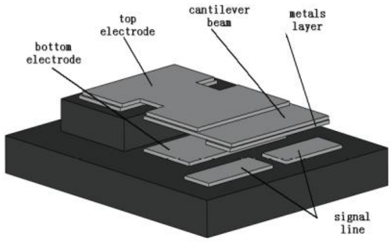


Fig. 2 Structure of Cantilever based RF MEMS switch

The switch structure has a cantilever beam that is fixed at one end and suspended above a gap in the signal line at the other end. The free end is layered with metal on the bottom part for connecting the signal line. When a bias voltage is applied between the top and the bottom electrode the electrostatic force will pull the cantilever down. As the actuation voltage overcomes the threshold voltage the cantilever snaps down on the signal line and connects the gap. [7]

III. RF MEMS SWITCH DESIGN

Conventional Cantilever Beam Structure:

i. Switch Design and Analysis

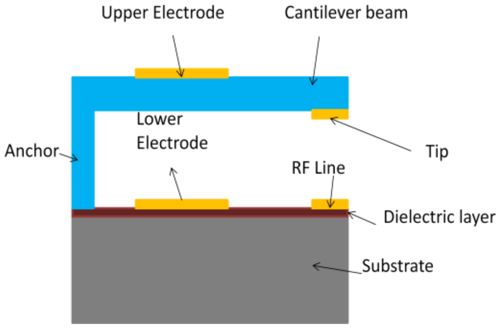


Fig. 3 (a): Schematic view of the conventional cantilever beam switch in open condition

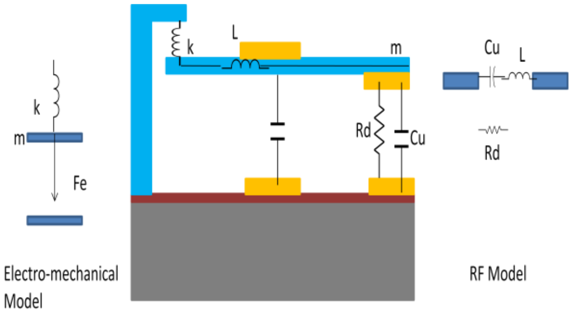


Fig. 3(b): Cantilever Beam modeled as a spring mass system and as RF model

The cantilever beam is modeled as a mass-spring system as shown in Fig 3(a) and Fig.3(b). The spring constant of the beam is represented by the following equation (1)

$$k = \frac{32Et^3w}{l^3} + \frac{8\sigma(1-v)tw}{l} \quad (1)$$

Where, E is Young's Modulus, t is beam thickness, l is beam length, w is bean width, σ is the residual tensile stress, ν is the Poisson's ratio.[8]The beam is actuated by an electrostatic force. The electrostatic force is defined as a function of the capacitance between the upper and lower electrodes and the bias voltage

$$F = \frac{QE}{2} = \frac{CVE}{2} = \frac{CV^2}{2(g+\frac{t_d}{\epsilon_r})} = \frac{\epsilon AV^2}{2(g+\frac{t_d}{\epsilon_r})^2} \quad (2)$$

Where V, g and C are the actuation voltage, gap height and capacitance between the lower and upper electrode, ϵ_r is the dielectric constant of the dielectric material above the lower electrode (shown in fig1), ϵ is dielectric constant of air. When the actuation voltage is applied, the beam is pulled down with the force which is distributed across the beam. The voltage at which the beam bends is given by the pull in voltage.

$$V_{PI} = \sqrt{\frac{8\,\mathrm{k}\,\mathrm{g_0}^3}{27\,\varepsilon_r\,\mathrm{A}}} \quad (3)$$

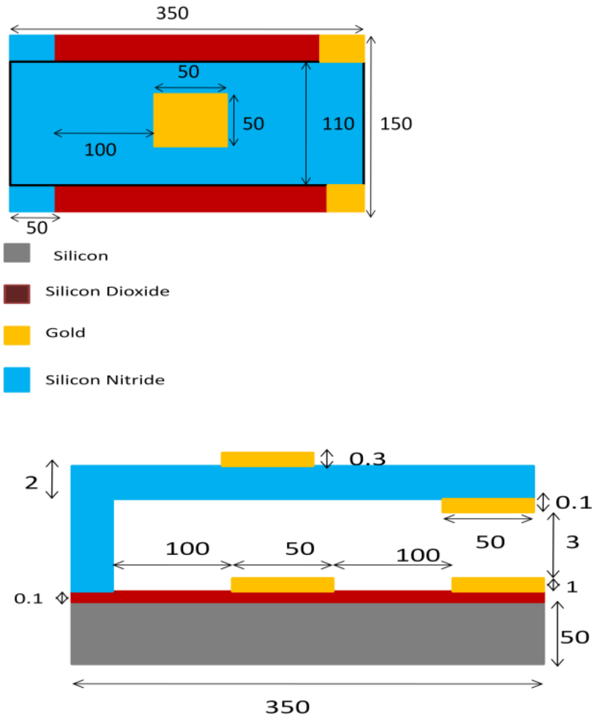
From equation (3) it is observed that the pull in voltage of the structure depends on gap between the cantilever and the actuating electrode, area of the actuating electrode and spring constant of the beam.

