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***Research paper***

# Ladder shaped RF mems switch for wireless application

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## Abstract

This paper analyses the different position of actuation electrode in an inline ladder shaped cantilever beam Radio Frequency (RF) Microelectromechanical System (MEMS) switch, which shows very good RF parameters over the range of (0-50) GHz along with low actuation voltage. The switch is designed and simulated by software Intellisuite 8.7v for electromechanical analysis and by EM software for RF analysis. From the simulated results, they obtained a low actuation voltage (2 V). It shows a very less insertion loss -0.008 dB at 8 GHz and high isolation loss –100 dB at 8 GHz.

***Keywords***: *Actuation Voltage; Cantilever Beam; Insertion Loss; Isolation Loss; RF MEMS*

## 1. Introduction

The Radio Frequency (RF) Microelectromechanical System (MEMS) switch is one of the first and most studied topic in RF MEMS technology. The advantages of these switches is that they offer RF performance similar to that of relay switches and miniaturized in size and cost as similar to FET based switches. These switches show excellent linearity, low power consumption, good return loss, low insertion loss, high isolation loss, wider temperature range etc [1]. But the major areas of concern with RF MEMS switches are its high actuation voltage, less switching time, packaging, low power handling capacity and reliability. Scientists from different parts of the world are trying to reduce the actuation voltage (because today’s IC technologies generally work at or below 5V). In 2017, Saffari, Moghadam and Tahmasebipour proposed a rotated serpentine concept whose actuation voltage was 5.8V and isolation loss approximately -49 dB at 13 GHz [2]. In 2017, Khan and Shanmuganantham designed a half crab shaped cantilever switch which shows actuation voltage of 1.2 V [3]. In 2017, Kageyama, Shinozaki, Zhang, Lu, Takaki and Seok Lee proposed an ohmic contact switch with Au-Au/ CNT contacts which shows very good RF parameters at higher frequencies but at the cost of high actuation voltage of 90 V [4]. The RF MEMS switch can also be used in ultra wide band (UWB) reconfigurable antennas for switching at different frequencies. In 2017, Ibrahim, Batmanov and Burte used RF MEMS switch for UWB reconfigurable antennas which operates at frequency range of 3.2 GHz to 12 GHz which shows insertion loss of -0.2 dB and return loss of -20 dB at 40 GHz in ON state and isolation is better than -20 dB in OFF state[5]. So this paper generally emphasizes the analysis and simulation of a ladder-shaped RF MEMS inline switch (considering different position of actuation electrode) to obtain low actuation voltage.

## 2. Proposed design

The ladder-shaped cantilever beam structure is designed by FEM using the software Intellisuite 8.7v, where the deflection and Mises stress are calculated under the influence of electrostatic actuation. Here, three different position of actuation electrode from the anchor of the switch is analyzed so as to get low actuation voltage and less switching time. Table 1 presents three different position of the design from the anchor of the switch; here all the beam parameters are kept constant. Figure 1.a and Figure 1.b represent the top view and side view of the switch. The material used for fabricating the device is aluminum (Al).

**Table 1:** Design Dimensions

| Position of electrode from anchor (µm) | Parameters | | | |
|---|---|---|---|---|
| | Length (µm) | Breadth (µm) | Thickness (µm) | Air gap (µm) |
| 50 | 300 | 100 | 1 | 2 |
| 100 | 300 | 100 | 1 | 2 |
| 150 | 300 | 100 | 1 | 2 |

