Analysis and Parametric Modeling of RF MEMS Capacitive Shunt Switch

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Abstract: - MEMS capacitive shunt switches with variable resonant frequencies are discussed in this paper. Advantages of such switches are low-loss performance (< 0.5dB), high isolation (> 40dB), High Capacitance ratio and ease of fabrication. The switches are placed over a 45/60/45 (μm) copper CPW and a FEM simulation software (Ansoft HFSS) is used to extract the S-parameter for different switch geometries. An equivalent lumped circuit model is constructed from the S-parameters and different values of inductance are calculated. The capacitance of the switches in the down-state is around 5.1pF and the inductances range from 2pH to 27pH which result in resonant frequency range of 13-50 GHz. The mechanical model of the switch is discussed and calculations of different characteristics of the switch such as the pull-in voltage and spring constant are outlined.

Key-Words: - MEMS shunt switch, Electrostatic actuation, Low-loss, High isolation, Parametric model, Low spring constant

1 Introduction

MEMS switches were first introduced by Peterson in 1971 [1]. Since then, many MEMS switches have been reported with different geometries and characteristics such as low insertion loss and high isolation which are suitable for microwave applications [2-4]. These switches showed a better performance than conventional FETs and PIN switches specially when used in microwave applications. The resonant frequency of MEMS switches is controlled by its down capacitance (C_{down}) and the parasitic inductance (L) [7]. In this paper it is shown that the resonant frequency can be controlled by changing inductance of the switch using various geometries of the inductive meanders as shown in Table 2. To visualize the electromagnetic characteristics of the switch, a FEM simulator (Ansoft HFSS) that is based on full wave analysis was used. The resonant frequency and inductance were extracted from the scattering parameters. At the end of the paper, it is shown that by combining several switches one can achieve better performance in terms of isolation and bandwidth.

2 Device Structure

The switch under experiment was originally developed by the University of Michigan [4]. Fig.1 shows the structure of the switch and its physical dimensions are listed in Table.1. The switch is placed 3 μm above a coplanar waveguide with dimensions (45/60/45 μm). Two actuation electrodes are placed under the supported membranes having an area of (190×190 μm^2) each.

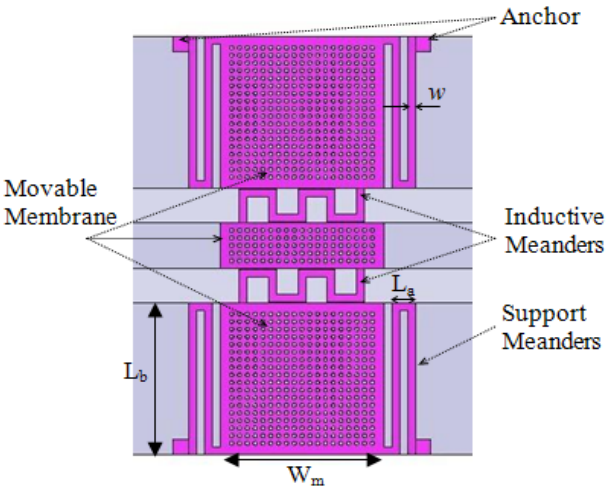


Fig.1 Model of the capacitive MEMS switch over CPW line.

Table 1 Physical dimensions of the MEMS switch.

L_a	20 μm
L_b	200 μm
W_m	210 μm
w	10 μm
Thickness (t)	2 μm
Material	Nickel
Mass	2.16×10^{-9} kg
Dielectric	Si_3N_4 (t_d = 0.15 μm)
Holes radius	2.5 μm

3 Mechanical Characteristics

The dynamic equation for motion of the switch is given by [5]:

$$m\frac{\partial^2 z}{\partial t^2}+b\frac{\partial z}{\partial t}+Kz=\frac{\varepsilon_o A V^2}{2(g+\frac{t_d}{\varepsilon_r}-z)^2} \quad (1)$$

where m is the mass of beam, b is the damping coefficient, K is the spring constant, and the right hand side of the equation is the electrostatic force due to actuation electrodes characterized by the actuation area A and voltage V applied on them, g is the initial gap height, ε_o and ε_r is the permittivity of air and the dielectric respectively, and t_d is the dielectric thickness.

