

Design and Analysis of Shunt Configuration-Based RF MEMS Switch

G V Ganesh, K Srinivasa Rao

Abstract: In this paper a shunt type RF MEMS switch design and analysis for tunable applications is presented. Switch works based on the electrostatic actuation principle. Theoretical calculated Switch parameters are compared with the electromechanical and electromagnetic simulation results. The effect of various materials like conductor and dielectrics & parameters like airgap, beam width on the electromechanical parameters of the switch is analyzed to get low pull-in voltage, high switching speed, better capacitance ratio, return loss, insertion loss, and isolation loss. The switch up and down state capacitance are 40.9fF and 4.45pF respectively. Down to up state capacitance ratio of this switch is 108.69. The designed switch has an actuation voltage of 32V. RF performance is simulated from 1-10GHz. In ON state switch has return loss of -35dB, insertion loss of -0.1dB. In the OFF-state switch has return loss of -1dB and an isolation loss of -11dB.

Index Terms: Shunt configuration, Electrostatic actuation, pull-in voltage, Switching speed, Capacitance ratio, Insertion loss, Isolation loss.

I. INTRODUCTION

An incredible growth in communication field has been taken place during last few years. The next generation communication requires devices with huge bandwidth, high linearity and low power consumption. RF MEMS switches are the alternative to replace conventional switches in communication applications. These types of devices can be developed by using MEMS (Micro Electromechanical systems) technology. Among all MEMS devices switches gain an attention because of their advantages [1-10]. The advantages of these switches over the other type of switches like Pin diodes or FET switches are Extremely low power consumption, as the power consumption is low the cost for device is reduced and increase in the efficiency. Very high isolation, very low insertion loss, compact device size so, the size of the circuit is small. The fabrication techniques of MEMS devices are same as that of silicon based microelectronic circuits [11,12]. These are also manufactured by bulk and surface micromachining techniques. Many RF MEMS switches are designed and fabricated during last few years [13-15]. Many capacitive shunt switches with good

actuation voltage, insertion loss and return loss have been reported in the literature [3-6]. These are used in the applications like VCO, phase shifters, filters, power amplifiers, capacitor banks etc. Two types of switches one is shunt and another one is series [17-20]. Here we demonstrated an Electromechanical analysis of a Proposed RF MEMS Capacitive Shunt Switch. We predict the electromechanical behavior of the switch for different materials, widths and thickness of beam, and for different air gaps and different dielectric materials. Based on this behavior optimized geometrical parameters are finalized for the switch. After that we analyze the RF Performance using HFSS. The organization of the paper is as follows: Section-II, explains the design and theoretical analysis of the proposed switch. Section-III deals about the results and discussions of the switches. Section-IV concludes the paper.

II. THE PROPOSED SWITCH DESIGN AND THEORITICAL ANALYSIS

The schematic of the proposed shunt switch is as seen in fig 1. Substrate is silicon (dielectric constant 11.68) with thickness 20 μm . An oxide layer of SiO₂ (dielectric constant 3.9) with thickness 15 μm is placed on top of the substrate. A metallic membrane placed over signal line of CPW (coplanar waveguide) and two sides are fixed on the anchors placed on the ground line. A dielectric layer Si₃N₄ (dielectric constant 7) of thickness 220nm is placed on the signal line. Submit your manuscript electronically for review.

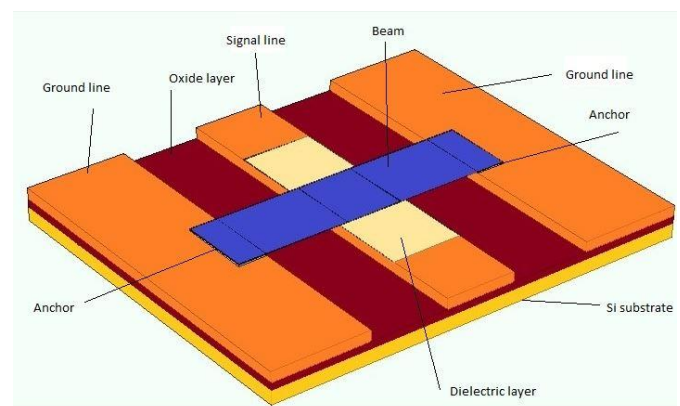


Fig. 1 Schematic of proposed RF MEMS switch.

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Typical dimensions of the proposed switch is as shown in TABLE I.

