Design of RF MEMS Capacitive Shunt Switch for X-Ku frequency Band

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Abstract – This paper proposes the design of thin bridge structured RF MEMS capacitive shunt switch with low spring constant and activation voltage is about 24 V. In this design, there are two actuation electrodes and a separate signal line. Both electrodes and a signal line are arranged such that, the whole arrangement isolates the DC static charge and the input operating signal. The switch return-loss in up-state condition and the isolation in down-state condition were found more than 20 dB over a wide frequency band of 4 to 18 GHz. The switch yields insertion loss in up-state and return-loss in down-state condition, lower than 0.5 dB at same frequency band. The simulated results were verified through the analytical method and found in close agreement.

Keywords – activation voltage, actuators, coplanar wave guide (CPW), down-state, up-state

I. INTRODUCTION

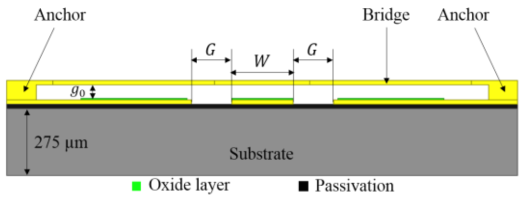
In the recent years, Radio Frequency (RF) Micro-Electro-Mechanical System (MEMS) switches have shown potential performance in miniature wireless communications devices, such as mobile phones and satellite components [1-4]. The RF MEMS switches have replaced the conventional solid-state switches like PIN diode, GaAs and FET based switches, etc. The RF MEMS switches have significant advantages over conventional RF switches. These include very low insertion loss, higher isolation, lower cost, lower intermodulation distortion, nearly zero power consumption and more linear characteristics over a large range of frequencies [5-7]. However, these advantages come with a challenge of maintaining low actuation voltage with high switching speed [8-11].

Typically, the fabrication process of RF MEMS is based on the surface micromachining techniques. It has a suspended thin metal membrane called ‘bridge’ (cantilever and fixed-fixed beam), which uses mechanical movement to achieve open or short circuit in RF transmission line [2]. Therefore, they are normally integrated with coplanar waveguides (CPW). The RF MEMS switches can be classified mainly into two categories based on their actuation methods and circuit configurations. Actuation method is executed in different ways like, electrostatic [12], electromagnetic [13], piezoelectric [14], thermal [15], etc. Based on the circuit configuration, the RF MEMS switches can be classified as Ohmic Contact [3] or Capacitive Contact [7]. Out of the several actuation methods listed above, the electrostatic actuation is the most preferred actuation method due to low power consumption. In this method, an electrostatic force is produced between an actuation electrode and the bridge for switching operation [2,3].

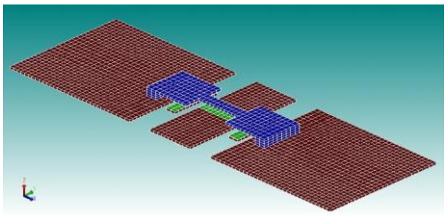
In this paper, a high-impedance CPW MEMS capacitive switch with low actuation (pull-in) voltage is proposed. Two pull-in electrodes with anchor support structure help to lower the pull-in voltage of the proposed RF MEMS switch.The switch operates over a wide frequency range of 4 to 18 GHz satisfying the criteria of isolation, return-loss, and minimum insertion loss.

II. SWITCH DESIGN AND STRUCTURE

Figure (1) shows shunt type RF MEMS switch. It consist of a cantilever beams, suspended above coplanar waveguide (CPW) line with G/S/G of 120/225/120 μm and characteristic impedance of 50 Ω. It has been built on high resistive silicon substrate with 275μm thickness. It also separated S/G/S line cantilever beam with silicon dioxide of 0.1 μm thickness. Figure 1 shows that flexible electrode bridge with fixed flexure suspension. These flexure suspensions are connected to both the ground lines. Bridge is made up of Gold with 570GPa and thickness of 1μm. It is suspended above G/S/G electrode with 3 μm initial air gap height. The lower electrodes are also made up of Gold material. A silicon Nitrite layer of 0.1 μm with 7.6 relative permittivity, covers the lower electrodes to avoid the direct electric contact between metal bridge and signal line. For a capacitive shunt switch, this dielectric layer is extended to cover the signal line in high capacitance mode (OFF state). In lower capacitance mode (ON state) air gap is higher than the dielectric layer, provides good metal to metal contact. In this shunt switch, bias voltage has not applied between signal (centre) conductor and ground conductor: there is no interference occurs with other semiconductor devices in practical circuits. Another advantage of separation of RF and DC signals provides more flexible circuits for practical modeling analysis. The bridge connects both the anchors. When electric force is applied between an actuation electron and a bridge, it generates force between them. The generated force pulls bridge towards actuation electrodes. Silicon nitrate is chosen as a dielectric material to provide isolation between the bridge and a signal line. The pull-in electrodes and bridge dimensions are fixed such that the pull-in voltage is maintained to less than 22 V. Two large fixture suspension actuation electrodes are used on both sides to provide better mechanical strength and very thin bridge on signal line (center line) to reduce the pull-in voltage and improve frequency responses shown in figure 1(b).