A range of different optimizing techniques is available for RF MEMS switches. One of the important parameter is the Pull in Voltage. . Wang et al. [9] studied the Pull in voltage optimization of the cantilever MEMS switch via beam shape and dimension. Spasos et al. [10] proposed actuation pulse optimization of RF MEMS switch by using Taguchi's method.

In this paper the optimization of the Pull in voltage is achieved by changing the beam geometry of the conventional beam structure. The simulations and optimization of the cantilever structure was performed using CoventorWare software. [11]

ii. Switch Model and Simulation

The proposed switch consists of a Silicon substrate with 50µm thickness with a relative dielectric constant of 11.6.A 0.1 µm thick layer of Silicon dioxide is grown on the Silicon substrate. A Coplanar Waveguide (CPW) is designed using 1 µm of Gold. A cantilever beam of Silicon Nitride is suspended above the signal line with a gap height of 2µm.



All the dimensions are in µm

Fig. 4(a), 4(b): Dimensions of the Conventional Cantilever beam switch structure

Fig. 4(a) and (b) shows the dimensions of the switch. This switch design is simulated in CoventorWare which gives the Pull in Voltage as 56.64V.

The Conventional Cantilever Beam structure is optimized for minimum pull in voltage. The Simulation is done using CoventorWare software.

The optimized Dimensions of the Conventional Cantilever beam are given in Table .1 for a pull in voltage of 56.64V

Parameters	**Values(μm)**
Cantilever Beam Length	350
Cantilever Beam width	110
Cantilever Beam Thickness	2
Air gap	2
Young's Modulus(Silicon nitride)	310
Poisson's ratio	0.27

Several beam geometries are incorporated in the conventional cantilever series switch design for the optimization of Pull in Voltage.

The following are the Beam structures designed and simulated for reduced Pull in voltage.

From equation (3) it is observed that the Pull in voltage of the structure depends on the gap height, the area of the actuating electrodes and the spring constant of the beam.

The spring constant of the beam depends on the various factors such as the structural shape of the beam, thickness, residual tensile stress and material properties such as Young's Modulus and Poisson's ratio. [13].

To decrease the actuation voltage of RF MEMS switches several methods were adopted such as:

a) Increase in area of electrostatic field
b) Decrease in air gap leads to increase in OFF state capacitance and thus leading to low switch isolation..
c) Reducing the equivalent spring constant

The actuation voltage is dependent on the spring constant k. The spring constant can be varied by varying the structure and materials without affecting the performance of the switch. Thus, the material used to build the cantilever beam, the shape of the beam and size of the anchors affects the spring constant of the beam

IV. DESIGNS FOR REDUCTION OF ACTUATION VOLTAGE:

The following are the Beam structures designed and simulated for reduction in mass of the beam which results in reduced Pull in voltage.

A. Beam with grooves

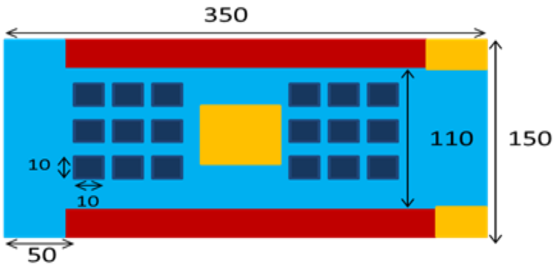


Fig. 5 Layout of the beam with grooves.

Fig. 5 shows the layout of the beam with grooves. The grooves are introduced in the beam structure. The grooves reduce the mass of the beam and eventually reduce the spring constant. The outer dimension of the cantilever beam is kept the same as that designed for the conventional cantilever.