Table I
Dimensions of The Proposed Switch

S. No	Structural Element	Dimension, μm
1	Substrate thickness	20
2	Ground and Signal line thickness	15
3	Dielectric layer thickness	0.22
4	Oxide layer thickness	10
5	Bridge Length	400
6	Bridge Width	140
7	Bridge Thickness	1
8	Airgap	3

Various parameters of the switch are explained below.

A. Spring constant

For shunt switch without residual stress the spring constant [2]

$$k = 32Ew\left(\frac{t}{l}\right)^3 \quad (1)$$

for a fixed-fixed beam with residual stress the spring

$$\text{constant } k = 32Ew\left(\frac{t}{l}\right)^3 + 8\sigma(1 - \nu)w\left(\frac{t}{l}\right)$$

For the series switch the membrane is fixed at one end it does not contains any residual stress. [1]

where σ =biaxial residual stress (Pa)

ν = Poisson's ratio

w = beam width

W = width of the signal line under the beam

B. Actuation Voltage

It is calculated by using below equation [2].

$$v_p = \sqrt{\frac{8kg_0^3}{27\epsilon_0 Ww}} \quad (2)$$

Here g_0 = Air gap, ϵ_0 = free space permittivity

C. Mechanical resonant frequency

The frequency of resonance of a mechanical spring is given by [2]

$$\omega_0 = \sqrt{\frac{K}{m}} \quad (3)$$

D. Switching time

The time taken to switch from On to OFF is switching time and inverse is its speed. The switching time is given by [2]

$$T_s = \frac{3.67V_p}{V_s\omega_0} \quad (4)$$

Where V_p =pull-in voltage

V_s =supply voltage, $V_s = 1.4V_p$

E. Up-state capacitance (C_{on})

The shunt switch is demonstrated by two short sections of transmission line and a lumped model as shown in fig 2.

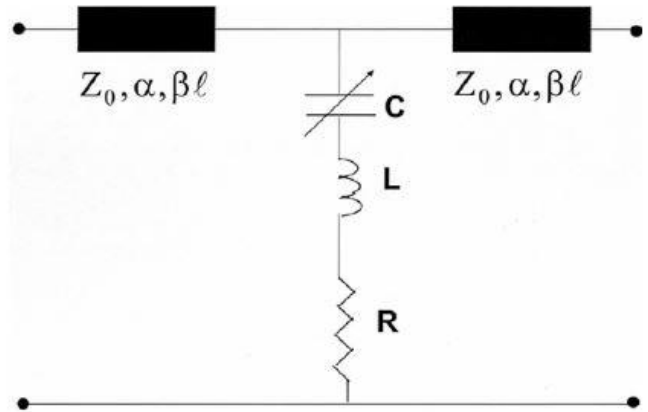


Fig. 2 LCR equivalent of RF MEMS shunt switch.

The Upstate Capacitance C_{on} is calculated as [2]

$$C_{on} = \frac{\epsilon_o Ww}{g + \frac{t_d}{\epsilon_r}} \quad (5)$$

Where, t_d = Dielectric layer thickness.

The reflection coefficient in the up state is given by [2]

$$S_{11} = \frac{-j\omega C_{on} Z_0}{2 + j\omega C_{on} Z_0} \quad (6)$$

The resonance frequency is given by [1]

$$f_0 = \frac{1}{2\pi\sqrt{LC_{on}}} \quad (7)$$

F. Down-state capacitance (C_{off})

The downstate capacitance can be calculated as [2]

$$C_{off} = \frac{\epsilon_o \epsilon_r Ww}{t_d} \quad (8)$$

G. Capacitance Ratio (C_{ratio})

The ratio of two capacitances is given by. [2]

$$C_{ratio} = \frac{C_{off}}{C_{on}} \quad (9)$$

Table II shows the theoretical parameter values of the proposed switch.

Table II
Rf Mems Shunt Switch Theoretical Values

Switch parameter	Shunt switch
Spring constant	5.53 N/m
Pull-in-voltage	18.89V
Switching time	36.64 μ s
Upstate capacitance	40.9fF
Downstate capacitance	4.45 pF
Downstate to upstate capacitance	108.69

III. RESULTS AND DISCUSSIONS

1. Electromechanical analysis of capacitive series switch

In effort to study the effect of geometric parameters on the performance of the switch, it is designed and simulated in COMSOL. Here we have taken beam width and thickness, airgap, conductor and dielectric materials as the geometric parameters. Each parameter is varied one at a time.

