A Proposed π-Structure RF MEMS Switch for Wide Bandwidth and High Isolation Applications

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Abstract—This paper presents a π-structure for RF MEMS switch based on numerical experimentation using 3D EM simulator. It has very low insertion and return losses in the ON-state and very high isolation in the OFF-state, over a wide bandwidth. It exhibits a minimum isolation of 50 dB, in the frequency range from dc to 50 GHz, and of 30 dB in the frequency range from 50 to 60 GHz. The insertion loss ranges from 0.2 to 2 dB and a minimum of 25 dB return loss up to 50 GHz. To the best of the authors' knowledge, this is the highest isolation reported so far for RF switches over such a wide frequency band. The switch is actuated by a DC voltage of 30 to 50 volt. Both shunt capacitive and series resistive switch fabrication processes on the wafer are compatible.

Keywords: RF MEMS switch, microwave components, switch modeling

1. Introduction

Micro-Electro-Mechanical (MEM) switches can be classified as cantilever beam switches or air-bridge (fixed-fixed) beam switches. Each of these can be electrically configured in series or parallel with an RF transmission line. They are designed to open the line or shunt it to ground upon actuation. The actuation mechanism can be electrostatic, magnetostatic or thermal. The type of contact for each of these switches can be metal-to-metal contact or capacitive coupling. The selection of the switch type depends on the required performance, application and manufacturing facilities. Such switches have displayed excellent RF characteristics. Both series-configured switches, at low radio frequency range, and shunt-configured switches, at high radio frequency range, exhibit a typical insertion loss of about 0.1 dB and isolation of about 30 dB [1-4].

Miniaturized RF MEMS switches are electromagnetic components, which can offer size reduction, flexibility and reduction in the power consumption. The advantages of the MEMS switches are their extremely low series resistance, low drive power requirements, and negligible inter-modulation distortion as compared to their solid-state counterparts. These MEMS devices are primarily designed for low-loss applications that do not require fast switching rates such as reconfigurable systems of airborne and satellite communication. MEMS switches are susceptible to replace current passive switches in wireless communication systems to add flexibility, programmability and increased level of integration.

The conventional RF metrics characterizing MEMS switches are: 1) The insertion loss in the ON-state; 2) The isolation (i.e. 1/|S21|) in the OFF-state; and 3) The return loss (i.e. 1/|S11|) in both states. During the course of this study, efforts have been done to improve these metrics. In other words, achieving high isolation in the OFF-state and low insertion and return losses in the ON-state. The complexity of our proposed structure is much less than that of different researchers, who tried to improve the isolation in the OFF-state by using multi-switch architectures [1-4]. The proposed switch is in the fabrication process, so the demonstrated results are based on numerical experimentations using 3D EM simulator (Sonnet software [5]).

2. π-Structure RF MEMS Switch

In many applications, a wider band and a higher isolation than that offered by single switches are required. In [2] a network of four parallel switches has been designed. While in [3-4], three alternative structures to achieve such a goal have been proposed, namely, two MEMS bridges, cross and series/shunt switches. In this contribution, we introduce a π-structure RF MEMS switch, which has been constructed as a shunt-capacitive/series-resistive/shunt-capacitive configuration as depicted in Fig. 1. High isolation at the high frequency portion of the band is provided by the shunt arm while at the low frequency portion this is achieved by the series arm. The series switch is constructed as fixed-fixed beam architecture; therefore, it is not very sensitive to the residual stress in the supporting beam. The fixed-fixed beam is usually easy to fabricate and does not require special processing compared to the dielectric beams or the thick low-stress electroplated cantilever [4]. Both shunt and series arms are fabricated simultaneously using the same steps, as the fabrication processes of both switches are compatible.