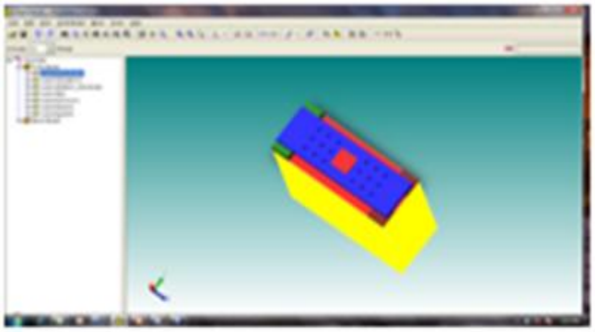


Fig. 6: Model of beam with grooves in CoventorWare

Fig. 6 shows the model of the cantilever beam with grooves in CoventorWare.

B. Beam with Holes

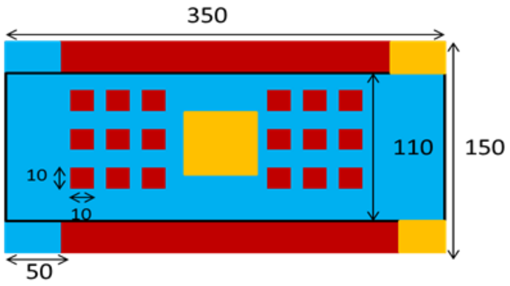


Fig 7. Layout of the beam with holes

Fig.7 shows the layout of the cantilever beam with holes. The holes are introduced in the beam to reduce the beam mass, to enhance the release of the beam by sacrificial layer removal, reduce the squeeze film effect, increase the switching speed and cause reduction in residual stress.

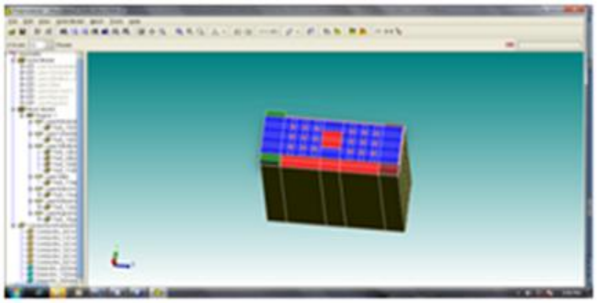


Fig. 8: Model of the beam with holes in CoventorWare

Fig. 8 shows the model of the beam with holes in CoventorWare.In this design the cantilever beam is patterned with 10µmx 10µm holes. These holes are called release etch holes. The outer dimensions of this design are the same as the conventional cantilever designed.

C. Beam with splits

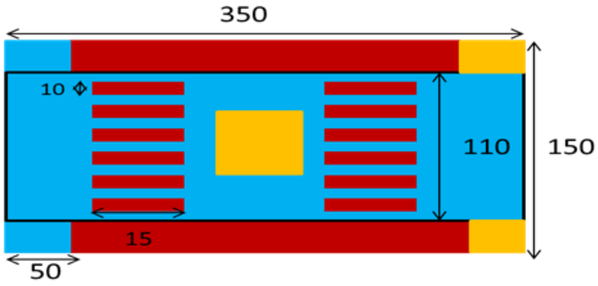


Fig 9: Layout of beam with Splits

Fig. 9 shows the layout of the Beam with splits. The design of this switch was done using splits in the beam in rectangular shape. The cantilever outer dimensions are the taken the same as the designed conventional cantilever .The cantilever was split into six strips each having a width of 10µm and a gap of 10µm.The splits are introduced in the design to reduce air damping as well as for the ease of the sacrificial layer removal.

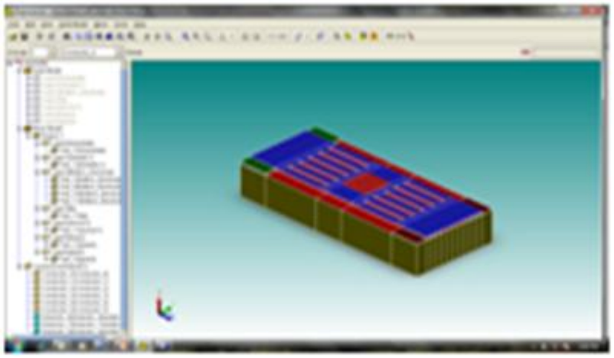


Fig. 10 Model of beam with splits in CoventorWare

Fig. 10 shows the model of the cantilever beam with splits in CoventorWare software.This design in comparison with the design with holes has the advantage of low stress at the anchor junction, higher spring constant and higher mechanical resonant frequency, making it more robust to the environmental effects and ease in structure release due to continuous large gap for etchant percolation.

