Parametric Analysis and Optimization of Non-Contact Transversally Actuated RF MEMS Switch with High Reliability for Wireless Applications

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***Abstract*— This paper presents the study of novel non-contact electrostatically actuated transverse RF MEMS switch. The proposed structure consists of transverse comb actuators which are used to turn the switch ON and OFF. Design is operated at the pull-in point which can achieve the displacement of 10.5 μm at 32.6 volts. To avoid short circuiting of the switch, stoppers are used at the distance of 10.5 μm from the spring beams. The proposed switch is free from stiction issues, which are common in series and shunt contact switches. The design was verified by simulating RF part in CST microwave studio while mechanical simulations were confirmed with the help of Intellisuite software. Simulated ON state insertion loss was -0.1331 dB, while OFF state isolation was -24.96 dB respectively at 6 GHz. The von-misses stress of maximum 39.53 MPa has been observed during operation of the switch which is much less than the 7 GPa critical strength of Silicon. Area of the tunable switch is 2.090 × 1.400 mm^2.**

Keywords— ***Comb drive structure, Electrostatic transverse actuation, Non-contact switch, RF MEMS switch, SOIMUMPs***

I. INTRODUCTION

In this modern era, the demand for efficient and smaller devices is increasing day by day and devices with low power consumption integrated with radio frequency (RF) applications are the most discussed subject these days. These RF systems are useful in many ways due to their inter-disciplinary characteristics which can provide great performance to the designer. RF systems based on MEMS technology have several advantages over conventional systems [1].

Switches are the most essential components in RF MEMS domain due to their high performance for various parameters which include isolation, insertion losses and low voltage requirement in the device. These switches can embed in high frequency applications which are the requirement of today's wireless communication system [2].

To operate RF MEMS switches, different types of actuation mechanisms are adopted which includes electrostatic, electro-thermal, piezoelectric and magneto-static actuation mechanisms [3]. Among these categories, Electro-thermal and Electrostatic mechanisms are the most widely used and are attractive actuation types. Electro-thermal actuators are very easy to fabricate, they require low actuation voltage, but their power consumption is very high with slow response time and cause thermal fatigue due to thermal cycle [4–6]. Electrostatic actuation method, on the other hand, offers high frequency, fast switching time and can be easily fabricated but it requires high actuation voltage [3].

After the first demonstration of radio frequency switches, many contact type RF MEMS switches have been designed up till now with different configurations. These configurations are categorized into two parts i.e. shunt capacitive switches and series ohmic switches. In series ohmic contact switches (metal-metal), there is a direct metal to metal connection between the metal plates [7, 8]. The drawback of this type of switch is that the contact resistance, performance degradation, arcing and stiction problem increases when the switch is in down state. While in shunt capacitive switches (metal-insulator-metal), the air gap is always present which acts as a dielectric between the two electrodes and is adjusted electromechanically due to which the capacitance between two metal plates can be varied [9]. The drawback of capacitive switches includes charge accumulation and charge trapping inside the dielectric layer which directly affects the reliability performance of the switch [10].

In recent literature, numerous MEMS switches have been exhibited to accomplish better RF performance. Shunt

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capacitive RF MEMS switch was presented in [11], with uniform and non-uniform spring structure. The insertion loss and isolation was obtained -0.12dB and -14dB respectively. Another design of switch was proposed by Li M. et.al [12], in which Insertion loss of 0.29dB while isolation of 20.5dB was achieved. Insertion loss and isolation are critical parameters and there is a trade off between isolation and insertion loss. Isolation of -22.5dB while insertion loss of -0.8dB has been reported in [13] for RF MEMS shunt switch. Recently, Shekar et al. [14] designed capcitive RF switch with an insertion loss of 0.25 and 0.7 dB at 20 GHz and 40 GHz respectively while isolation was 30 dB. Yang et al [15] published an article with the design having insertion loss of 1dB and isotion of 12 dB at 20 GHz to minimize the residual stress.

To address the above-mentioned issues, a novel non-contact type RF MEMS switch design has been proposed in this paper. A small air gap is always present between the variable capacitors due to which there is no direct contact between the comb plates, thus the contact resistance and stiction issues are eliminated. The switch is implemented using SOIMUMPs [16] process of MEMSCAP. The structure of the proposed design consists of moveable and fixed combs moving in normal direction to each other. The design is operated at pull-in voltage point. The proposed structure provides the best mechanical performance with no deformation among competing designs of similar specifications.