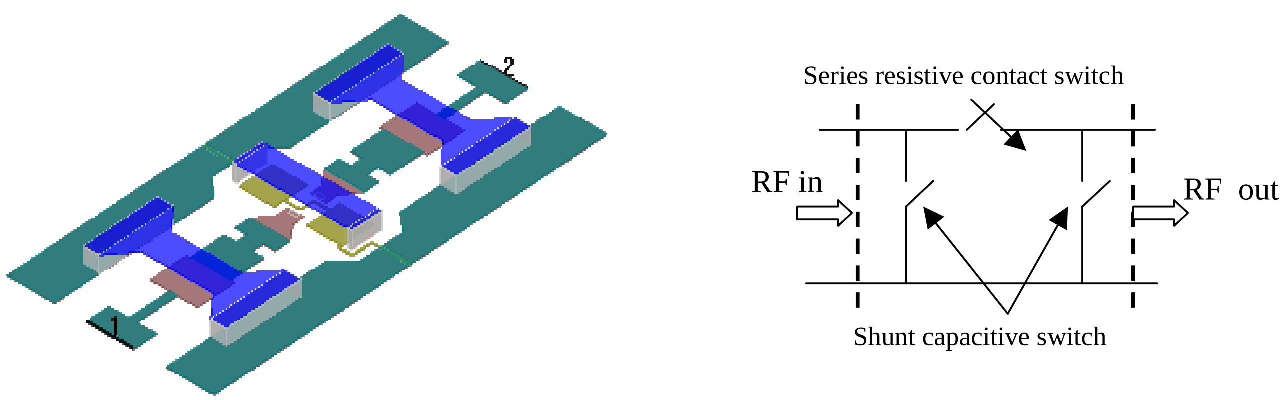


Fig. 1 The proposed π-structure RF MEMS switch

The simulated results for this switch are shown in Fig. 2. This structure has been designed and optimized using 3D EM simulator. The optimized ON-state return loss (S_{11}) is a minimum of 25 dB from dc to 50 GHz, and a minimum of 12 dB up to 60 GHz. The insertion loss (S_{21}) is less than 0.4 dB up to 50 GHz. The OFF-state isolation (S_{21}) is greater than 40 dB up to 50 GHz. The isolation is only degraded above this frequency due to the existence of a resonance at 54 GHz.

The π-switch is built on high resistivity silicon substrates (5 kΩ.cm) of 630-μm thickness, with a 1-μm-thick layer of silicon dioxide is used as a buffer layer. The switch circuit is constructed on the top of the buffer layer using 3-μm-thick aluminum 50Ω-CPW line with dimensions of G/W/G = 80/120/80 μm. The bottom electrode of the switch is built using 0.3 μm of refractory metal. This film provides a high value of the conductivity, which leads to the low loss performance. In addition, it achieves a good contact between the membrane and the lower electrode due to its smooth surface finish. Therefore, it minimizes any air gab between them, which results in a maximum down-state capacitance for the shunt branch. A thin film of silicon nitride of a 0.1 μm thickness is placed on the top of the lower electrode to prevent the dc control signal from shorting the supply during the switch actuation. However, it allows the RF signal to capacitively couple the upper membrane with the lower electrode. The metallic switch membrane is 0.6-μm thick layer of gold. This membrane has high conductivity, which produces low RF resistance and good mechanical properties. The pull-down electrodes are connected using high resistivity bias lines up to the edge of the ground plane of the CPW line. The silicon nitride layer is used to isolate the bias lines from the ground plane.