D. Beam with flexures

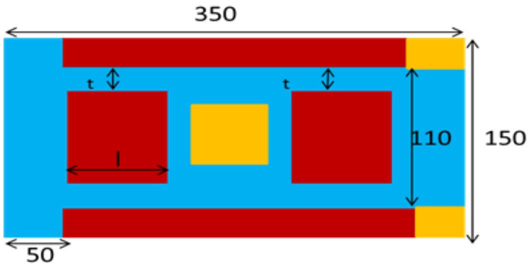


Fig.11 Layout of the beam with flexures

Fig 11 shows the layout of the beam with flexures. The flexures introduced in the beam .The spring constant of this beam structure is given by

$$k_z = 4\ E\ w \left(\frac{t}{l}\right)^3 \ldots..(4)$$

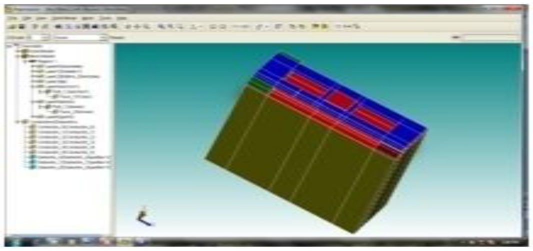


Fig 12: Model of Beam with Flexures in CoventorWare

Fig.12 shows the model of the cantilever beam with flexures in CoventorWare. The width t of the beam was analyzed for 10 µm and 30 µm. It is observed that the Pull in voltage is 41.015V for flexure with width 30 µm and 12.109V for flexure width of 10 µm. The outer dimension of the beam is kept same as the designed conventional beam.

E. Butterfly shaped Beam

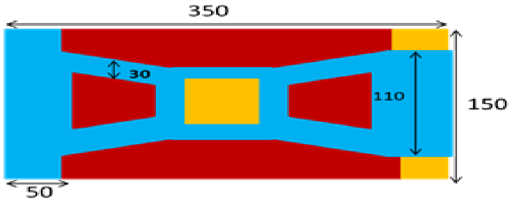


Fig. 13: Layout of Butterfly shaped Beam

Fig. 13 shows the layout of the butterfly shaped beam. The flexures are of width 30 µm. The butterfly shaped structure gives a lower Pull in voltage of 30.859V compared to the beam with rectangular flexures.

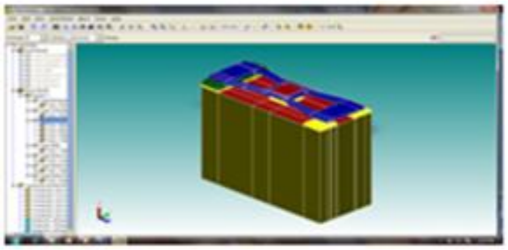


Fig. 14 Model of Butterfly shaped Beam in CoventorWare

Fig. 14 shows the model of the cantilever butterfly shaped beam in CoventorWare software

F. Meandered Beam:

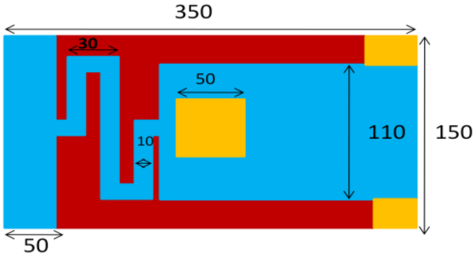


Fig 15: Layout of beam with meanders

Fig. 15 shows the layout of the meandered cantilever beam. Meander structure resembles the properties of spring in real world which provides reduction in spring constant to a great extend.

The spring constant of the meandered beam is given by

$$k_z=[\frac{(8N^3a^3)+2Nb^3}{3EI_x}+ abN[3b+2N+14N+1a3GJ-Na2[2Na EIx+2N+1bGJ1]22(aEIx+bGJ)-Nb3 2(aGJ+bEIx)]-1. \quad (5)$$

Where N is the no. of meanders, a is the primary meander length and b is secondary meander length.[13,14]. The torsion modulus G is given by the equation G=$\frac{E}{2}(1+\gamma)$.The axis moment of inertia is denoted by the equation $I_z = wt^3/12$.The torsion constant J is given by J=0.413xI_p where $I_p is$ polar moment of inertia denoted by $I_p = I_x + I_z$.The total spring constant is given by k=mk_z where m is the number of serpentine arms.

Table 2 shows the dimensions of the meander structure.

