Design and Simulation of Novel RF MEMS Cantilever Switch with Low Actuation Voltage

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ABSTRACT

In this paper a novel RF MEMS cantilever type switch with low actuation voltage is presented. The cantilever beam of switch is supported by two L-shaped springs to reduce the spring constant. The switch is simulated using Intellisuite software. The actuation voltage of switch is achieved about 2 volt and the size of the switch is $110\times60\mu^2$m, that in compared with other electrostatic cantilever beam switch, it has a small size, low spring constant and as a result low actuation voltage. Its fabrication is simple due to its simple design. The S-parameters of switch have been simulated with HFSS 9.1 that the results show the insertion loss of 0.07 dB, return loss 0f 25 dB and 17 dB isolation till 40 GHz frequency. The results show proper performance of switch in this frequencies band and it had less insertion loss compare pervious work and with these properties of switch, return loss and isolation did not changed much.

KEYWORDS: Constant Spring, MEMS Series Switch, Electrostatic Actuation, S-parameters, RF MEMS.

1. INTRODUCTION

In the field of wireless communication, the micro electromechanical system is a major component of electronic devices. Wireless communication systems for space application require electronic component with high level of reliability and low power consumption, and for integration in satellites, they need to be miniaturized. The most important MEMS device in the RF area is RF MEMS switches. It is one of the best options compared with FET and Pin diodes switches, and they are capable of being integrated with ICs. But one of the disadvantages of RF MEMS switches is high actuation voltage which can cause major problems in wireless systems. In recent years, many research works have been devoted to improving the performance of these switches and reduce the actuation voltage. In previous work, three bars connected between anchor and beam in order to reduce spring constant [1]. By devolving the model for spring constant of a non uniform cantilever with a wider section at the end of the beam was another method to reduce the actuation voltage [2]. There are also other works with different structures and using dimple on the tip of the cantilever in order to increase contact force and reduce the actuation voltage [3]-[9] The problem of previous works is complexity of fabrication without much reduction of actuation voltage. In this paper, a novel design of beam with low spring constant using two L-shaped has been presented to reduce the actuation voltage compared with other works and the switch size was also reduced. In following sections, design and modeling of switch have been described.

2. DESIGN OF SERIES SWITCH

The MEMS series switch is designed on a coplanar waveguide (CPW) line with dimension of G/S/G=20/60/20µm for 40 GHz frequency in order to achieve better performance (see Fig. 1). For designing of switches to achieve low actuation voltage the beam material is critical, so gold was selected for CPW and cantilever beam because of its high elastic modulus and low compressive residual stress. Also gold has enough stiffness to allow the cantilever bridge or beam return to its original position after disconnecting the voltage. The silicon nitride has been used as a dielectric layer. The dielectric layer is used for isolation of DC control voltage and allows only the RF signal to couple with the transmission line of the CPW. Beams with low spring constant have very low restoring force in down state, which may not be sufficiently high to pull up the switch, particularly in humid or contaminated environments. Although low spring constant is essential to obtain low voltage switches, but down-state stickiness should be prevented. This problem of switches can be overcome by putting dimple on front of the beam. The dimple has been used to reduce the stress sensitivity and increase force to contact between beam and transmission line and to prevent stickiness problem [1].

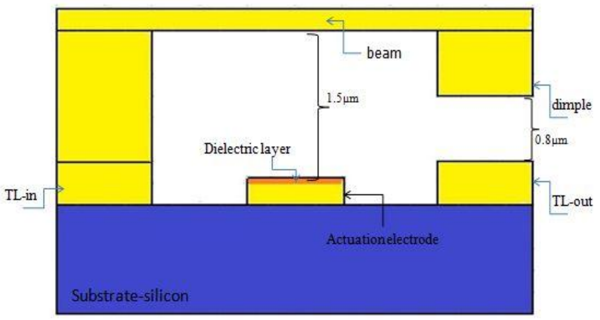


Fig. 1. Cross section of Series switch structure

3. MODELING OF SWITCH

High frequency micro electro mechanical switches are considered and analyzed using equivalent electrical and mechanical circuit models. Figure 2 shows the new structure of switch which two L-shaped springs are used. The dimensions of each spring are shown in figure.