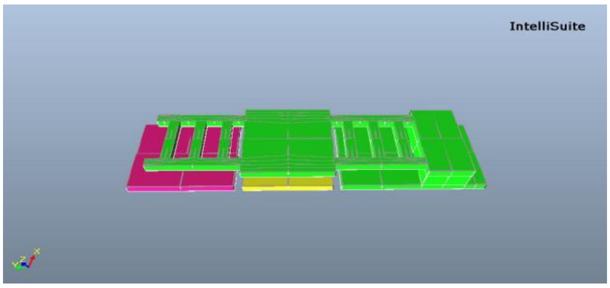

**Fig. 1: (A)** Top View of Switch.

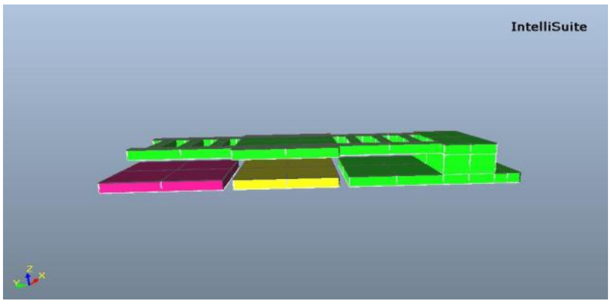

**Fig. 1: (B)** Top View of Switch.

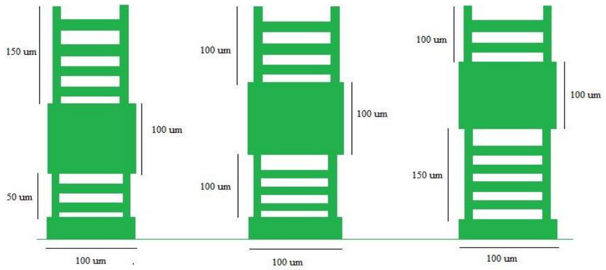

**Fig. 2:** Schematic Representation of Different Position of Electrode from the Anchor

## 3. Mathematical modeling

The mathematical modeling of the RF MEMS switch is comprises of two parts: (1) electromechanical analysis, (2) electromagnetic analysis.

### 3.1. Electromechanical analysis

Here we generally focus on the mechanical parameters of the beam such as its Young's modulus, spring constant, moment of inertia, electrostatic force between the electrodes, pull-in voltage and switching time etc. When force F is applied at the free end of the beam it gets deflected by Δx and it is [6]

$$F = K\,\Delta x \qquad (1)$$

where K represents spring constant of cantilever and is given by

$$K = 2Ew\left(\frac{t}{l}\right)^3 \frac{1-\frac{x}{l}}{3-4\left(\frac{x}{l}\right)^3+\left(\frac{x}{l}\right)^4} \qquad (2)$$

Where E is Young's modulus of the material. The concept behind the electrostatic actuation is simply the electrostatic force between the two parallel plates. The capacitance between two plates is given by [7]

$$C = \frac{\varepsilon W w V^2}{g} \qquad (3)$$

Where g is beam height above the lower electrode and ε represents the permittivity of the medium. The electrostatic force is given by the [8]

$$F_e = -\frac{\varepsilon W w V^2}{2g} \qquad (4)$$

Where V is applied bias voltage between the cantilever beam and the lower electrode and $F_e$ is electrostatic force. So after equating the electrostatic force with the spring force and solve for V we get the pull-voltage [8]

$$V_p = V\left(\frac{2g_0}{3}\right) = \sqrt{\frac{8K g_0^3}{27\varepsilon W w}} \qquad (5)$$

where $V_p$ is "pull-in voltage" or "actuation voltage" and $g_0$ is the beam height for zero bias voltage. The frequency of the cantilever beam is given by [9]

$$w_0 = \sqrt{\frac{K}{m}} \qquad (6)$$

where m is mass of the cantilever beam. The quality factor (Q) of the beam is also important factor for determining the switching speed of the switch. From experiments it is found that if $Q \leq 0.5$, switch shows slow switching time and if $Q \geq 2$, it shows long settling time after releasing. So for better performance Q = [1]. The switching time is given by [9]

$$t_s = 3.67\frac{V_p}{V_s w_0} \qquad (7)$$

For $V_s \geq 1.3\,V_p$

### 3.2. Electromagnetic analysis

RF MEMS switch is a passive and highly linear two port device. The scattering (s) parameters are used to find out the electromagnetic analysis of these switches. The series RF MEMS switch is represented by lumped element which is derived by s-parameters both in up-state as well as in down state. When the switch is in up-state (or in OFF condition) $S_{21}$ gives the isolation of the switch from that we can find out the $C_s$ (series capacitance between the transmission line and the beam) and the $C_p$ (parasitic capacitance), and then $C_u$ for inline series switch [8]

$$Cu = Cs + Cp \qquad (8)$$

When the switch is in down state (or in ON condition) $S_{21}$ gives the insertion loss and $S_{11}$ gives the return loss of the switch. In down state RF MEMS cantilever behaves as the series resistance which is given by the [8]

$$Rs = Rc + 2\,Rsl + Rl \qquad (9)$$

Where $R_c$ is contact resistance, $R_{sl}$ is t-line resistance, and $R_l$ is bridge resistance.