A. Effect of beam width

For a fixed values of beam length and thickness, fig 3 shows the displacement graphs for different beam width values. As pull-in voltage is inversely proportional to beam width, as it increase pull-in voltage decreases. Beam with 140 μ m has a lesser actuation voltage compared to 100 and 120 μ m. So, we have chosen beam width of 140 μ m.

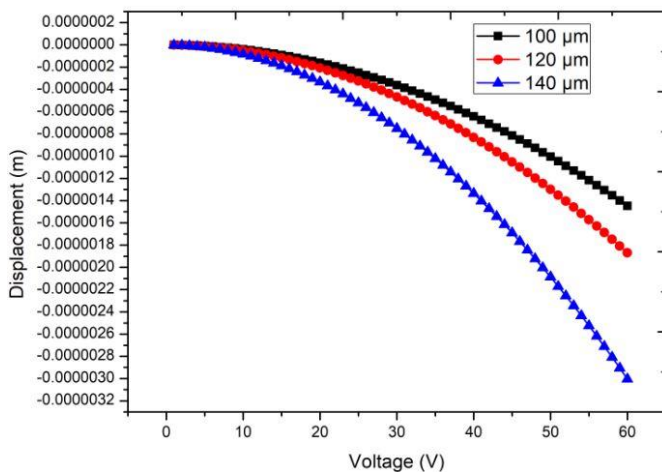


Fig. 3 Simulated displacement graphs for various beam width values.

B. Effect of airgap

Fig 4 shows the graphs for the displacement, with varied airgaps. By varying airgap from 0.5 to 3 μ m observe the displacement. As air gap decreases the voltage required reduces. But in fabrication point of view less airgap is not suggestable.

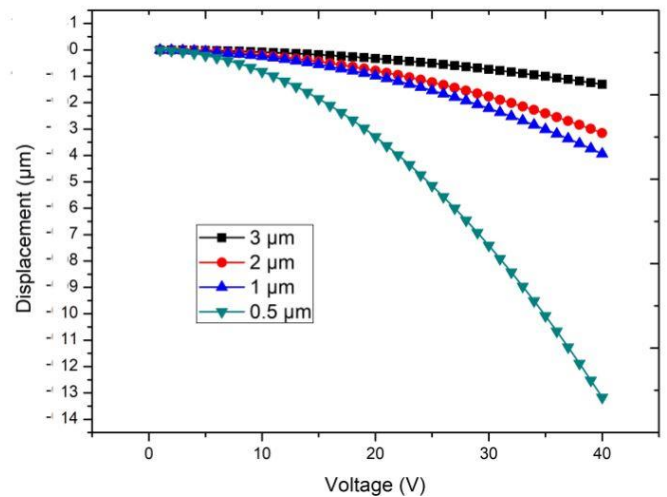


Fig. 4 Simulated displacement graphs for various airgap values.

C. Effect of beam thickness

The effect of beam thickness on actuation voltage is as shown in fig 5. It is clearly evident that with decreased beam thickness, the actuation voltage also decreases. Beam with 0.5 μ m has a lesser actuation voltage compared to 1 and 1.5 μ m.

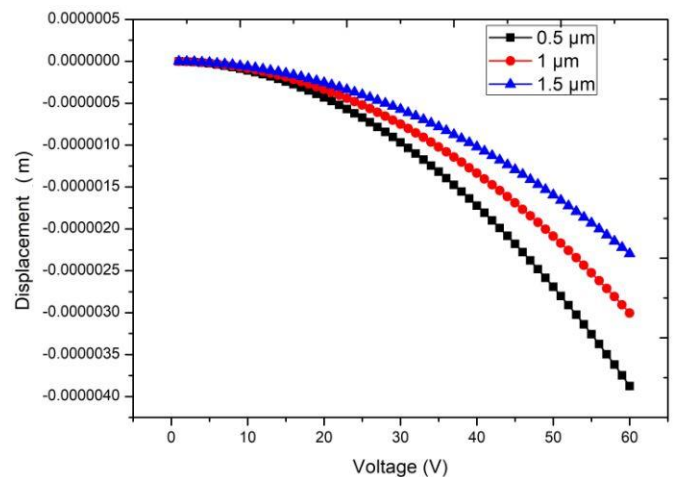


Fig. 5 Simulated displacement graphs for various beam thickness values.

