Equivalent Circuit Modelling of RF MEMS Series DC-Contact Switch and Actuated Voltage Analysis

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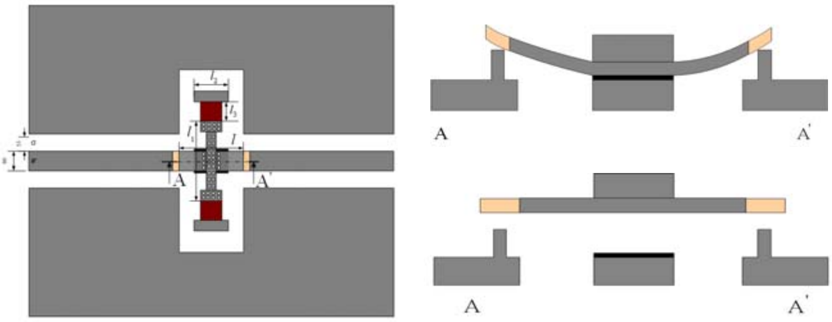
1. Introduction

Radio Frequency Micro electromechanical System (RF MEMS) are RF circuits manufactured with MEMS technology, taking features of compactness, light weight, zero DC power consumption and very high cut-off frequency, and therefore demonstrate huge application potentiality in wireless communication and microwave fields. Among of them, RF switches are key elements in the process of microwave and high frequency signals switching. Many researches on the equivalent circuits of the RF MEMS switch have been made. However, almost all of them were built after the switches were designed and fabricated and were developed by fitting the measured *S* parameters. Nevertheless, these models can not provide useful guidance for the design of RF MEMS switches, the value of the elements in the equivalent circuits depend on the measured *S* parameters, not on the geometrical parameters of the switch. In our work, the initial model of the RF MEMS switch is designed firstly, an equivalent circuit is thus proposed, the formulas for each elements inside are given. The equivalent circuit is numerically simulated with ADS, while the practical structure of the switch is simulated by HFSS. Good agreement can be observed between these two results, indicating the accuracy of the equivalent circuits and the design validity for the proposed switch.

2. RF MEMS Series DC-Contact Switch

The switch is shown in Fig.1, which is built on a section of CPW printed on a dielectric substrate with thickness 500um and dielectric constant 11.9, the width of the central strip is 90 um, the gap between central line and the ground plane is 53 um. In the switch, the signal lines are connected by a section of gold cantilever with thickness 1.5 um and length 250 um. A supporting cantilever of thickness 4 um and length l_1 = 300um is positioned above the gold cantilever. Both ends of the supporting cantilever are connected with the gold anchors through the dielectric material with length l_3 =100um, helping to achieve good impedance matching between the switch and the CPW. In addition, several holes with size of $10\times10\text{um}^2$ are used in signal transmission to support cantilever, decreasing the damping coefficient and reducing the switching time. In addition, five poles of 1.5 um high are introduced to connect signal transmission cantilever and central strip of CPW, increasing the contact pressure and area and then helping the cantilever have enough deformation [1]. Considering the contact resistance in a practical switch, two sections of high impedance lines are used to replace the both ends of the gold cantilever.



(a) (b)

Fig. 1 (a) the structure of DC-contact switch, (b) Cross-section at “on” and “off” states

3. The Equivalent Circuit Of The DC-Contact RF MEMS Switch

3.1 The equivalent circuit at down state (“on” state)

The signal line above the actuated plate is a section of CPW with characteristic impedance Z_1, and the rest of transmission cantilever can be regarded as inductors, resistors respectively. Furthermore, considering the slot capacitance of the switch, the resultant equivalent circuit is shown in Fig. 2.