## 4. Results and discussions

### 4.1. Electromechanical results

The switch is designed and simulated in software Intellisuite 8.7v for electromechanical analysis. At three different positions actuation electrode is placed from the anchor and its pull-in voltage as well as mises stress is analyzed so as to get an optimized value.

#### 4.1.1. At x = 50 µm

The vertical displacement of the switch is 2.16254 µm as shown in Figure 3.a and the mises stress of the switch is approximately 5.5034 Mpa as shown in Figure 3.b the vertical displacement of the switch with the applied voltage shows actuation voltage of ~ 3.4 V as shown in Figure 4.

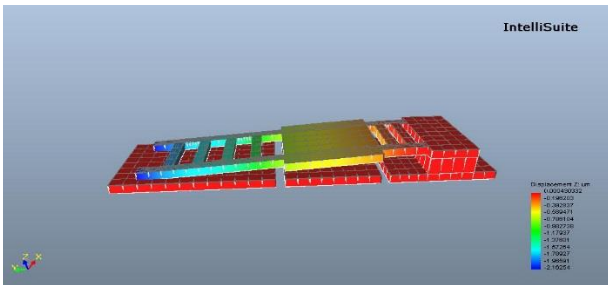

**Fig. 3: (A)** Switch Displacement.

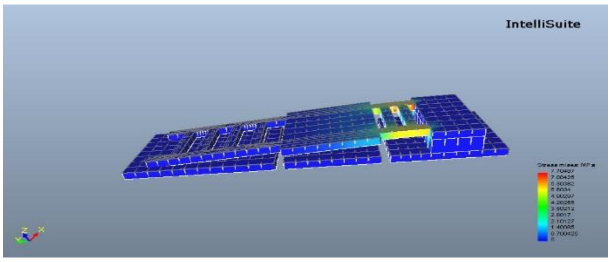

**Fig. 3 (B)** Switch Mises Stress.

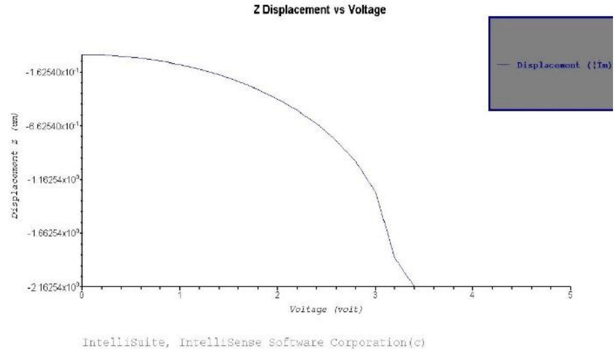

**Fig. 4:** Voltage vs. Beam Vertical Displacement.

### 4.1.2. At x = 100 µm

The vertical displacement of the switch is 2.03802 µm as shown in Figure 5.a and the mises stress of the switch is approximately 3.55543 Mpa as shown in Figure 5.b the vertical displacement of the switch with the applied voltage shows actuation voltage of ~ 2 V as shown in Figure 6.