D. Effect of beam and dielectric material

To get best performance of the switch proper conductor and dielectric material should be selected [16]. Out of the three conductors selected gold, shows the best displacement for smaller voltage, as shown in fig 6.

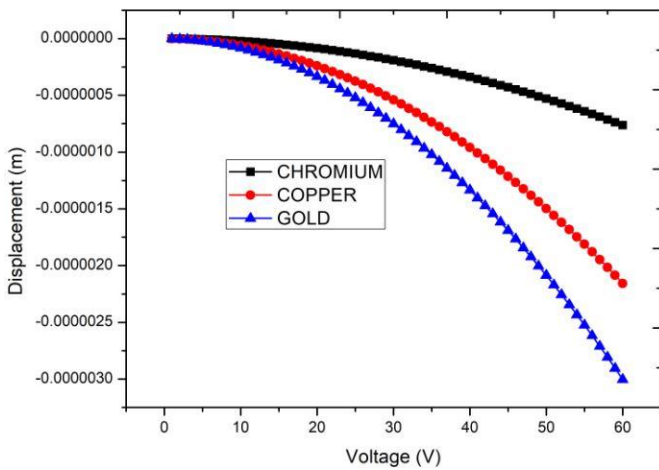


Fig. 6 Simulated displacement graphs for various conductor materials.

Out of three dielectrics selected, Si_3N_4 shows the best displacement for smaller voltage, as shown in fig 7. The remaining two are almost same displacement graphs.

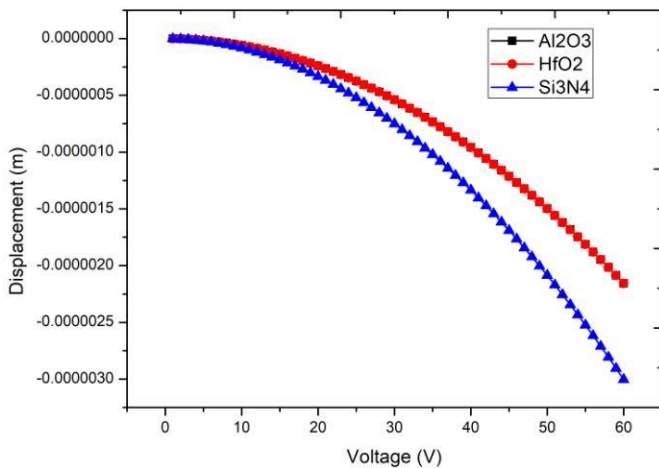


Fig. 7 Simulated displacement graphs for various dielectric materials.

E. Switching time analysis

Switching time is a function of V_p , V_s and w_0 of the switch taken from equation (4). The plot of source voltage vs switching time is as shown in fig 8. At pull-in voltage i.e. 18.89, the switching time is observed to be $36.64\mu\text{s}$.

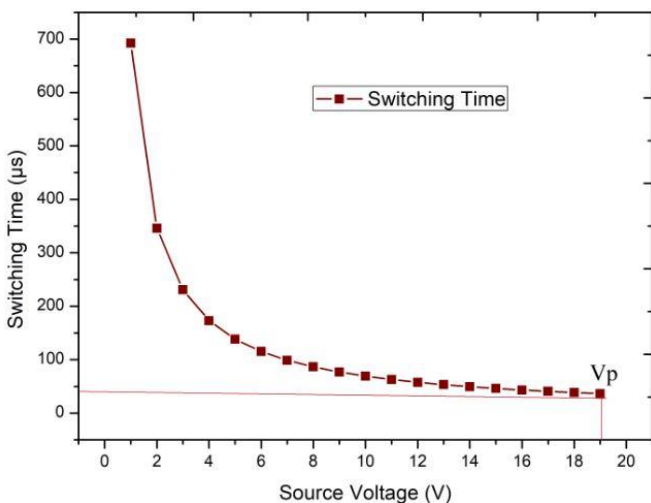


Fig. 8 Switching time vs source voltage.

F. Up and downstate capacitive analysis

Capacitance ratio is a measure of the capacitance difference between two states of the switch. Up state capacitance is relay on the dielectric thickness and relative permittivity, beam area. From the fig. 9 the upstate capacitance of 40.9pF and down state capacitance of 4.45pF obtained. So that the capacitance ratio obtained is 108.69.

