Design and Analysis of MEMS Switch for RF Applications

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Abstract—**This paper describes the design process of MEMSswitch and analysis of the MEMS switch structures for finding certain switch parameters to develop a highperformance RF MEMS switch with low voltage, low insertion loss and high isolation.The RF MEMS switchis designed using physical level approach by using 3DMEMS commercial software packages COMSOLMultiphysicsand Intellisuite. Theoptimization analysis is also simulated to obtain the low voltageby adjusting the air gap distance and top electrode designstructure. The RF performance is then simulated using theelectromagnetic analyzer, *Emag*to calculate the insertion loss andisolation value during the ON and OFF state conditions respectively. Severaldesigns are proposed and the best performance switch gives a lowvoltage actuation of 4V with low loss of8 dB and highisolation of -40 dB at 1.5GHz. The switch resistance of single switch is high. In order to reduce the effective switch resistance, 10 miniature RF MEMS switches have been placed in paralleland result in switchresistance of 5.9Ω**

Keywords—**MEMS, RF switch, isolation, low voltage, insertion loss, COMSOL Multiphysics, Intellisuite.**

I. Introduction

The exponential growth of wireless communications requires more sophisticated system design to achieve higher integration, power saving and robustness. System design concentrates in developing high frequency, low scale configurations to follow the trends of the market for smaller, technologically more advanced applications. In the same manner, technological advances in radio-frequency (RF) front-ends, such as reconfigurable antennas, tunable filters, phase sifters, switching networks etc require state of the art switches to allow operation in cognitive wireless networks.MicroelectromechanicalSystem integration of miniature mechanical elements such as sensors, actuators and associated electronics on a single substrate. RF MEMS switches are of interest because of the potential for low-loss, wide bandwidth operation, as they have demonstrated superior RF characteristics compared to FET and diode-based switches. RF-MEMS switches are the one which replaces the conventional GaAs FET and PIN diode switches in Radio-Frequency communication due to their low power consumption, low insertion loss, high isolation and due to its linear behaviors. Reducing the actuation voltage of RFMEMS switches enhances their performance significantly and broadens the range of their applications including portable devices which require low actuation voltage [1].

HaslinaJaafar et aldeveloped a high performance RFMEMS switch with low voltage; low loss and high isolation switches have a better performance at lower frequency [2].T. Kuenzig et al discussed the working principle of the active restoring mechanism based on micro-heaters, integrated beneath each anchoring area, that when activated by an electric current, enable the recovery of the switch from stiction (i.e. Missed release)[3]. RomainStefanini, et al discussed about new way to design MEMS switches for RF application using miniature MEMS cantilevers. Furthermore, 10–20 element back-to-back switch arrays are developed and result in a marked improvement in the reliability of the overall switching device. A series-shunt design is also demonstrated with greatly improved isolation[4].Richard Chan *et al* discussed about a cold switching test method is developed to identify the root cause of sticking as a failure mechanism. The switch structure includes “separation posts” that eliminate sticking failure and has demonstrated lifetimes as high as 7x10^9 cold switching cycles [5].Seong-Dae Lee et al report a novel RF MEMS switch with low actuation voltage and long life time by adopting a freely moving contact pad structure [6].

II. PARAMETERS THEORY

Basically, there are two distinct parts for an RF MEMSswitch: the actuation (mechanical) section and the electricalsection. Mechanical part of RF MEMS switch can be operatedusing four mechanisms, which is electrostatic, thermal,magnetic, and piezoelectric. However, this paper will describethe RF MEMS design using electrostatic mechanism and piezoelectric mechanism. RF MEMS switch can move in two directions, which isvertically or laterally, depends on the requirement and it canalso be designed in series or shunt configurations which use metal-to-metal or capacitive contact. This paper will describe the shunt configuration.

Electrical energy is easily transported by means of conductors such as wires or busbars, which can be controlled by relays or switches. In a simple electric circuit, theprincipal parts are a source of electrical energy, a load or an output device and a completepath for the flow of current. If any one of the above requirements is not fulfilledcurrent cannot flow in the circuit and the energy from the source cannot be deliveredto the output device. Various parameters to be considered in the design of RF switchesare (a) transition time; (b) spring constant; (c) switching transients; (d) RF power handling;(e) matching with circuit; (f) bandwidth; (g) insertion loss; (h) isolation; (i) switchresistance; (j) actuation voltage; (k) lifetime; (l) resonant frequency; (m) interception andlevel of distortion; (n) phase and amplitude tracking. However this paper describes the parameters such as actuation voltage of both electrostatic and piezoelectric switch, Insertion loss, Isolation and switch resistance of electrostatic switch.