Folded meanders are attached to the square plates responsible for the electrostatic actuation. The main purpose for these meanders is lowering the membrane's spring constant (kz). This meander geometry results in kz approximated by [5]:

$$k_z=\frac{E w \left(\frac{t}{L_a}\right)^3}{1+\frac{L_b}{L_a}\left(\left(\frac{L_b}{L_a}\right)^2+12\frac{1+v}{1+\left(\frac{w}{t}\right)^2}\right)} \quad (2)$$

where E and v are the Young's modulus and the Poisson's ratio of the metal (200 GPa and 0.31 respectively for Nickel). The sum of spring constants at all meanders results in the total spring constant (K) which is equal to:

$$K=\frac{4k_z}{N} \quad (3)$$

where N is the number of meanders at the suspension (N=2 in this case). From the equation above it's clear that the spring constant decreases with increasing meander number.

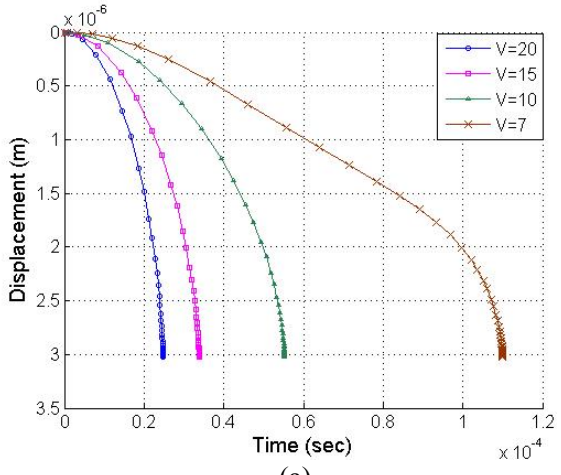
The voltage applied between the pull in electrode and actuation area of the membrane is a function of the spring constant derived previously and is usually (1.2-1.4) $\times Vp$ where Vp is the pull-in voltage and is given by [2]:

$$V_p=\sqrt{\frac{8K_z g_o^3}{27A\varepsilon_o}} \quad (4)$$

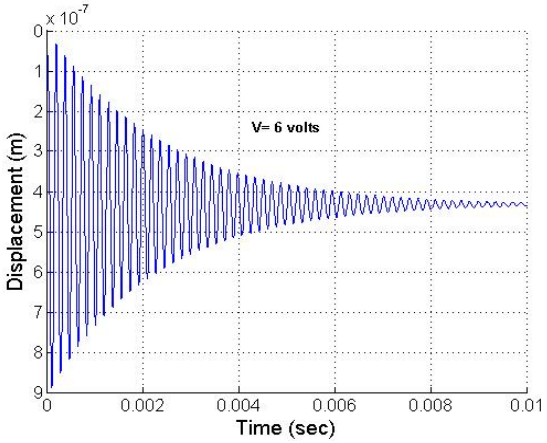
where g_o is the gap between the bridge and ground, and A is the actuation area.

It is tempting to increase the number of meanders so as to lower the spring constant and thereby lower Vp, but problems such as stiction could arise from such procedure [6].

Equation (1) was solved using MATLAB for different applied voltages. The time needed for the switch to move a distance of 3 μm is shown in Fig.2 (a) for applied voltages of 7, 10, 15, and 20 volts. The switching time for the voltages applied is 110μs, 55.2μs, 33.8μs, and 24.7μs respectively. In Figure.2 (b) the applied voltage is less than the required pull-in voltage (6 volts) and hence the switch will not make it to the ground. Instead it will move for a short distance (about 0.8μm) and then starts vibrating up and down for a while until it almost settles around 0.435μm. It should be noted that at V= 7 the switch took longer time to snap down. At this voltage the system is at the critical voltage (around V_p) at which the switch could operate.