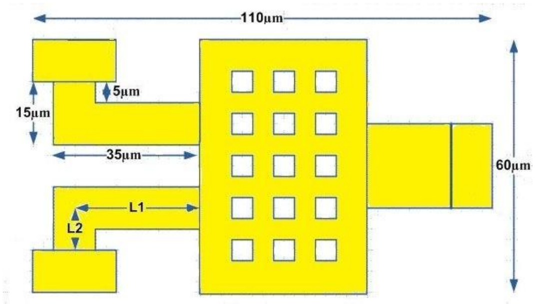


Fig. 2. Series switch structure

Since the cantilever beam is not fixed at one end, any residual stress within the beam is released, and the spring constant does not contain a residual stress component. The spring constant of beam depends on the physical parameters and due to a uniform force applied the beam, which spring constants can be obtained as equation 1, 2 [10].

$$K_{L1} = \frac{2EWt^3}{3L^3} \qquad (1)$$

$$K_{L2} = \frac{2EWt^3}{3L^3} \qquad (2)$$

Where E is young modulus, t is thickness of the springs, W is width of springs and L1 and L2 are length of two series springs. Spring constant equivalent will be as equation 3.

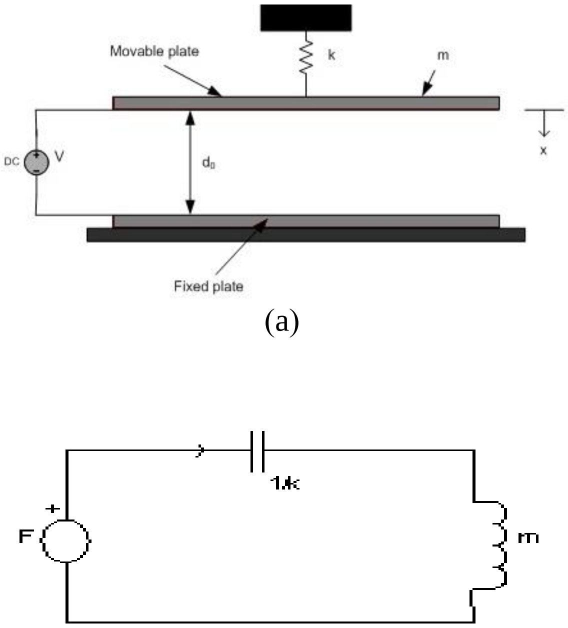
$$K_{eq} = \frac{(K_{L1} \times K_{L2})}{K_{L1} + K_{L2}} \qquad (3)$$

and tow L-shaped springs of beam are shunt together and because of theirs symmetry properties total spring constant can be calculated as equation 4.

$$K_T = 2 \times \left(\frac{2}{3}\frac{E\,Wt^3}{(L_1^3 + L_2^3)}\right) \qquad (4)$$

Where KT is total spring constant of springs.

Fig.3.a shows both electrical and mechanical model of the two plate that have capacitive structure which with applied voltage, the beam toward parallel downward , for this structure of switch, due to a capacitive structure and L-shaped springs, with applied voltage between to plate will be supposed the beam downward almost parallel, therefore for analyzing of actuation voltage, this model will be used [11]-[15].



(a)

(b)

Fig. 3. Equivalent switch circuit a) equivalent mechanical circuit b) equivalent electrical circuit

Applying a voltage between the top and bottom plate leads to an electrostatic force that causes a change in capacitance. Change in capacitance, causes the actuation voltage change too. As the applied voltage increases, the electrostatic force pulls down the top plate and the distance between the two plates is reduced. The capacitance of height d0 and dielectric layer thickness is calculated as shown in equation 5.

$$C = \frac{\varepsilon_0 A}{g_0 + \frac{t_d}{\varepsilon_r}} \tag{5}$$

Where td and εr are thickness and relative dielectric constants of the dielectric layer respectively, A is area of electrode actuation and g0 is distance between transmission line and beam without applied voltage. For a capacitive structure analysis, electrical model should be transformed to mechanical model and then be considered in mechanical mode. Transforming of electrical to mechanical model can be done using table1.