II. Design of non-contact RF MEMS switch

In the proposed switch design, electrostatically actuated transverse mechanism is used in which the movement of the plates or combs is normal to each other in a specific direction as shown in Fig. 1. The CPW transmission line has been selected because of uniform transmission of signal. In the RF part of RF MEMS switch, numbers of comb plates are 2 × 3 i.e. total of 6. The isolation of the design can be varied by decreasing or increasing the number of comb fingers. The isolation decreases on increasing the capacitance area and vice versa. So, to get the desired results, the length, width and numbers of comb fingers of the switch are kept in such a way that the insertion loss is minimum and provide the maximum desired isolation.

When the voltage is applied on the actuator part of the switch, the electrostatic force is generated between the combs of actuator that helps the movable combs of actuator to displace from their original position as shown in Fig. 1. The reduction in gap between the combs of actuator allows the moveable plates of RF part to move forward thus decreasing the gap between moveable and fixed plates to turn the switch ON as illustrated in Fig. 2 (a). In this state, though the plates do not make a direct contact with each other because a gap of 0.5 μ m is always present between them but RF signal passes from input to output. The degradation and stiction issues of the series and shunt contact switches are mitigated in this design using non-contact transverse electrostatic actuation configuration which makes the design more reliable.

When the voltage is removed from the actuator, the combs move backward to their original position due to the restoring force of the springs generating a gap of 11 μ m between combs of RF part as shown in Fig. 2 (b).

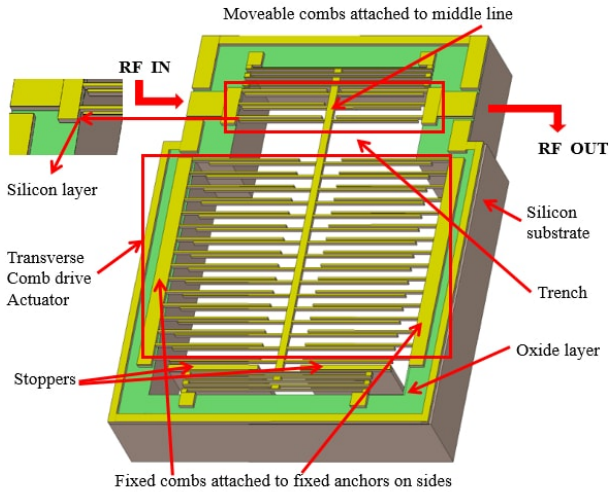

Fig. 1. Proposed design of the RF-MEMS switch

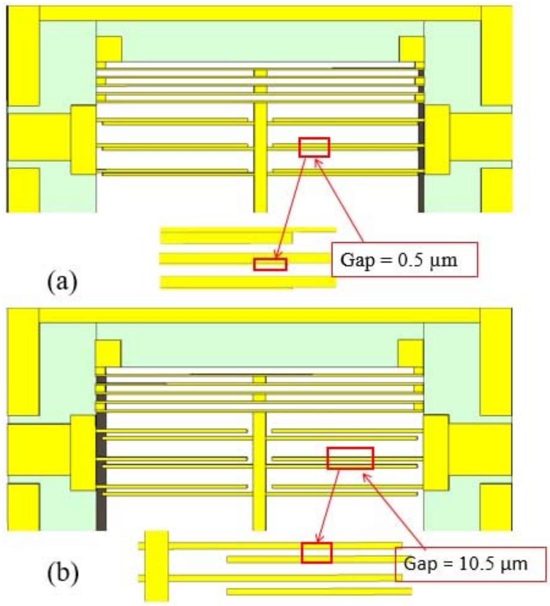

Fig. 2. (a). ON state of the RF-MEMS switch (b). OFF state of the RF-MEMS switch

The design is operated at the pull-in voltage point of 32.6 volts. To avoid short circuiting of the switch and to stop spring's free movement, the stoppers are substituted in the design at 10.5 μ m from the spring beams. When the voltage is applied on the actuator, mechanical movable structure tends to move in upward direction turning the switch ON. The simulated voltage and displacement graph of the design is shown in Fig. 3. The graph shows the behavior of switch at the applied voltage. At the initial values of the applied voltage, displacement is increasing slowly while after 32.6 volts, an abrupt increase in the displacement has been observed. The pull-in voltage value can be calculated from the Equation 1 [17].