(a)



(b)

Fig.2 Time vs. Displacement of the switch when the applied voltage is (a) greater than V_p (V= 7,10,15,20 volts) and when it is (b) less than V_p (V= 6 volts)

4 RF Characteristics

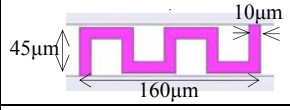
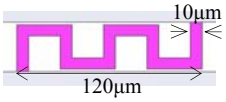
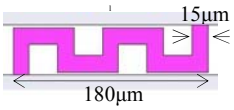
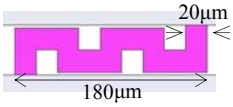
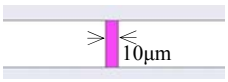
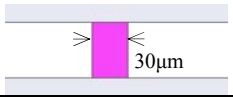
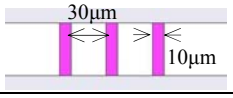
As mentioned earlier the switch was analyzed with a full-wave analysis simulation software (Ansoft HFSS) [8] when using different geometries of the inductive beams. In the up state position all the switches showed low insertion loss. The up-state capacitance (C_{up}) is around 46 fF for all switches.

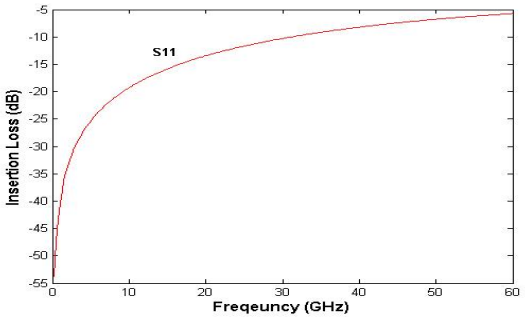
The resulting s-parameters showed different isolations and resonant frequencies as shown in Fig.3. They were fitted to get the inductance for each switch. Table.2 shows the values for *fr* and *L* for each case. The down capacitance (C_{down}) is the same for all switches (5.1 pF) and the capacitance ratio (C_{down}/C_{up}) is 110:1. Where,

$$\frac{C_{down}}{C_{up}} = \frac{\varepsilon_o \varepsilon_r A / t_d}{\left(\frac{\varepsilon_o A}{g + t_d / \varepsilon_r} \right) + C_f} \qquad (5)$$

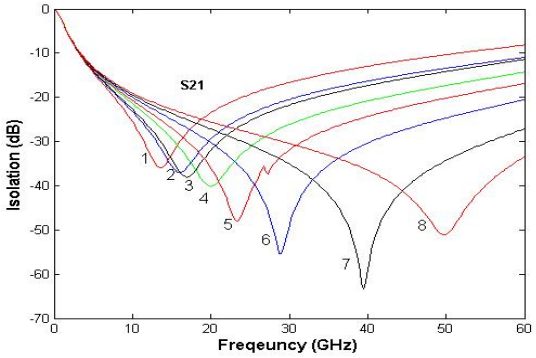
From Table 2 it is clear that the resonant frequency increases as the inductance decrease. By carefully controlling the width and shape of the meanders one can get maximum isolation at any desired resonant frequency.

Table 2 *fr* and *L* for 8 different inductive beams

	Inductive Meander	*fr* (GHz)	*L* (pH)
1		**13.5**	**27.3**
2		**16**	**19.4**
3		**17**	**17.2**
4		**20**	**12.4**
5		**23.25**	**9.2**
6		**29**	**5.9**
7		**39.5**	**3.2**
8		**49.75**	**2**



(a)



(b)

Fig.3 (a) Insertion loss in up-state and (b) isolation in down-state for the switches. Numbers correspond to the inductive beams in Table 2

Inductive beams 1 and 2 have lengths 160 μm and 120 μm respectively and their width is 10 μm. The length was fixed at 180 μm for beams 3 and 4 and the width was changed to 15 μm and 20 μm respectively. Beams 5 and 6 are rectangular in shape having widths 10 μm and 30 μm respectively. For beams 7 and 8 three rectangular shaped beams were used with fixed width of 10 μm while varying the distance between them to 30 μm and 60 μm respectively.