Table 1. Transforming electrical to mechanical

electrical		mechanical
I	→	dx/dt
L	→	m
1/C	→	K
V	→	F

Whereas the electrical equivalent circuit, as shown in Fig. 3.b, is given by equation 6.

$$L\frac{di}{dt} + \frac{1}{c}\int idt = V \tag{6}$$

Using the electrical to mechanical transforms, the motion of beam equation is found to be as equation 7.

$$m\frac{d^2x}{dt^2} + k(g_0 - g) = F \tag{7}$$

Where m is the bridge mass, F is a mechanical restoring force, g0 is the initial gap and g is the displacement value of the beam when electrostatic force applied to the beam. The electrostatic force derives from the energy stored in the capacitor. It is calculated using equation 8.

$$F_E = -\frac{d}{dx}\left(\frac{1}{2}CV^2\right) = \frac{\varepsilon_0 A V^2}{2\left(g_0 + \frac{t_d}{\varepsilon_r}\right)^2} \tag{8}$$

Due to the stiffness of the beam, equating the applied electrostatic force with the mechanical restoring force of equation 5 with equation 6, the motion of beam equation versus applied voltage is found to be as equation 9.

$$m\frac{d^2x}{dt^2} + K(g_0 - g) = \frac{\varepsilon_0 A v^2}{2\left(g_0 + \frac{t_d}{\varepsilon_r}\right)^2} \tag{9}$$

The g0 is the distance between actuation electrode and beam that is 1.5μm displacement. The actuation voltage is applied between these plates. To calculate the actuation voltage, assuming vacuum condition and ignoring air damping, the second derivative of displacement in equation 5 equals to zero, therefore equation 5 can be simplified to equation 10.

$$K(g_0 - g) = \frac{\varepsilon_r \varepsilon_0 A v^2}{2\left(g_0 + \frac{t_d}{\varepsilon_r}\right)^2} \tag{10}$$

For the switch to stay in the down state position, the electrostatic force must be larger than the restoring force. The hold down voltage of beams will calculated as equation 11.

$$V = \sqrt{\frac{2K(g_0 - g)\left(g_0 + \frac{t_d}{\varepsilon_r}\right)^2}{\varepsilon_0 \varepsilon_r A}} \tag{11}$$

In series switches type, in the down-state position, metal-to-metal contact switches present a more complicated case because the force on the actuation electrode is not the same as the force on the contact points. Contact force for a metal-to-metal series contact switch is 0.3-0.6 of electrostatic force on actuation electrode, (F_c =(0.3-0.6) F_e =α F_e). So actuation voltage for cantilever will be results in equation 12. [10]

$$V_h = \sqrt{\frac{2\alpha K(g_0 - g)\left(\frac{t_d}{\varepsilon_r} + g_0\right)^2}{\varepsilon_0 A}} \tag{12}$$

The actuation voltage should be kept as low as possible, Different methods has been taken for reduction in actuation voltage of switch, As results, with increasing actuation electrode area, the actuation voltage will decrease, but it has limits for increasing area, and decreasing of gap between actuation electrode and beam, is another way for reduction in actuation voltage, but it deteriorates isolation of switch. In this paper, the parameters of switch have been optimized and the new design of springs has been considered that had low spring constant, and simple design was its properties. With putting dimple on tip of the beam contact force increased and therefore the actuation voltage decreased. The gap between transmission line and dimple on tip at the free end of the beam is equal to 0.8 μm, and the gap between actuation electrode and the beam is considered 1.5μm displacement, solving the actuation voltage is obtained to be equal to 2.54 V.

4. RESULTS AND DISCUSSION

A RF MEMS capacitive switch was designed and simulated. Actuation voltage is simulated by Intellisuite software. In figure 4, for a beam deflects of 0.8μm displacement, 2-V is needed. Low actuation voltage was achieved. This is as actuation voltage, that compares with solving actuation voltage in equation 10, which was 2.54 volt, does not had much difference, and the actuation voltage of switch with this dimension was low.