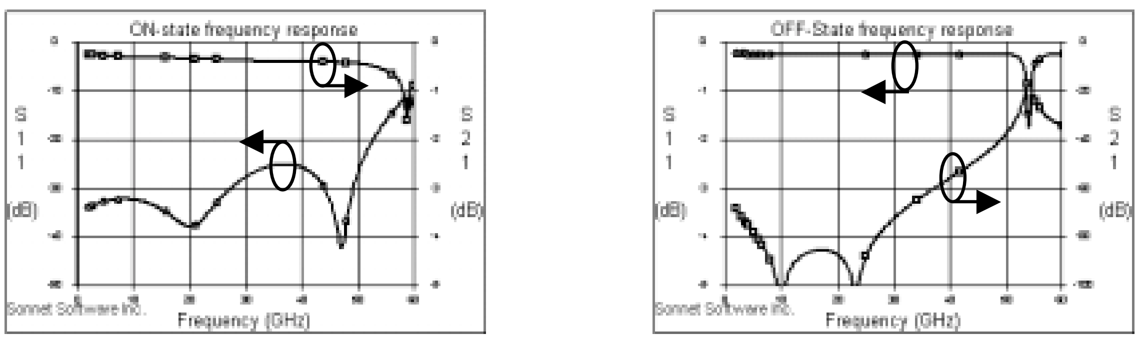
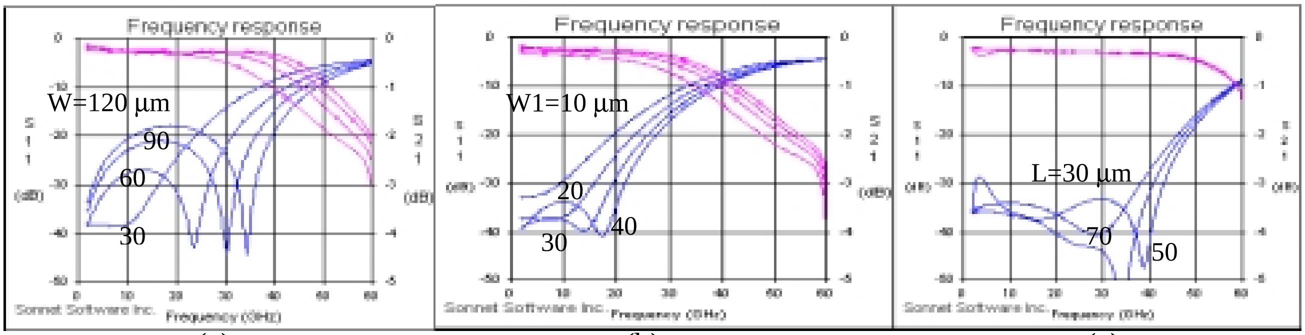


Fig. 2 The frequency response for the π-type RF MEMS switch at the ON and the OFF-states

3. Numerical Experimentations for the Proposed π-Switch

The frequency responses shown in Fig. 2 for the proposed π-switch have been achieved by a try-and-error optimization. Some of these trials are depicted in Fig. 3. A transmission line of 230-μm length is used to connect the shunt and the series arms. This structure produces good isolation over a wide bandwidth. The very high isolation (> 80 dB) is hard to obtain in practices due to the noise floor effect. Our target has been to improve the return loss while keeping the high isolation over a wide band. This has been achieved by incorporating a matching network between the series and the shunt arms. Fig. 3a shows the results of inserting an inductive element between the series and the shunt arms of length λ/8 at 20 GHz and changing its width. The results of inserting another inductive element of λ/8 length at 40 GHz and changing its width, are illustrated in Fig. 3b. The response due to changing the length of the inductive element while maintaining its width at 40-μm is shown in Fig. 3c.

In all cases, the isolation at the OFF-state is not affected by inserting these inductive elements. This is because the isolation is controlled by the gap width in the series resistive switch at low frequencies and by the down-state capacitance of the shunt switch at high frequencies. It is enough to control the width of the inductive elements to obtain a very low return loss for a selected frequency range within our band without disturbing the isolation. The power handling of the switch is also affected by the width of the inductive elements, which puts a limitation on how much narrow width we can reach.

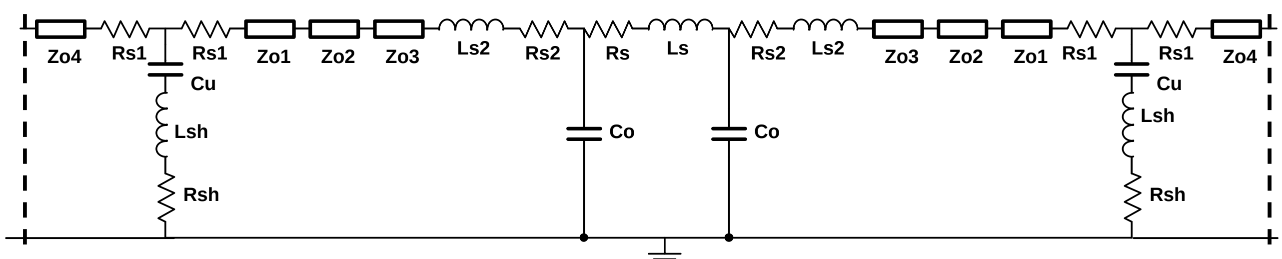


(a) (b) (c)