III. SWITCH OPERATION

Figure 1 shows the side view of a standard RF MEMS switch. When a certain amount of voltage is appliedbetween bottom electrode and the pull down electrode,electrostatic force is created and will pull the cantilever downfrom the arm of anchor and complete the RF signal path atdown-state. Short circuit occurred between two terminals ofRF transmission line has made the RF signal can pass through and transmitted as shown in figure 2. The cantilever is then back to the originalposition once the voltage supply is removed and hencedisconnects the transmission of RF signals.

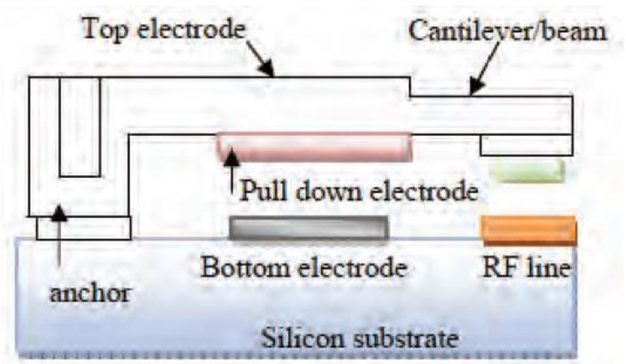

Figure.1. Schematic view of RF MEMS switch in open condition

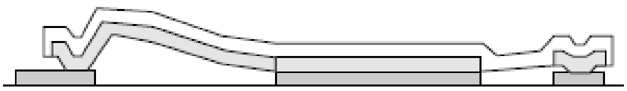

Figure.2. Schematic view of RF MEMS switch in closed condition

In RF MEMS switch, there are several parameters need to beconsidered in mechanical modeling such as actuation voltage, Insertion loss, Isolation , Spring constant and Switch resistance.

IV. MATHEMATICAL RELATIONS

The total RF MEMS switch acts like a mass- spring-damper system as shown in figure 3.

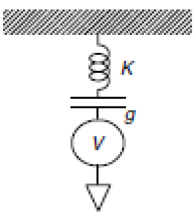

Figure 3.Equivalent mechanical model

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Whereg -gap between electrodes

K -spring constant

V - Voltage applied

1. ACTUATION VOLTAGE

An electrostatic force is induced on the beam when a voltage is applied between a fixed-fixed or cantilever beam and the pull down electrode. The voltage need to be pulled down the top electrode is called as actuation voltage or pull-in voltage. The electrostatic force exists in the plates of a capacitor under applied voltage. The beam over the pull down electrode is modeled as a parallel-plate capacitor in order to approximate the electrostatic force. When the width of beam is w and the width of pull down electrode is W, the parallel capacitance is

$$C = \frac{\xi_0 A}{g} = \frac{\xi_0 W w}{g} \qquad (1)$$

Where g is the height of the beam over electrode is the permittivity of space and A is the area of contact.

The electrostatic force applied to the beam is

$$F_e = \frac{1}{2}V^2 \frac{dC(g)}{dg} = -\frac{1}{2}\frac{\xi_0 W w V^2}{g2} (2)$$

Where V is the voltage applied between the beam and electrode

By equating the applied electrostatic force with the mechanical restoring force due to the stiffness of the beam,

$$\frac{1}{2}\frac{\xi_0 W w V^2}{g2} = k(g_0-g)(3)$$

Where g_o is the zero bias bridge height or the air gap of the top electrode to the bottom electrode.

And solved the equation, the voltage is

$$V=\sqrt{\frac{2k}{\xi_0 W w}}g^2 (g_0 - g)(4)$$

The beam position become unstable at (2/3)go, thus the pull down voltage is

$$V_p = V(2g_0/3) = \sqrt{\frac{8k}{27\xi_0 W w}}g_e^3 (5)$$

Cantilevers beam has lower spring constant than fixed-fixed beam in same t/l ratio, and thus has lower pull-down voltage.