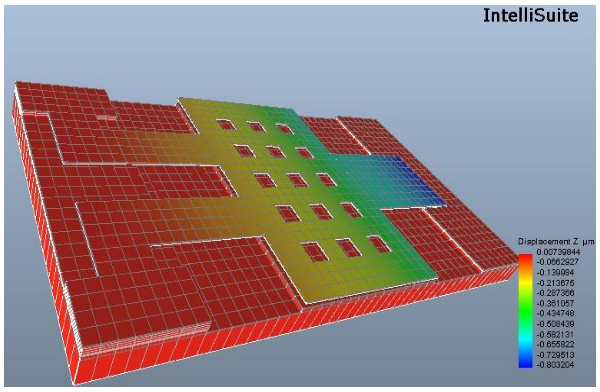


Fig .4. Simulated switch voltage in Intellisuite software

The switch should be matched with input and output circuits because of the small capacitance between the beam and transmission line in the off state position, as there is not an ideal match and part of the signal will be passed to ground by this capacitor, which decrease isolation of switch. These switches have only air gap and as a result have less capacitance in comparison to capacitive contact switches that have both gap air and dielectric layer. The contact material selection is based on material hardness and resistivity, and metal to metal contact was chosen here because it provides lowest contact resistance. The front end of the cantilever beam and CPW transmission line has been addressed by introducing a dimple under the front tip of the beam to reduce residual stress and the metal to metal stickiness which improves the isolation of the switch. At low frequencies the insertion loss is the contribution of resistive loss of signal line, and at high frequencies the insertion loss can be attributed to both resistive loss and skin depth effect. S-parameters have been simulated by HFSS9.1 software. As seen S-parameters for switch in this state for V, Ka frequencies band is shown in figure (5), (6). It is 0.07 dB insertion losses, 25 dB return loss and 17 dB isolation till 40 GHz frequency. The results show proper performance of switch in this frequencies band and it had less insertion loss compare pervious work and with these properties of switch, return loss and isolation did not changed much.

5. CONCLUSION

In this paper a novel RF MEMS switch with low actuation voltage is presented using two L-shaped springs. The parameters of switch have been optimized and the new design of springs has been considered that had low spring constant. With placing a dimple on tip of the beam to increase the contact force and to reduce the contact area for prevention of stickiness effect was considered. The actuation voltage was simulated with Intellisuite and 2 volts was achieved, which compare as pervious work, with this size had lower actuation voltage and its simple design was another property that fabrication of it will be simpler. The result of S-parameters of the switch have been simulated in HFSS9.1 software which show good performance in 0.07 dB insertion loss, 25 dB return loss and 17 dB isolation till 40 GHz frequency. The results show proper performance of switch in this frequencies band and it had less insertion loss compare pervious work and with these properties of switch, return loss and isolation did not changed much. The size of the switch is 110×60μ^2m, which in comparison with electrostatic actuation RF MEMS series switches has small size and low actuation voltage. Fabrication of this switch is simple and has very low insertion loss in 40 GHz frequency.

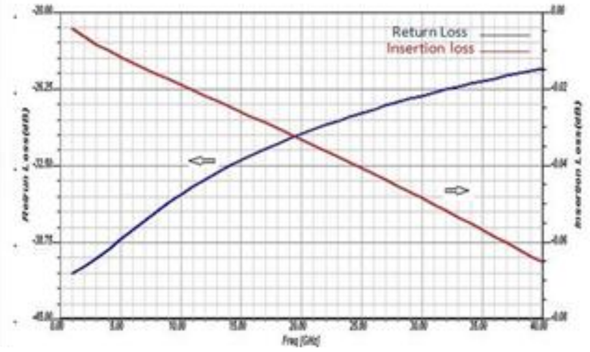


Fig. 5. Simulated result of designed switch in on state

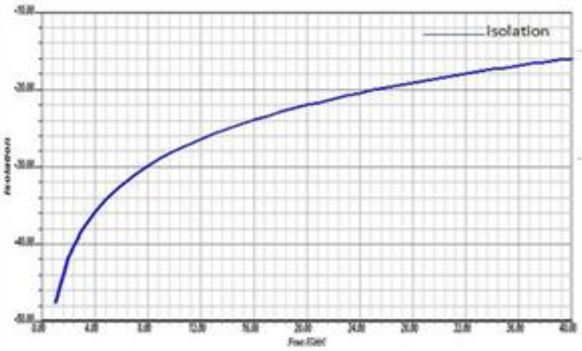


Fig. 6. Simulated result of designed switch in off state

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