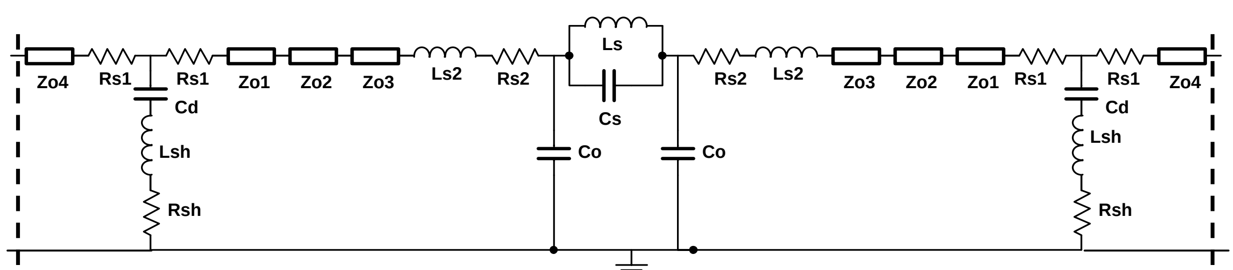
Fig. 3 The On-state S-parameters for the proposed π-switch through the optimization process

4. Circuit Modeling for the Proposed π-Structure RF MEMS Switch

The π-switch is first characterized using the 3D EM simulator to extract its S-parameters at both ON and OFF-states. In addition, the EM circuit simulator (Microwave Office software [6]) has been used to find out an appropriate equivalent circuit for the π-switch. The shunt arm is modeled by one lumped CLR branch, which represents the bridge with the capacitance changing its values from up-state to down-state. The series arm is modeled by a series capacitance at the up position (OFF-state) and by a series inductance and resistance branch at the down-position (ON-state). A combination of series resistance and inductance models the taper in the series arm. The distances between the series and the shunt arms are modeled by transmission lines of different characteristic impedances. The electrical circuit model for the proposed π-switch is shown in Fig. 4. This model is used to fit, as close as possible, the switch S-parameters, which have been obtained using the EM simulator. The modeled and the simulated results for both states are shown in Fig. 5.



(a)



(b)

Fig. 4 Electrical circuit model for the proposed π-switch at the a) ON-state and b) OFF-state