2. SPRING CONSTANT

Mechanical operation of RF MEMS switch starts with the spring constant derivation of the fixed-fixed or cantilever beam. Linear spring constant, k (N/m), is used in the most RF MEMS devices. Common use of fixed-fixed beam is due to its relatively high spring constant and easy in manufacturing[7].

Spring constant for fixed-fixed beam, k', is the stiffness of the bridge which accounts for the material characteristics such as Young's modulus, E (Pa), and the moment of Inertia, I(m^4).

The general expression for this spring constant is

$$K=32Ew(t/l)^3 (27/49) + 8 \sigma (1-v) w (t/l) \quad (6)$$

Where w is width of the beam, t is the thickness of the beam, l is the length of the beam and v is the Poisson's ratio. From the equation, the dimension and specifications like size of the beam can be vary in order to reduce the spring constant, and thus control the other parameters such as reduce the actuation voltage consumed during the switching operation.

3. INSERTION LOSS

The insertion loss of an RF device is a measure of its efficiency for signal transmission.In the case of a switch, the insertion loss is specified only when its state is such thatsignal is transmitting or when the switch is in the ON state. This is specified in termsof the transmission coefficient, S_{21}, in decibels, between the input and output terminalsof the switched circuit. Usually specified in decibels, one of the design goals for mostof the RF switches is to minimize the insertion loss. The insertion loss tends to degradewith increase in frequency for most of the solid-state switching systems. Compared withthese, RF MEMS switches can be designed to operate with a small insertion loss atseveral gigahertz. Resistive losses at lower frequencies and skin-depth effects at higherfrequencies are the major causes for losses [8].

The transmission coefficient between two points in a circuit is often expressed in decibelsas the *insertion*

$IL = -20 \log |T|$ dB(7)

4. ISOLATION

The isolation of a switching system is specified when there is no signal transmission. This is also measured as S_{21} between the input and output terminals of the switched circuit, under the no-transmission state or when the switch is in the off condition. A large value (in decibels) indicates very small coupling between input and output terminals. Thus the design goal is to maximize the isolation.

In RF MEMS switches isolation may degrade as a result of proximity coupling between the moving part and the stationary transmission line as a result of leakage currents.

V. DESIGN OF MEMS SWITCH

The MEMS switch is designed using commercial software packages CMOSOL Multiphysics and Intellisuite.

TABLE1. Design parameters of MEMS switch

Parameter	Dimensions (µm)	Materials used	Colour
Substrate	210x60	Silicon	Green
Bottom electrode	60x60	Aluminium	Blue
Cantilever beam	210x20	Silicon nitride	Yellow
Upper electrode	60x60	Aluminium	Red
Anchor	30x20	Aluminium	Rose
Transmission line connected to the substrate	20x20	Gold	Purple
Transmission line connected to the cantilever beam	20x40	Gold	Light green

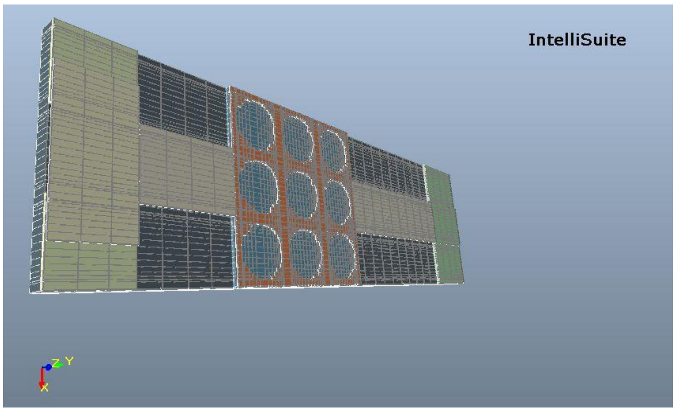

Fig.4.Resultant structure when switch is off state.