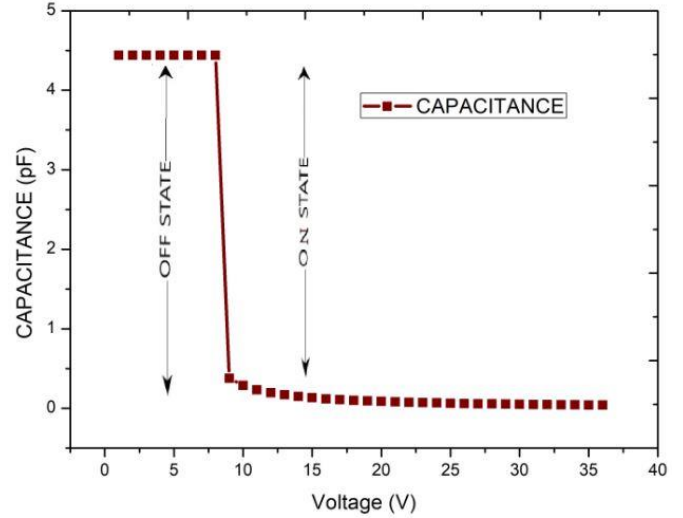


Fig. 9 Shunt switch capacitance vs voltage curve.

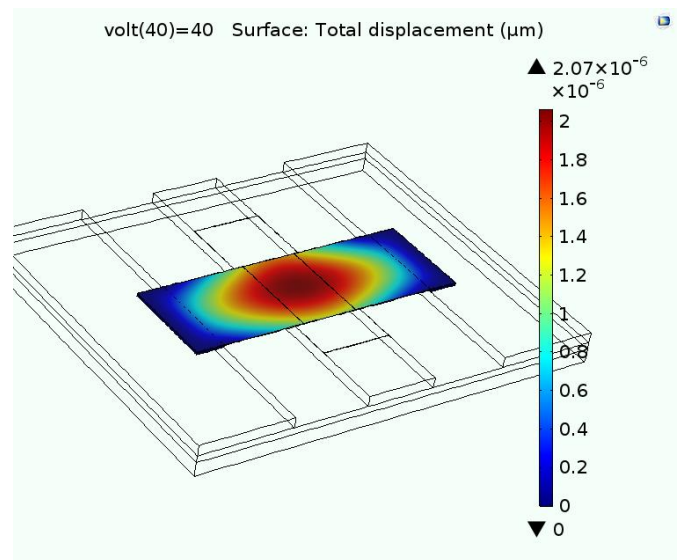


Fig. 10 Beam deflection.

2. Electromagnetic Analysis Of Capacitive Shunt Switch

Radio frequency performance analysis is done with the help of HFSS software. Insertion return and isolation are the important parameters has to be evaluated for the device for the validating switch performance. The air gap maintained in the middle of top and bottom electrode is $3\mu\text{m}$ gap having Si_3N_4 as dielectric material. the frequency range measured from 0-10GHz frequency range.

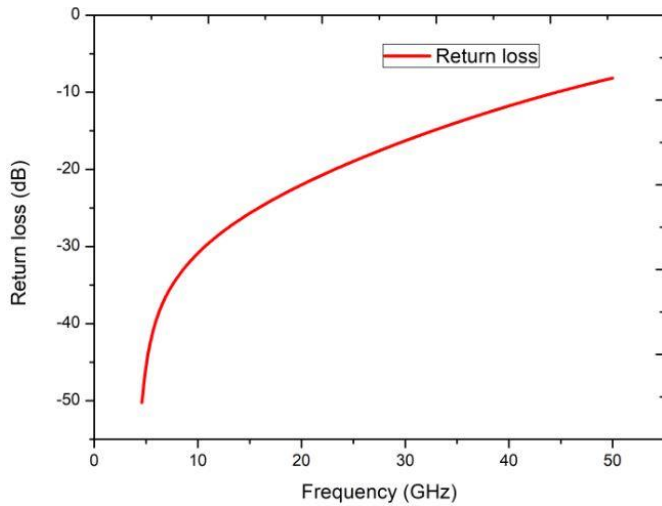


Fig. 11 Return loss (S_{11}) of shunt switch in its ON state.

The electromagnetic simulation is carried out from 0-10 GHz and analyzed the parameters. The return loss in ON condition is in the range of -5-35 dB is observed from the Fig. 11. Fig.7 shows the excellent insertion loss in ON condition is in the range of -0.01-0.5 dB.