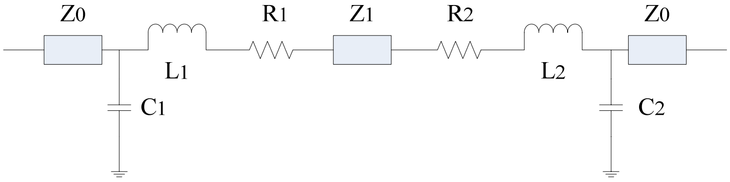


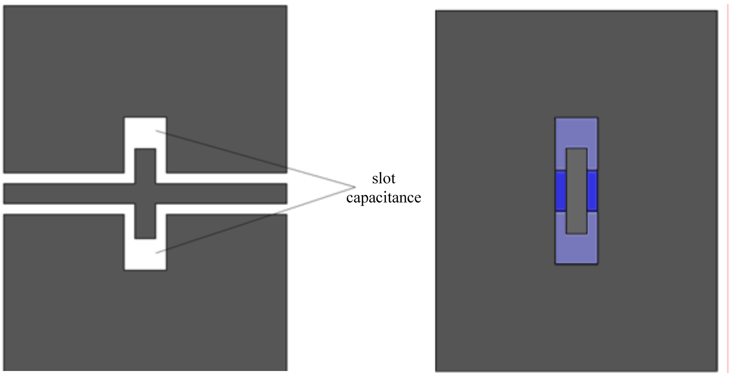
Fig. 2 Equivalent circuit of the RF MEMS switch at down state

The inductance can be calculated with the formula in [2,3], in this work, the inductance of 75um long transmission line is $L_1 = L_2 = 14.8$ pH. The resistance of high-impedance lines can be calculated from $R = l/S/\sigma$, where S is the cross section area of the high-impedance lines [2], which can be expressed as

$$S = \begin{cases} 2\delta_b(w_b + t_b - 2\delta_b) & t_b \ge 2\delta_b \\ t_b w_b & t_b \le 2\delta_b \end{cases} \tag{1}$$

Of which δ_b is the skin depth, w_b and t_b are the width and thickness of the high-impedance line, respectively. Here $t_b = 4um$, $\delta_b = 1/\sqrt{\pi f \mu \sigma}$, $t_b \ge 2\delta_b$, so resistance changes with the frequency.

Simple model of the DC-contact switch at down state is shown in Fig. 3(a). It is difficult to calculate the slot capacitance of the switch, its complementary structure is thus proposed, in which the central conductor and the ground are removed, thus replacing the slot with a conductor, as illustrated in Fig. 3(b). The total inductance can be found by subtracting the parallel inductor from ring inductor. Because the slot capacitance where the parallel inductor locates is very small, it can be ignored.



(a) (b)

Fig. 3 (a) Simple model of the DC-contact switch, (b) Complementary structure of the slot

The ring inductance L_1 and parallel inductance L_2 can be found through the formulas, the total inductance is $L = L_1 - L_2$, then the slot capacitance is easy to get,

$$C = \frac{4\varepsilon_0 L}{\mu_0} = \frac{4\varepsilon_0 (L_1 - L_2)}{\mu_0} = 16.3\, fF$$

The practical switch is analyzed by HFSS while the equivalent circuit can be simulated with ADS as the circuit elements known. The insertion losses of the equivalent circuit and the practical switch are both illustrated in Fig. 4, the curve with empty circles representing the result of the equivalent circuit simulated by ADS, while the curve with solid circles is from HFSS simulation of the practical switch. We may note that, good agreement can be observed between these two results, demonstrating the accuracy of the proposed equivalent circuit. In addition, the return loss is over 20dB in the whole band.

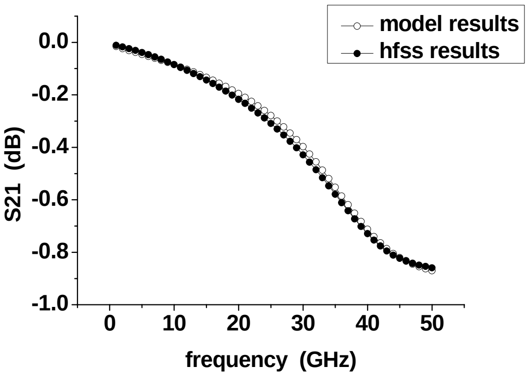


Fig. 4 Comparison of insertion losses from the equivalent circuit and practical geometry of the RF MEMS switch (down state)

3.2 The equivalent circuit at up state ("off" state)

At "off" state, only capacitances existing in the *CLR* equivalent circuit will be considered, saying, the capacitances C_1 and C_2 between the ends of cantilever and signal transmission line.