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$$V_p = \frac{2Xo}{3}\sqrt{\frac{k_m}{1.5C_o}} \tag{1}$$

Where, *Xo* is the initial gap between combs, *Co* is the initial capacitance of the actuator, and *km* is the 3 mechanical stiffness of the beams.

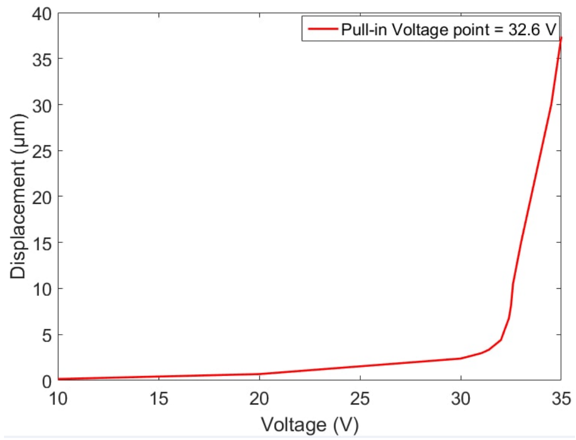

Fig. 3. Plot of voltage vs. displacement values

III. DESIGN OPTIMIZATION

This paper is more focused on parametric analysis which has not been reported in literature yet. To analyze the RF performance of the RF MEMS switch, parametric analysis was done. Parametric analysis of the device was needed to analyze the effect of change of different parameters, when the switch undergoes the fabrication process. As the dimensions of the fabricated device are not always the same, therefore, optimization of the switch has been done to check its performance within specific range of length, width and gap. These length, width and gap of combs affect significantly the performance of RF MEMS switch. To optimize these parameters, performance of switch has been analyzed by varying the values of these parameters at the frequency of 6 GHz. Fig. 4 and Fig. 5 shows the parametric analysis of the switch at different values of the length and width to analyze the effect on isolation. The trend shows that on decreasing these factors, the isolation increases and vice versa.

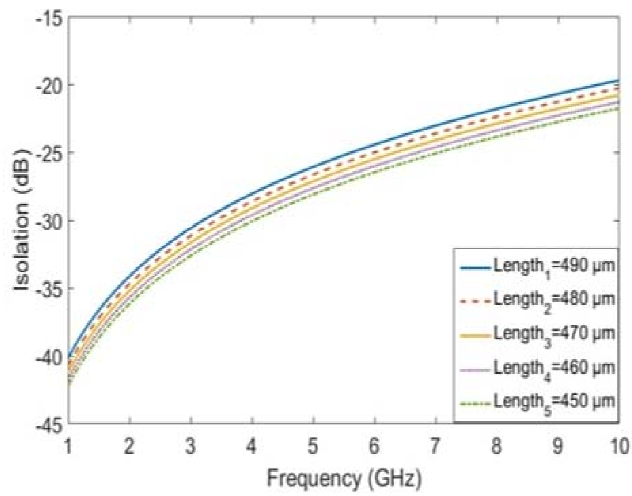

Fig. 4. Plot of isolation vs. comb length

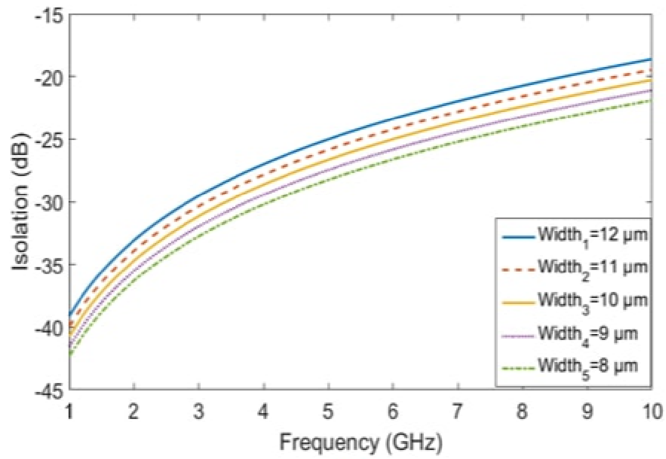

Fig. 5. Plot of isolation vs. comb width

Fig. 6 shows the parametric analysis of the switch at different values of the lengths to check its effect on insertion loss. It is observed that no significant change occurs on increasing or decreasing the length. However, it can be seen that on increasing the length of the comb, the insertion loss decreases.