Parameters	Values(µm)
Primary Meander length(a)	30
Secondary Meander Length(b)	10
Thickness	2
Width of the beam	110
Air gap	2
Young's Modulus(Silicon nitride)	310
Poisson's ratio	0.27
Torsion constant J	0.413Ip

Table 2 Dimensions of the meandered beam

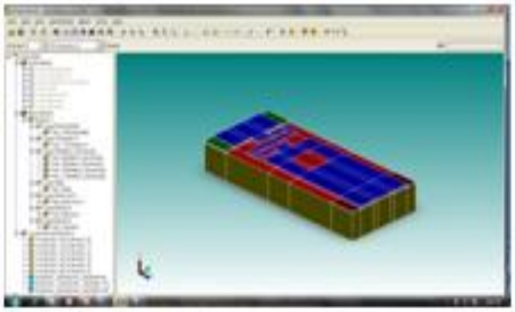


Fig. 16 Model of beam with meander in CoventorWare

Fig. 16 shows the model of the beam with meander in CoventorWare software.

V. COMPARISON

Table 3 shows simulated results of the Pull in voltage of the various beam geometries..

Beam Type with	Pull in Voltage
Conventional	56.640
Grooves	23.828
Holes	12.109
Split	41.015
Rectangular flexure (30µm)	30.859
Rectangular flexure (10µm)	26.171
Butterfly shaped	44.140
Meander	11.328

Table 3. Pull in voltage of the various beam geometries

It is observed from the Table. 3 that the Pull-in voltage is minimum for the meander shaped beam i.e. 11.328V.

VI. PROPOSED DESIGN:

It is concluded from the previous Section V that the Cantilever Beam with the Meander Structure gives the Minimium Pull in Voltage compared to the other geometries thus we have proposed a Novel Beam structure with Meanders.

The Proposed beam design is as shown the Fig. 17.It is a meander shaped beam with splits. The meander structure causes reduction in spring constant. The meander structure causes change in the width of the beam. But this structure also reduces the strength of the structure .This may cause breaking of the beam. To avoid breaking of the beam the mass of the beam needs to be reduced.

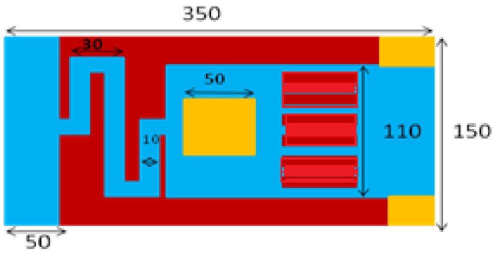


Fig. 17: Layout of the proposed design

To reduce the mass of the beam we introduce a split beam structure. The split beam gives it low stress, high spring constant, higher mechanical resonant frequency and better release and etching of the sacrificial layer.

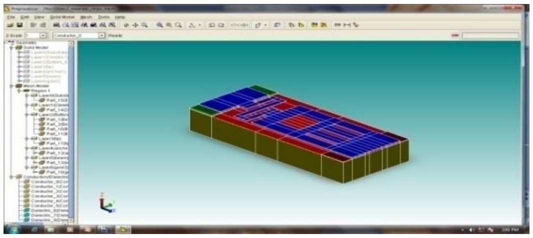


Fig. 18 Model of the proposed design in CoventorWare

Fig. 18 shows the model of the switch in CoventorWare Software.

The Proposed Design of the RF Switch designed in VCoventorWare has a substrate of Silicon with a thickness 400µm .The cantilever beam is of Silicon Nitride of length 350 µm, width 110 µm and thickness 2 µm. The air gap is 2 µm. The outer dimensions of the proposed design are same as the conventional beam structure. Table.4 gives the dimension of the proposed switch structure.

Parameters	**Values(**µm)
Primary Meander length(a)	30
Secondary Meander Length(b)	10
Thickness	2
Width of the beam	110
Air gap	2
Young's Modulus(Silicon nitride)	310
Poisson's ratio	0.27
Torsion constant J	0.413Ip
Split Length	30
Split Width	10
No. Of Splits	3

Table 4: Dimensions of the Proposed Switch

VII. RESULTS AND DISCUSSION

A. Electromechanical Characteristics

The electromechanical analysis of the switch structure is done using CoventorWare Software. For the proposed beam structure the actuation voltage is found to be 6.64V from simulation result. The pull in voltage reported by Z. Wang, et al is 57.6V [16] and by is Mohammadmahdi Vakilian , et al is 23 V [17]. Fig 7 shows the mechanical design and analysis of the proposed switch at different actuation voltages. It is observed that the actuation voltage of the proposed design is very less compared to the other beam geometries.