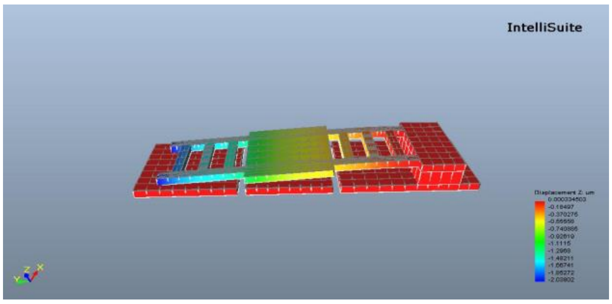

**Fig. 5: (A)** Switch Displacement.

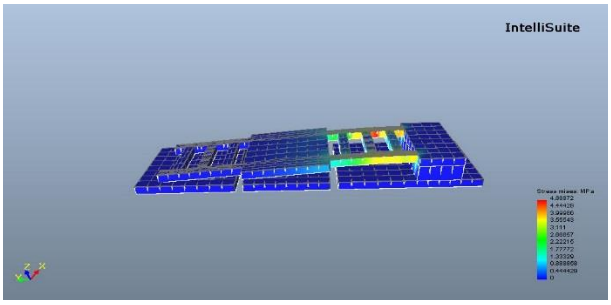

**Fig. 5 (B)** Switch Mises Stress.

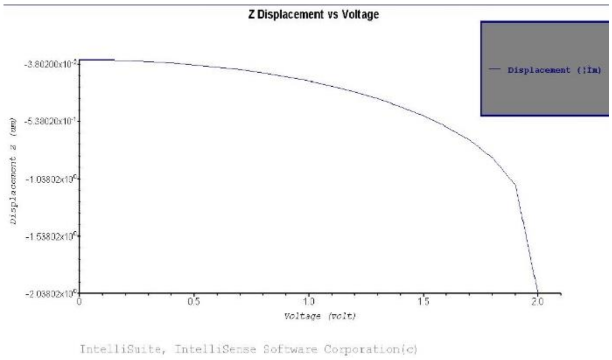

**Fig. 6:** Voltage vs. Beam Vertical Displacement.

### 4.1.3. At x = 150 µm

The vertical displacement of the switch is 2.24942 µm as shown in Figure 7.a and the mises stress of the switch is approximately 4.43583 Mpa as shown in Figure 7.b the vertical displacement of the switch with the applied voltage shows actuation voltage of ~ 1.16 V as shown in Figure 8.

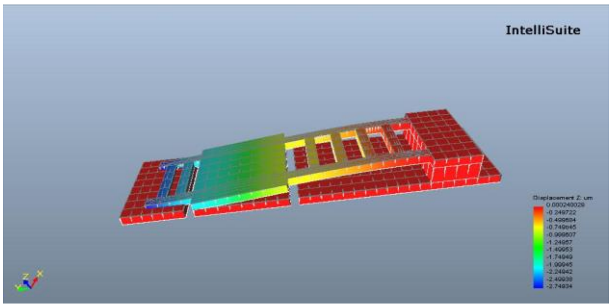

**Fig. 7: (A)** Switch Displacement.

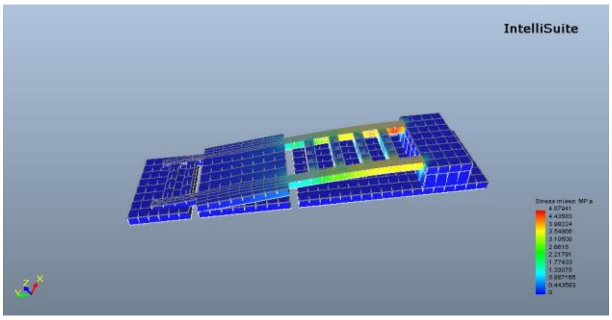

**Fig. 7: (B)** Switch Mises Stress.

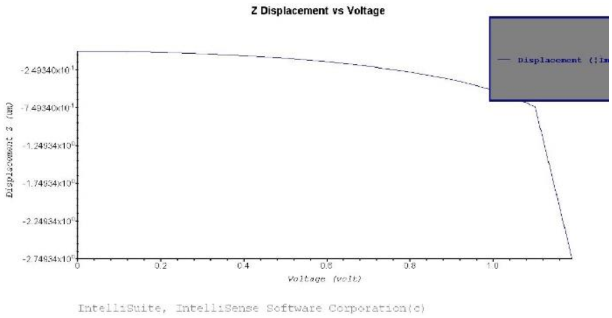

**Fig. 8:** Voltage vs. Beam Vertical Displacement.

**Table 2:** Comparison Table of Actuation Voltage

| Position of electrode from anchor (µm) | Parameters | |
|---|---|---|
| | Actuation voltage (V) | Mises stress (Mpa) |
| 50 | 3.4 | 5.5034 |
| 100 | 2 | 3.55543 |
| 150 | 1.16 | 4.43583 |

So from Table 2, it is clear that switch with position of electrode at x = 100µm is showing good electromechanical results, pull-in voltage of 2 V along with considerable mises stress of 3.55543 Mpa which is below than the critical stress of the beam.

### 4.2. Electromagnetic results

For electromagnetic analysis switch is designed and simulated in HFSS 15.0 software. Simulated results are of switch which is at position x = 100µm from the anchor.