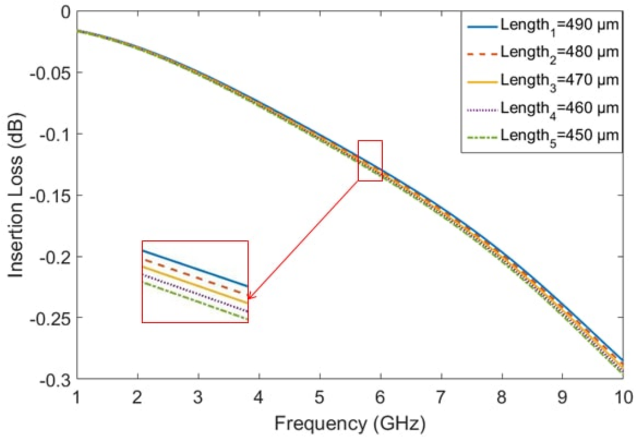

Fig. 6. Plot of insertion loss vs. comb length

Parametric analysis of the proposed design was also done to optimize the maximum and minimum gap between the combs for isolation and insertion loss within specific range of frequency (1 GHz to 10 GHz). From the graphs it can be clearly observed that on increasing the gap, isolation increases as shown in Fig. 7.

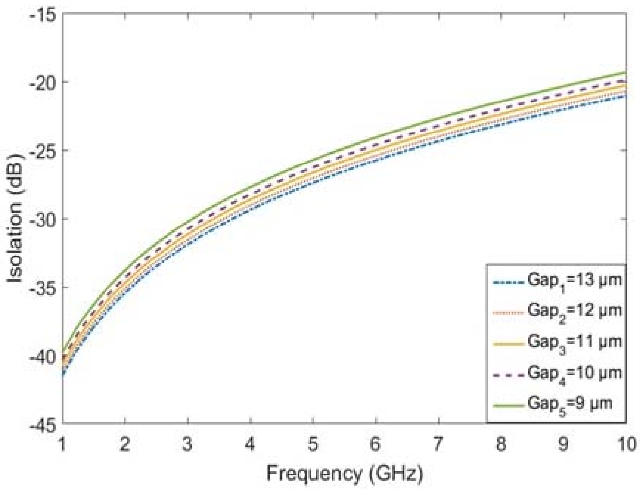

Fig. 7. Plot of isolation vs. varying gaps

On the other hand, varying gap did not affect the results of insertion loss greatly as shown in Fig.8, where within the range of 0.1 to 0.8 μm gap the insertion losses are almost same and did not change significantly.

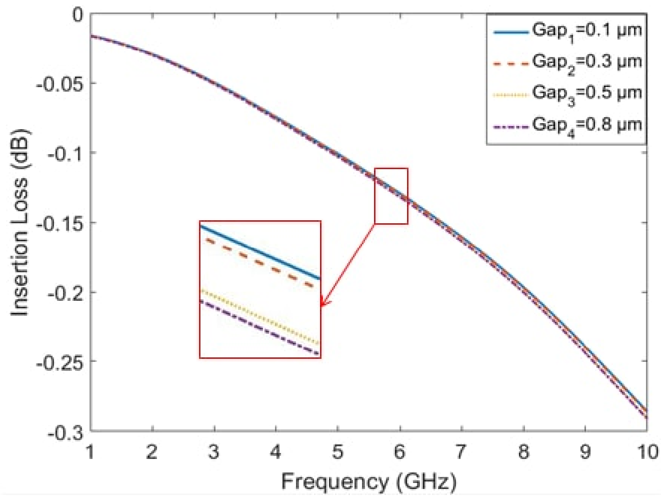

Fig. 8. Plot of insertion losses vs. varying gaps

IV. Result and Discussion

The RF electrical design of the proposed structure is simulated in CST microwave studio and the mechanical simulations were done in Intellisuite software. The optimized lengths and widths of comb fingers of RF and actuator part are listed in Table 1.