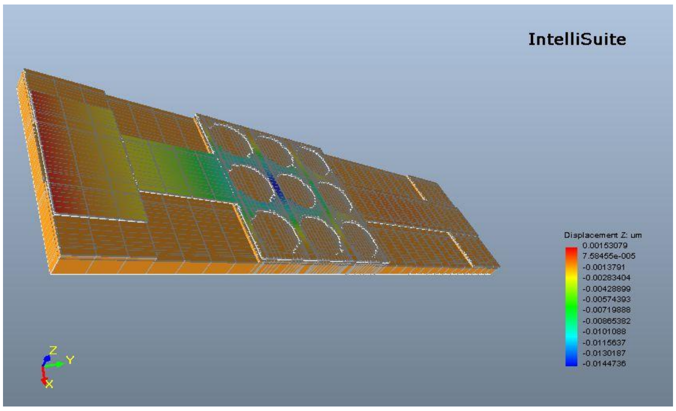

Fig.5.Resultant deformed structure when switch is on state and Displacement of upper beam in Z-axis .

First the switch is designed with the help of Intellimask using the parameters and dimensions given in Table1.The holes present in the upper electrode is to reduce the weight of the electrode.Further it reduces the actuation voltage.This is the optimization method proposed in this paper. The switch is designed with airgap of 0.5µm.Further the designed switch is exported to 3D Builder for obtaining the 3D view as shown in Figure 4.For obtaining 3D view the height is given for substrate,beam,upper and lower electrodes,anchor and transmission lines.Further fig.4.Shows the switch in OFF state.

The upper electrode is supplied with 5V.The lower electrode is grounded. The substrate and the anchor are fixed .Due to fixed substrate and anchor, during TEM analysis the displacement occurs in the beam in Z-direction. The switch is designed with air gap of 0.5µm. At 4V the displacement is about 0.5µm.So the actuation voltage is 4V.

Fig.5. shows the switch in ON STATE. Fig.6. shows the graph between applied voltage and displacement of switch in Z- direction. From the graph it is clear that after actuation voltage of 4V the switch is in closed condition so there is no displacement in Z- direction. This actuation voltage is

obtained under the fixed condition of the anchor and the substrate.

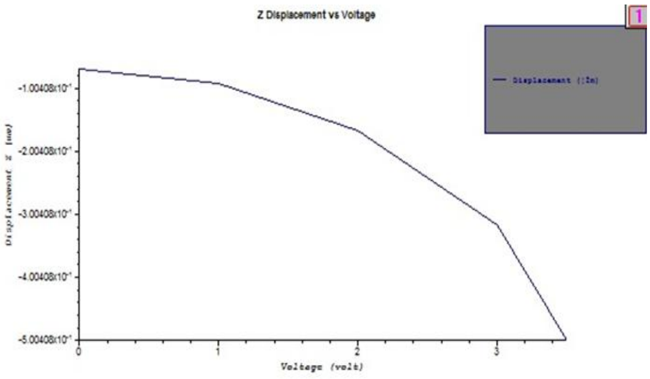

Fig.6. Actuation voltage and displacement.

To find the isolation of the designed switch it is exported to the emag analyser. In emag analyser the switch is simulated with the frequency range of 1 MHz to 30 GHZ in OFF condition. The magnitude of S_{21} parameteris obtained from the analysis. From the Fig.7.Various isolation is found for various frequencies. From table 2 it is clear that high frequencies give high isolation

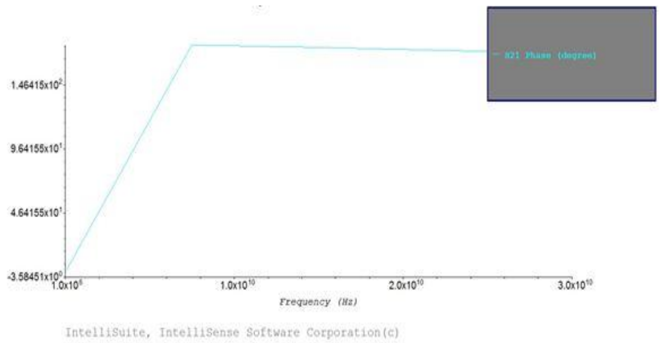

Fig.7. Isolation of switch from 1MHz to 30 GHz.