(a) Side view of proposed RF MEMS switch



(b) Top View and Contact Area

FIG. 1 Proposed RF MEMS Capacitive Shunt Switch

A.Principal of Operation

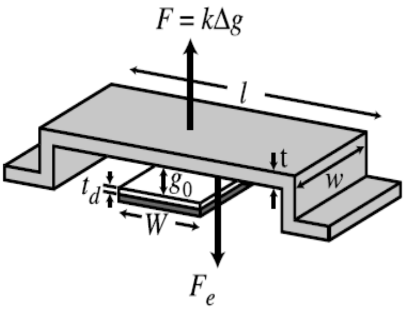


FIG. 2 Fixed beam structure

The CPW line consists of a center conductor and two ground conductors as shown in Figure 1. and 2 The center conductor is used for signal transmission. When zero DC voltage is given to an actuation electrode, the bridge remains in up-condition and then the RF signal can transmit through the signal line. The DC voltage applied to the actuation electrodes can produce electrostatic force to attract the bridge in downward condition [2]. In this condition, the RF signal will be capacitive coupled between the bridge and a signal line. All parameters used for designing RF MEMS shunt switch are list in Table 1.

$$c = \frac{\varepsilon_0 A}{g_0} = \frac{\varepsilon_0 W w}{g_0} \qquad (1)$$

$$F_e = \frac{1}{2} V^2 \frac{dC_{g_0}}{dg_0} = -\frac{1}{2} \frac{\varepsilon W_1 L_1 V^2}{g_0} \qquad (2)$$

$$V_P = V^2 \frac{g_0}{3} = \sqrt{\frac{8k}{27\varepsilon_0 W_1 L_1}} \, g_0^{\,3} \qquad (3)$$

A parallel plate capacitance can be expressed as Eq. (1), where g_0 is air beam height above the electrode. The electric force is produced by applying electric potential and capacitance between the bridge and the signal line as given in Eq. (2). Variance in capacitance depends on air gap between the bridge and the signal line [2]. Under the applied electric field, the cantilever beam moves towards the signal line. In addition to this, spring constant must be associated with the distance moved under the amount of applied force. Beam movement is balanced by mechanical restoring force due to the stiffness of the beam. Beam becomes unstable when beam height becomes 2/3 of zero potential beam height (g_0). So, maximum pull down electric force (Activation Voltage) can be given up to the displacement of $(2/3)g_0$, as mentioned in Eq. (3). Activation or pull in voltage depends on spring constant (k), beam height (g_0) and width of the signal line (W) as mentioned in Eq. (3).

Table 1: Proposed RF MEMS Switch Design Parameters

Design parameter	Material	Dimension (µm)
Bridge	Gold	t = 1 l = 650 w = 50
Bridge height	Air	g_0 = 3
Dielectric layer	Si3N4	t_d = 0.1
Signal line	Gold	ts = 1
G/W/G	Gold	120/225/120

B. Electrical Model of the RF MEMS Shunt Switch

The electrical equivalent model of the proposed RF MEMS switch is shown in Figure 3. The impedance offered by the switch is given by Eq. (4).

$$Z = R + j\omega L + \frac{1}{j\omega c} \qquad (4)$$

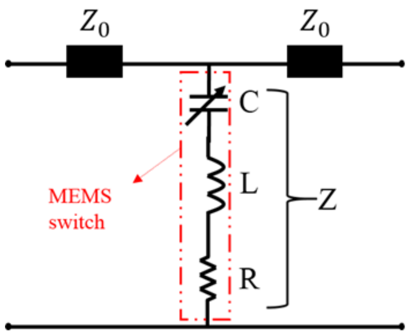


FIG. 3 Electrical Model of the RF MEMS Switch

The resonant frequency of the switch is can be shown as,

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad (5)$$

In Eq. (5), C can be up-state capacitance (C_u) or down-state capacitance (C_d) depending upon the applied pull in voltage to the bridge. Actual impedance offered by the switch for different applied frequencies is given by Eq. (6).

$$Z = \begin{cases} \dfrac{1}{j\omega C} & for \quad \omega << \omega_0 \\ R & for \quad \omega = \omega_0 \\ j\omega L & for \quad \omega >> \omega_0 \end{cases} \qquad (6)$$

The RLC model acts as a capacitive switch below the resonant frequency and an inductive switch above the resonant frequency. At resonance, the RLC model acts as the series resistance of the MEMS bridge[2].