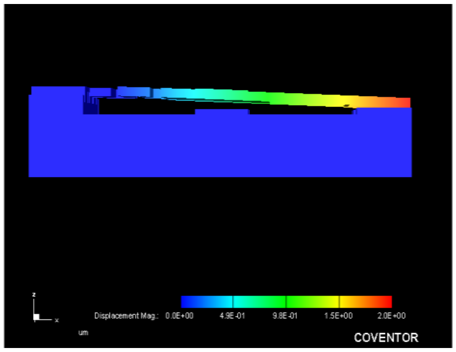


Fig. 19: Actuation Voltage of the Proposed Design 6.64V

B. RF Characteristics

The RF characteristics of the RF MEMS switch are analyzed using HFSS software. Fig. 20 shows the layout proposed design in HFSS. The Scattering parameters of the proposed structure are simulated using HFSS as shown in Fig 21-23.

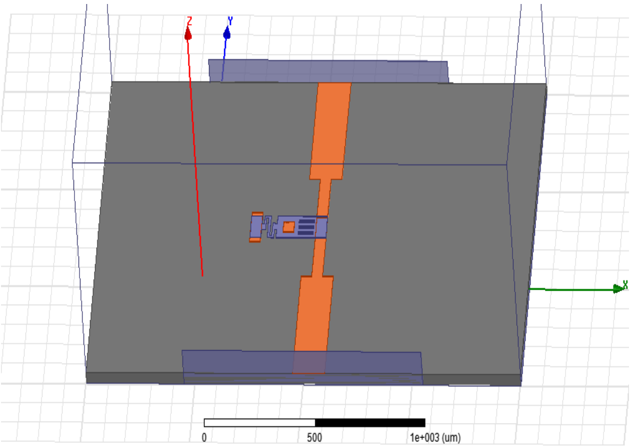


Fig 20: Simulation of the proposed switch in HFSS

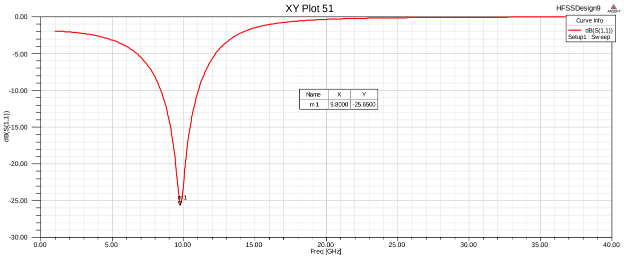


Fig. 21 Return Loss when switch is ON

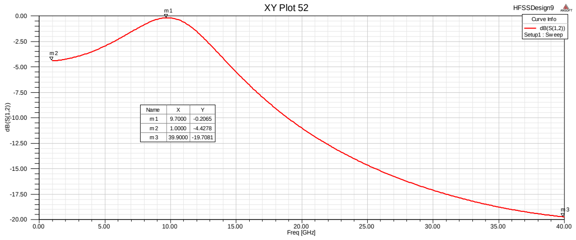


Fig 22: Insertion loss when switch is ON

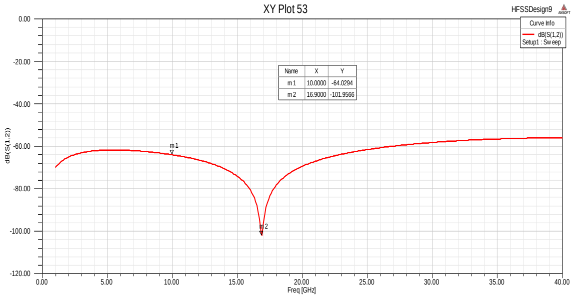


Fig. 23 Isolation when switch is OFF

The switch has insertion loss of -0.2065dB and isolation of -64.02 dB at resonant frequency of 9.7 GHz. The return loss of the MEMS switch is -25.65 at 9.8 GHz.

VIII. CONCLUSION:

In this paper, the different beam designs are compared and a new design is proposed which gives a low actuation voltage keeping the RF performance of the switch the same. The proposed design has a pull in voltage of 6.64 V which is very low compared to the other beam geometries for the same outer cantilever dimensions. The RF characteristics show that the switch provides good isolation and less insertion loss. It should also be noted that the RF characteristics of all the beam geometries remain the same due the same dimensions of the contact bar and the beam. The actuation voltage of the switch is thus dependent on the switch geometries, material of the switch and the spring constant.

ACKNOWLEDGEMENT:

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