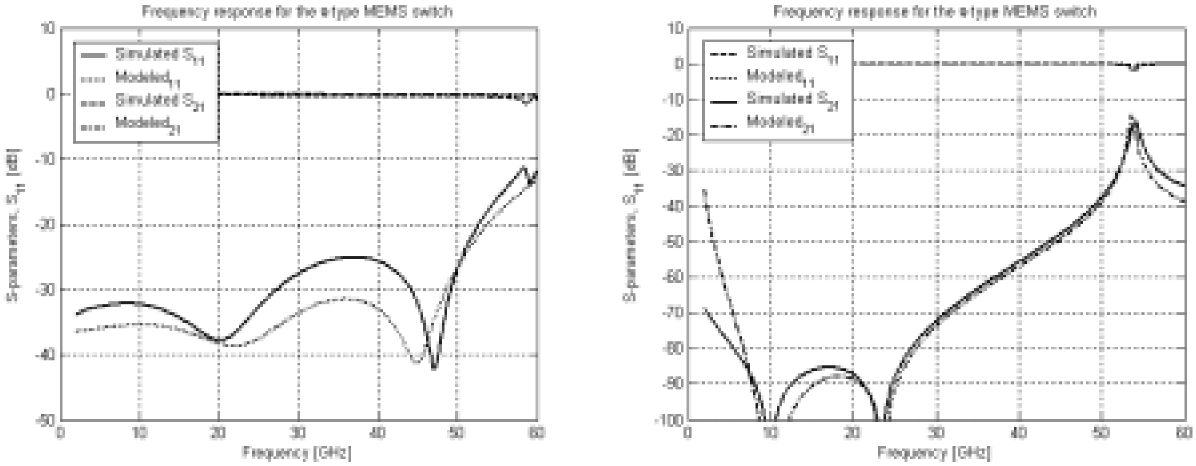


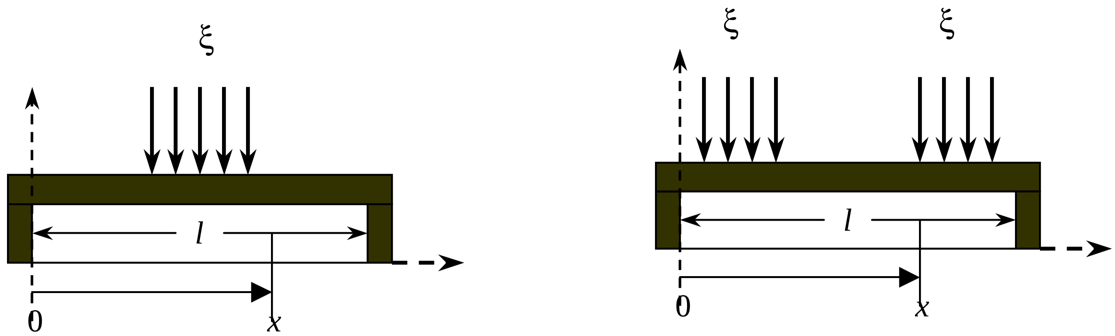
Fig. 5 The simulated and the modeled S-parameters for the π-structure RF MEMS switch

5. Mechanical Modeling for the Proposed π-Structure RF MEMS Switch

The ON-state is defined by the ability of the RF signal to pass. This takes place when the series switch is actuated to the down position which closes the gap in the center conductor of the CPW line while the shunt switch is not actuated (in the up position). In the OFF-state, on the other hand, all switch positions are reversed so that the RF signal is blocked. To actuate the switch for the ON-state, the lower electrode of the series switch is dc-biased with respect to the series switch membrane. To actuate the switch for the OFF-state, the center conductor of the CPW line is dc-biased with respect to the ground. This dc-bias produces an electrostatic force, which pulls the membrane down. This mechanism can be modeled as a spring having linear characteristic [7]. The pull-down voltage value is given by:

$$V_p = V(2g_o/3) = \sqrt{\frac{8k}{27\varepsilon_o W w} g_o^3} \tag{1}$$

Where g_o is the gap height, w is the membrane width, W is the lower electrode width, and k is the effective spring constant. For the different load distributions shown in Fig. 6, the spring constant k can be approximated by:



(a) (b)

Fig. 6 The load distribution for (a) the shunt switch and (b) the series switch

$$k = 32 E w \left(\frac{t}{l}\right)^3 \frac{1}{8(x/l)^3 - 20(x/l)^2 + 14(x/l) - 1} + 8\sigma(1-\upsilon)\, w \left(\frac{t}{l}\right) \frac{1}{3 - 2(x/l)} \tag{2}$$

for the shunt-switch and

$$k = 4 E w \left(\frac{t}{l}\right) \frac{1}{(x/l)\left(1 - (x/l)\right)^2} + 4\sigma(1-\upsilon) w \left(\frac{t}{l}\right) \frac{1}{1 - (x/l)} \tag{3}$$

for the series-switch

The first term is due to the stiffness of the bridge. It accounts for the material characteristics such as Young's modulus of the membrane material (E) and the moment of inertia (I), which is given by ($wt^3/12$), where t is the thickness of the membrane. And l is the beam length. The second term is due to the biaxial residual stress (σ) within the beam and the Poison's ratio for the beam martial (ν). For our optimal design we can expect that the pull down voltage will be in the range of 30-50 volt for E=70 Gpa, ν =0.35, t=2 µm, l=280 µm, w=80 µm, W=120 µm, and g_o=2 µm.

6. Conclusion

The proposed π-switch results in a minimum return loss of 25 dB in the range from dc to 50 GHz, and of 12 dB up to 60 GHz along with a minimum insertion loss of 0.4 dB up to 50 GHz in the ON-state. At the OFF-state the isolation is > 40 dB up to 50 GHz. The expected actuation voltage for this π-switch lies in the range of 30 to 50 volt. This switch is suitable for applications where a high isolation, low loss and good matching are required.

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