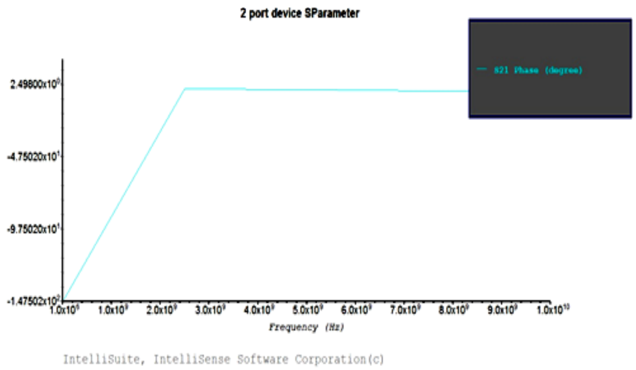

Fig.8.Insertion loss for the frequency 1MHz to 10Ghz

To find the Insertion loss of the designed switch it is exported to the emag analyser. In emag analyser the switch is simulated with the frequency range of 1 MHz to 10 GHZ in ON condition. The magnitude of S_{21}parameteris obtained from the analysis. From the Fig.8 various Insertion loss is found for various frequencies. From table 2 it is clear that high frequencies gives high Insertion loss.

TABLE2. Design parameters of MEMS switch

Isolation (dB)		**Insertion Loss (dB)**	
1.5 GHz	**1.8 GHz**	**1.5 GHz**	**1.8 GHz**
-40 dB	-48 dB	-8 dB	-8.4dB

.The RF performance of the rest switches designs are shown in Table 2. From the Table 2, both isolation and insertion lossis decrease when the operating frequency is increased from 1.5GHz to 1.8GHz. Thus, the switches have a betterperformance at lower frequency and performance is droppingwhen the frequency is increasing.

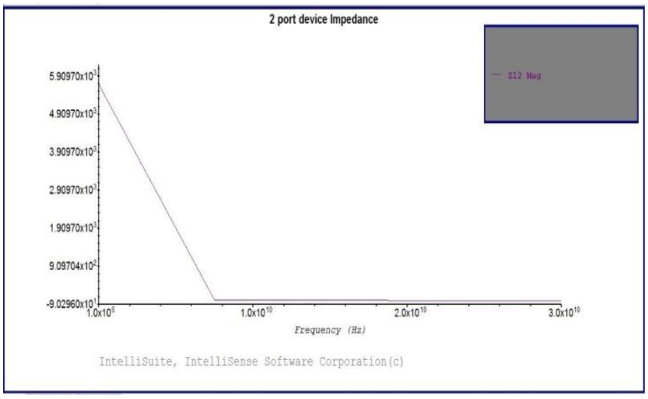

Fig.9. Switch resistance from 1 MHz to 30 GHz

From the Fig.9.it is found that the resistance of single switch is very high. So the 10 switches are arranged in parallel to get low resistance as shown in fig. 10. The low switch resistance provides high signal to pass through the switch. It also reduces the insertion loss and increase the Isolation [9].

To reduce the switch resistance 10 switches are arranged in parallel [10].

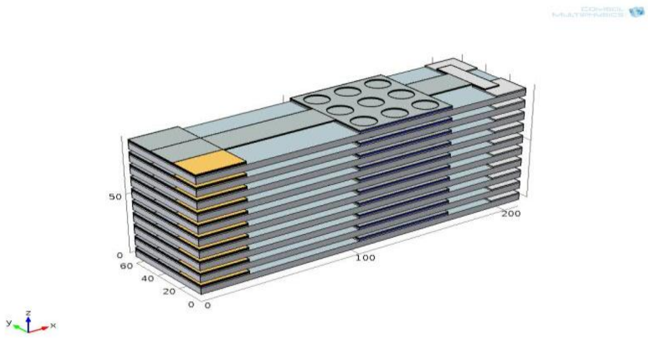

Fig.10. Switches in Parallel.

VI. CALCULATED PARAMETERS

- Spring constant= 4.5
- Insertion loss= -8dB
- Isolation= -40dB
- Switch resistance=5.9Ω
- Operating frequency=1.5GHz
- Actuation voltage= 4V

VII. CONCLUSION

The switch parameters like actuation voltage, Insertion loss, Isolation, switch resistance, Operating frequency, and spring constant are found. The optimization method for designing the MEMS switch is also proposed in this paper. The switch resistance for single switch is high. So in order to reduce the effective switch resistance 10 switches are arranged in parallel. By reducing the switch resistance we can reduce the loss of the signal. The switch performance is high when operating frequency is kept at low.

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