#### 4.2.1. Off condition

When the switch is in upstate then it is in OFF condition (i.e, it will not allow power to transfer from port 1 to port [2] in that case $S_{21}$ will give the isolation of the switch and from Figure 9. it is clear that isolation of switch is -100dB at 8 GHz and -80 dB at 35 GHz.

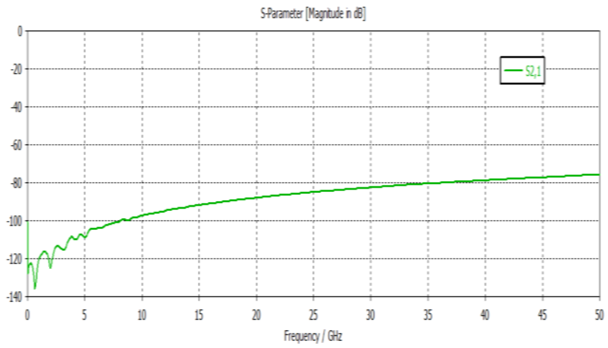

**Fig. 9:** Isolation ($S_{21}$) in Off State.

#### 4.2.2. On condition

When the switch is in down state then it is in ON condition and in that $S_{11}$ gives return loss and $S_{21}$ gives the insertion loss. So from Figure 10.a and Figure 10.b it clear that the return loss is -45dB at 8 GHz and -32 dB at 35 GHz and insertion loss is -0.008 dB at 8 GHz and -0.023 dB at 35 GHz.

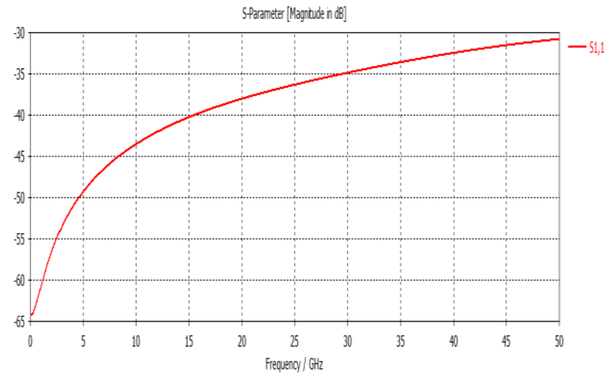

**Fig. 10: (A)** Return Loss ($S_{11}$) in on State.

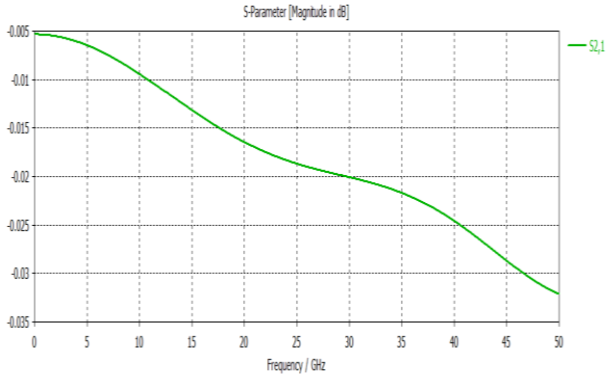

**Fig. 10: (B)** Insertion Loss ($S_{21}$) in on State.

**Table 3:** Comparison Table

| References | Parameters | | | |
|---|---|---|---|---|
| | Actuation voltage (V) | Isolation loss (dB) | Insertion loss (dB) | Return loss (dB) |
| Ref [2] | 5.8 | -49 at 13 GHz | - | -0.24 at 13 GHz |
| Ref [6] | 5 | -74 at 28 GHz | -0.13 at 28 GHz | -24.5 at 28 GHz |
| Proposed design | 2 | -80 at 35 GHz | -0.023 at 35 GHz | -32 at 35 GHz |

## 5. Conclusion

For electromechanical analysis the switch was designed and fabricated in Intellifab module of the software Intellisuite 8.7v. From the simulations performed, the optimized actuation voltage achieved ~ [2] V for position of electrode at x = 100µm from the anchor of the switch. The electromagnetic analysis of the switch is performed in HFSS.15 which shows very good RF parameters, insertion loss of -0.008 dB at 8 GHz and -0.023 dB at 35 GHz, isolation of -100 dB at 8 GHz and -80 dB at 35 GHz. We can further work on the contact resistance, bandwidth, and on material analysis. We can also include graphene, which is a future material for Nano Electro Mechanical System (NEMS).

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