C. Up (ON)-state Return-loss

In ON-state (up-state) condition of the switch, the impedance can be approximated by,

$$Z = \frac{1}{j\omega c} \qquad (7)$$

Similarly in ON-state (up-state), the reflection coefficient can be given by,

$$S_{11} = \frac{-j\omega C_u Z_0}{2 + j\omega C_u Z_0} \qquad (8)$$

$$|S_{11}|^2 = \frac{(wC_u Z_0)^2}{4 + (wC_u Z_0)^2} \qquad (9)$$

The up-state return-loss should be below 20 dB[2].

D. Down (OFF)-state Return-loss

$$S_{11} = \frac{-jwC_d Z_0}{(2 - 2w^2LC) + jw(2R + C_d Z_0)} \qquad (10)$$

Compared to shunt capacitance C, R and L are small,

$$|S_{11}|^2 = \frac{(wC_d Z_0)^2}{4 + (wC_d Z_0)^2} \qquad (11)$$

The down-state return-loss should be lower than 0.5 dB.

E. Up (ON)-state insertion loss

$$S_{21} = \frac{2}{2 + jwC_u Z_0} \qquad (12)$$

$$|S_{21}|^2 = \frac{4}{4 + (wC_u Z_0)^2} \qquad (13)$$

From Eqs. (11) and (13), insertion loss will be given by,

$$|S_{21}|^2 = \frac{1}{|S_{11}|^2}\left(\frac{C_u}{C_d}\right)^2 \qquad (14)$$

The insertion loss in up-state should be lower than 0.5 dB.

F. Down (OFF) -State isolation

$$S_{21} = \frac{(2 - 2w^2LC_d) + j2wRC_d}{(2 - 2w^2LC_d) + jw(2RC_d + C_d Z_0)} \qquad (15)$$

$$|S_{11}|^2 = \frac{4}{4 + (\omega C_d Z_0)^2} \qquad (16)$$

The isolation in down-state should be below 20 dB [2].

III. RESULTS AND ANALYSIS

As shown in Figure 1, by applying an electric force to the actuation electrodes, the electrode is attracted to downward, depending upon the spring constant as given in (3). In the proposed design of the bridge, the spring constant decreases, this result into an air gap displacement of the bridge by 66% with an activation voltage of 24 V. This activation voltage can be compared with the close form formula as given in (3). The comparison of results is shown in Table 2.

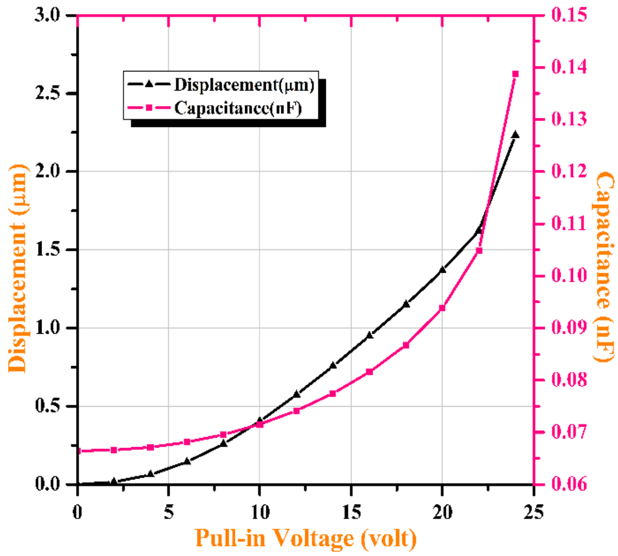


FIG. 4 RF MEMS Pull-in Voltage Vs Displacement and Capacitance

TABLE 2: Comparison of Analytical and Simulated Result of Activation Voltage

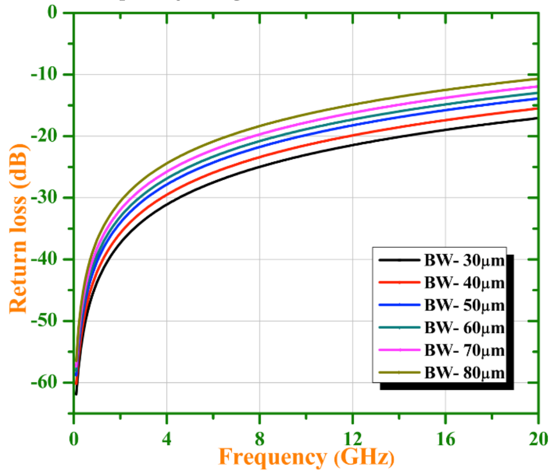
Analytical Results		Simulated Results
Spring Constant	Activation Voltage	Activation Voltage
0.4 N/m	25.46 V	24 V