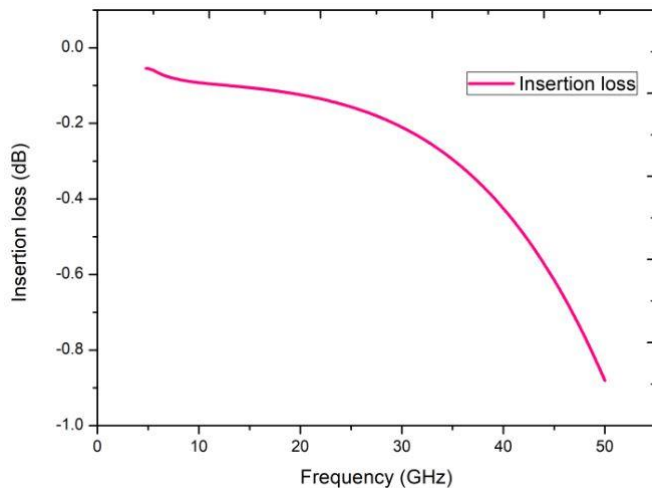


Fig. 12 Insertion loss (S_{21}) of shunt switch in its ON state.

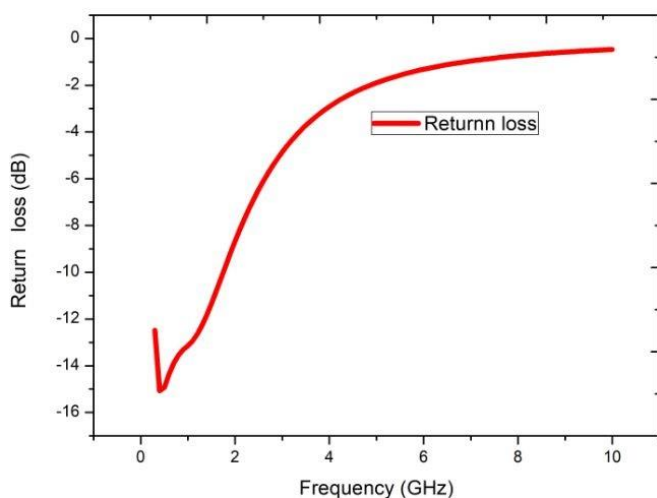


Fig. 13 Return loss (S_{11}) of shunt switch in its OFF state.

The return loss in OFF condition is in the range of -1-15 dB is observed from the Fig. 13. Fig. 14 shows the isolation in OFF state which is in the range of -1-11 dB.

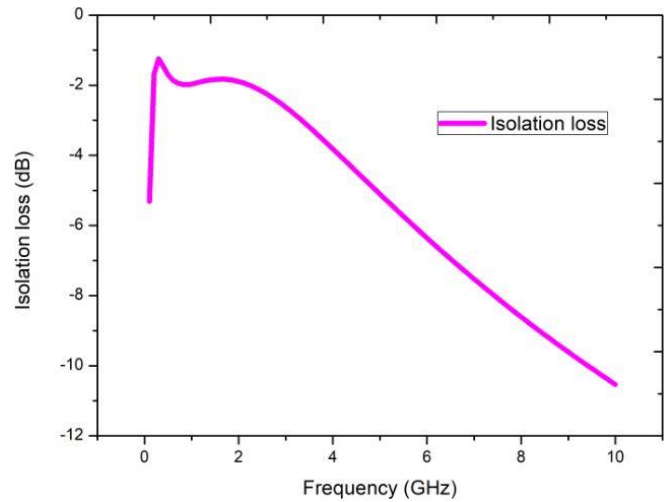


Fig. 14 Shunt switch Isolation loss (S_{21}) in its OFF state.

IV. CONCLUSION

In this paper, a shunt type RF MEMS switch electromechanical and electromagnetic analysis as a function of different parameters is presented. Switch simulated actuation voltage is 32V. As observing form the graphs, during the ON state the return loss is less than -35 dB at 10 GHz and the insertion loss is higher than -0.1 dB at 10 GHz. In the OFF state the isolation (S_{21}) is higher than -11 dB at 10 GHz for the switch. The switch has a reasonably high capacitance ratio of 108.69. The switch shows excellent RF characteristics and is highly useful in tunable filter applications.

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