TABLE 1. OPTIMIZED DIMENSIONS OF PROPOSED DESIGN

Parameters	Values (µm)
Optimized lengths and widths of actuator combs	
Length of actuator combs	600
Width of actuator combs	20
Gap between actuator combs	11
Length of stopper	400
Width of stopper	30
Optimized lengths and widths of RF combs	
Length of comb fingers	480
Width of comb fingers	10

Analysis for the isolation and insertion loss to check the performance of the proposed switch in OFF and ON state was also performed at the optimized dimensions of the switch obtained from the parametric analysis. The maximum isolation achieved through the proposed structure of the switch with gap of 10.5 μ m is -24.96 dB at 6 GHz as shown in Fig. 9, while the insertion loss was -0.1331 dB as shown in Fig.10.

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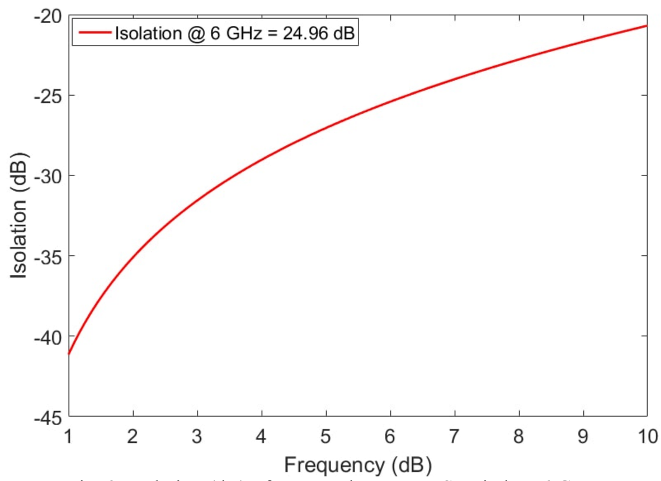

Fig. 9. Isolation (dB) of proposed RF MEMS switch at 6 GHz

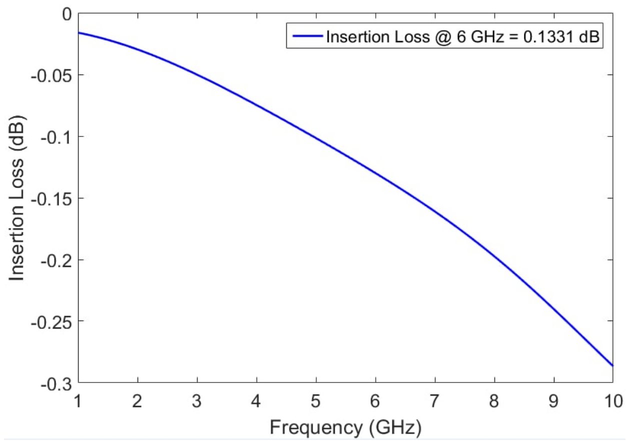

Fig. 10. Insertion losses of proposed RF MEMS switch at 6 GHz

A. Displacement Analysis

Displacement of the switch varies with the varying voltage values. When the voltage is applied, electrostatic force is induced between the fixed and moveable combs of the actuator due to which the gap between the plates of RF part increases or decreases depending on the values of applied voltage. Different voltage values were applied on the switch for which different displacement results were obtained. At the initial values of applied voltages, no significant deflections were observed in the switch. But after pull-in point, sudden increase in the displacement values of the switch occurred and at 32.6 volts, the maximum displacement of 10.5 μ m was achieved. The simulated displacement result plots of the switch in y-axis are shown in Fig. 11. From the results, it is observed that the maximum displacement has been achieved in y-axis.