Up-state and down-state capacitance values are also compared with analytical method and the comparisons are shown in Table 3.

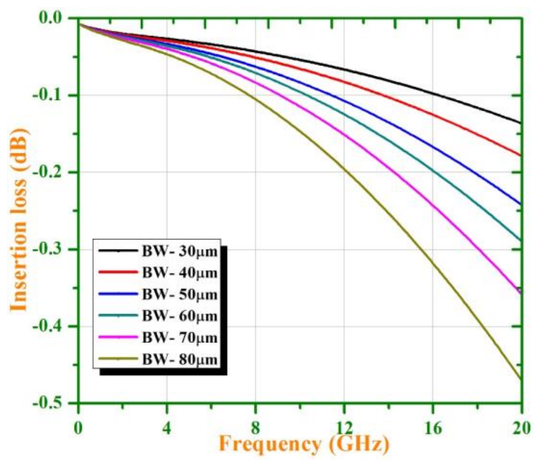
TABLE 3: Comparison of Analytical and Simulated Result of RF MEMS Shunt Switch Capacitance

Operation	Switch Capacitance (Analytical Results)	Switch Capacitance (Simulated Results)
Up-state	0.069 nF	0.065 nF
Down-state	0.132 nF	0.14 nF

Figure 4 shows that the air gap displacement of the bridge moving downward to 2 µm, which results in an increase in signal line capacitance from 0.065 nF to 0.14 nF. From Figure 5, it can be concluded that by keeping the bridge width to 125µm, the best performance of the switch can be obtained in the wide frequency range of 14 to 41 GHz.

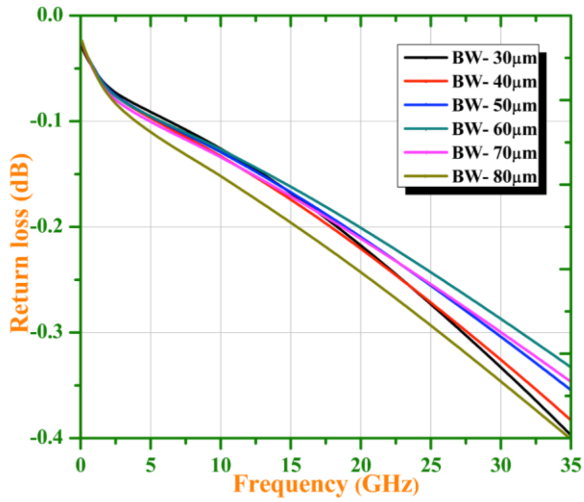


(a)

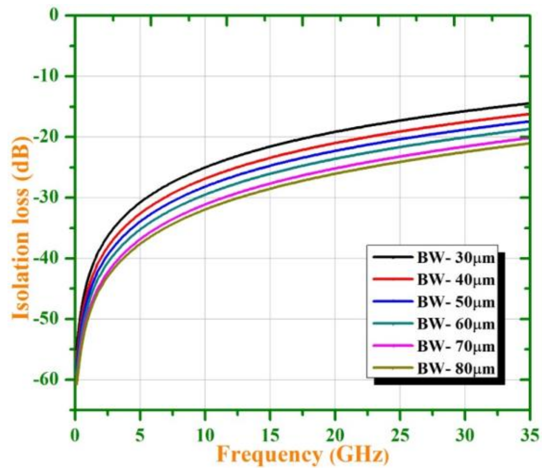


(b)

FIG. 5: Signal Analysis of Up-state (a) Return loss (b) Insertion loss



(a)



(b)

FIG. 6: Signal Analysis of Down-state (a) Return loss (b) Isolation

IV. CONCLUSION

Reliable RF MEMS shunt capacitive coupled switch has been design and optimized for RF and microwave applications. The required return-loss and insertion loss are obtained over a wide frequency range from 4 to 18 GHz. The deployment of thin and two separate actuation electrodes in the bridge obtain 24V Activation voltage.

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