5 Parallel switches

Higher isolation and wider bandwidth greater than the ones of a single switch is sometimes required by applications. To accomplish this, several switches with different inductances could be connected in parallel. Fig.4 illustrates the layout of the switches over the CPW and their RF characteristics are shown in Fig.5. Four switches using the inductive beams 1 to 4 from Table.2 were used. The simulation results showed isolation higher than 60 dB between 15 and 45 GHz. The simulation resulted in isolation greater than 90dB at 15 GHz but it is expected that the actual isolation will be lower than the one obtained. Yet previous measurements of similar switches [7] showed that the isolation will be greater than 40 dB for the range of frequencies stated above.

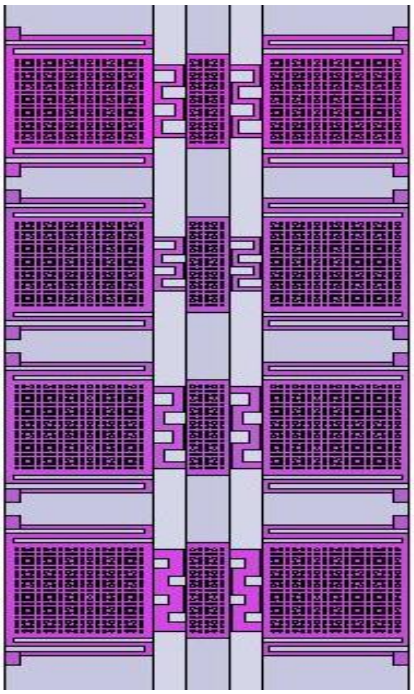
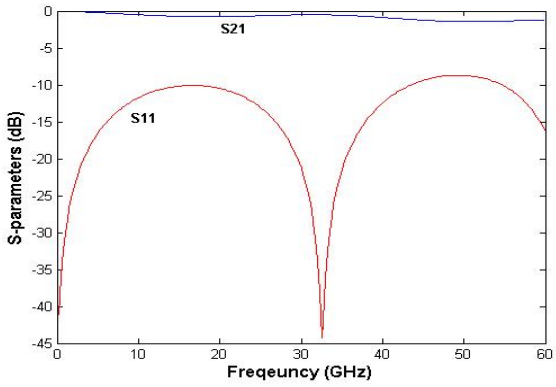
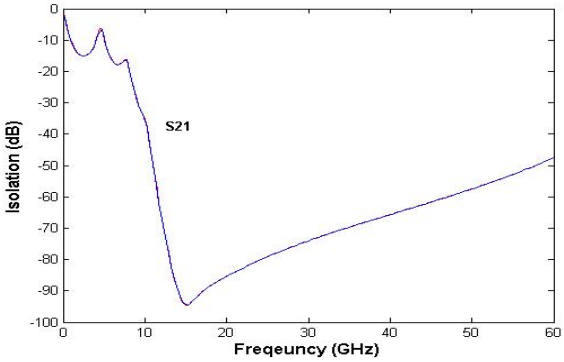


Fig.4 Four switches in Parallel.



(a)



(b)

Fig.5 Simulated results for the parallel switches in (a) the up-state and (b) down-state

6 Conclusion

The implementation of different geometries of inductive meanders was demonstrated to design resonant switches. The simulation results showed high isolation, low insertion loss, and low pull-in voltage. Single switches can be used to selectively isolate a preferred frequency or in a network to get maximum isolation over a wide range of frequencies. Different applications such as tunable filters can benefit from these types of switches.

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