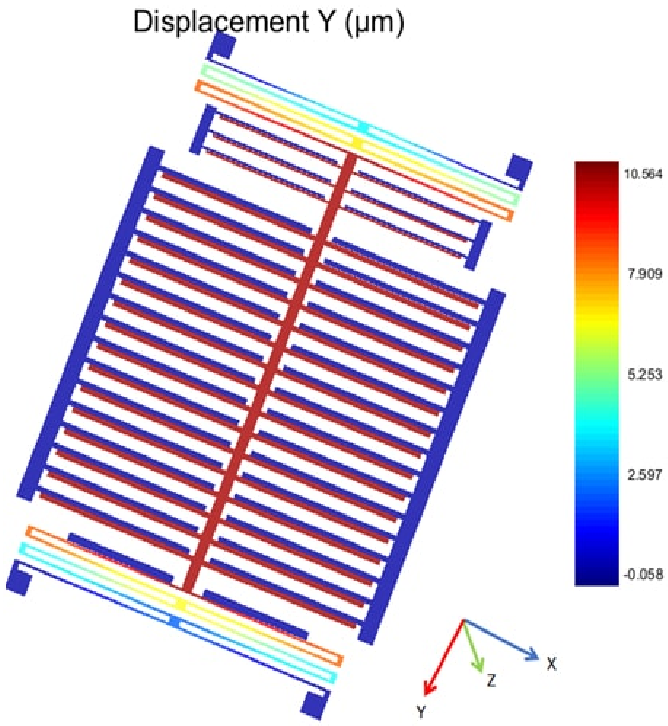

Fig. 11. Displacement of proposed RF MEMS switch in y-axis

B. Stress Analysis

Critical points of the switch were analyzed using Intellisuite software. Maximum von-misses stress of 39.53 MPa was observed during the operation of the switch which is much less than the critical strength of Silicon i.e. 7 GPa [18–20]. From the results, it was observed that maximum stresses are on the sides and middle of the spring beams. Fig. 12 shows the stresses at different points of springs of the design.

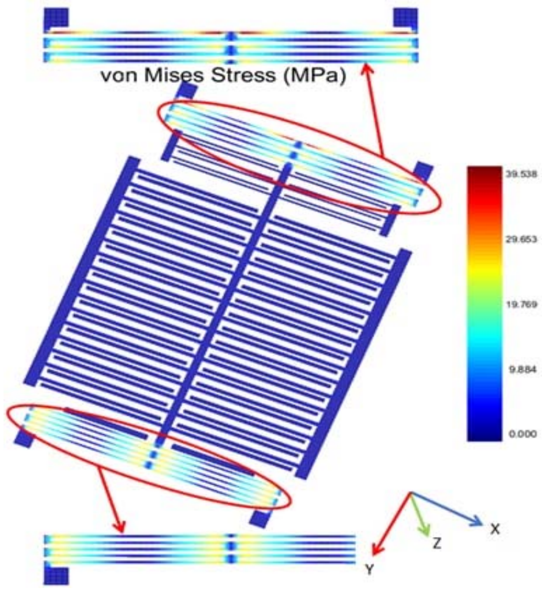

Fig. 12. Stress analysis of the proposed design

For the proposed design, modal analysis was performed to predict different modes of frequencies of the switch to avoid its resonance and vibrations with the external frequency [21-25]. If the external frequency matches with any mode frequency of the switch, the system may start to resonate and show a destructive behavior. First5 modes of the switch design were analyzed using Intellisuite software which are listed in Table 2.

TABLE 2. MODE ANALYSIS

No. of Modes	Frequency (Hz)
1st	3473.2
2nd	6082.48
3rd	8077.99
4th	11795.7
5th	13133.1

V. CONCLUSION

In this paper, design and analysis of a non-contact RF MEMS switch has been discussed. The switch is operated on electrostatic transverse actuation method. Direct contact between the plates of the switch has been avoided which makes the switch free from reliability issues. Insertion loss of the proposed design is 0.1331 dB while isolation is 24.96 dB at 6 GHz. Maximum von misses stress of 39.53 MPa has been observed which is much less than the critical strength of the Silicon i.e., 7 GPa. It is observed that the performance of the switch is much better than capacitive and ohmic RF MEMS switches due to higher isolation and low insertion loss of switches within the frequency range of 1 to 10 GHz. The proposed RF MEMS switch is promising for wireless applications, WLAN systems and reconfigurable antennas for wide frequency bands.

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