$$C = \frac{\varepsilon_0 ab}{g_0} + \frac{\varepsilon_0 b}{\pi}(1+\ln(1+\frac{2\pi a}{g_0}+\ln(1+\frac{2\pi a}{g_0}))) \tag{2}$$

Where a, b is the width and length of the signal transmission line, g_0 is the gap between cantilever and transmission line. In the equivalent circuit for "off" state, only two capacitances are considered. Similarly, the software ADS is used to simulate the equivalent circuit, and the practical configuration of Fig.1 is simulated by HFSS, both results are illustrated in Fig.5. The curve with empty circles represents the ADS-simulated isolation of equivalent circuit, while the curve with solid circles is the HFSS-simulated results of the practical switch.

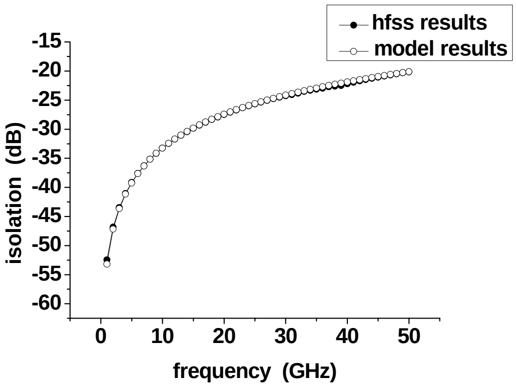


Fig.5 Comparison of isolations from the equivalent circuit and practical geometry of the RF MEMS switch (off state)

As we can see, the isolation of the switch at off state is quite big, over 20dB in the whole frequency band. In addition, good agreement between the isolations for the equivalent circuit and the practical switch can be observed very clearly, further indicating the validity and accuracy of our equivalent circuit model proposed for the RF MEMS switch.

4. Analysis of the Actuated Voltage

The actuated voltage is given by $V_p = \sqrt{\frac{8k}{27\varepsilon_0 A} g_0^3}$ [4], where k is the effective spring constant, g_0 is the nominal gap height and A is the actuated plate area. If the shape of the cantilever is changed, the effective spring constant k will change, however, it is hard to know the exact value of k, and thus difficult to calculate the required actuated voltage for the RF MEMS switch. In this way, the software ANSYS is used to analyze the actuation voltage through electro-mechanical coupling analysis [5]. Fig. 6 displays the deformation of the cantilever. Different colours present different deformation. The ends of the cantilever have the biggest deformation. We may note that, when the actuated voltage is 27.3V, the enough deformation can help the cantilever to touch with CPW, the DC-contact switch is thus on.

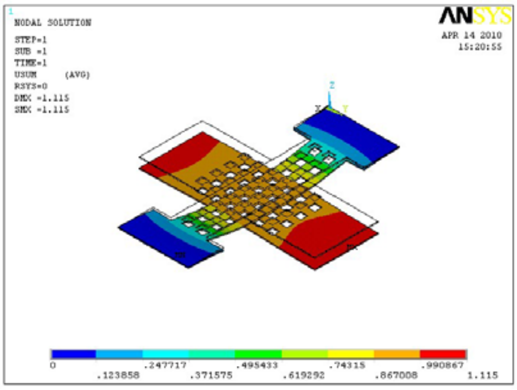


Fig. 6 deformation of the cantilever

5. Conclusion

A novel RF MEMS Series DC-contact switch is proposed and designed in this paper. The equivalent circuit for this switch is investigated and proposed at “on” and “off” states. The formulas for the circuit elements are given. Comparisons between the results of the equivalent circuits and practical switch are made, good agreement can be observed very clearly, implying the good performances of the switch and the validity of the proposed equivalent circuits. Unlike other equivalent circuits, the values of the circuit elements are obtained by fitting the measured S parameters; the circuit elements of the model in this work are calculated from the formulas related to the geometrical parameters and can thus provide some useful guidance for the design of RF MEMS switch. In addition, ANSYS is used to simulate the actuated voltage of RF MEMS switches, which can be further reduced by some techniques.

Acknowledgement

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