Electrical Lumped Model for Implemented RF-MEMS Capacitive Switch on Semi-suspended Coplanar-waveguide

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Abstract— A novel electrical lumped model for an RF MEMS capacitive switch which is implemented on a semi-suspended coplanar-waveguide is proposed and studied. The quality factor is mathematically studied taking the effects of air-gaps and substrate resistance into consideration. Results indicate that increasing the equivalent resistance of transmitting line and the switch, series resistance, in down-state has negative effect and can considerably decrease the quality factor. Increasing the capacitance of the switch also has a negative effect on the quality factor. Increasing the substrate resistance improves the quality factor. Lower capacitance can allow the switch to operate with a wider bandwidth of high quality factors and larger capacitance can make the bandwidth narrower.

1. INTRODUCTION

Micro-electro-mechanical systems (MEMS) are growing rapidly in the integrated and packaging device area especially for interfaces working with motion, light, thermic radiation, etc.. Furthermore, it offers incredible performance, high signal linearity, and low insertion loss for switches. Although they suffer from some minor drawbacks such as complexity, reliability issues, they operate with high quality factor with relatively small size [1]. PIN diodes, FETs switches cannot fulfil the expected performance for today's communication systems while MEMS switches can operate with great performance even with frequency above 100 GHz [2].

2. BACKGROUND REVIEW

In a MEMS switch an external effort is sometimes needed to stabilize the switch in "on" or "off" state. They can be used for many applications [3, 4]. Capacitive shunt switches are very suitable for wireless equipment since their power consumption and fabrication process are low and simple respectively. A capacitive shunt switch consists of a metal bridge (membrane) connected to RF ground moving in vertical direction. Without the electrical effort, the signal line is isolated from the metal bridge and it can pass through the switch. When the electrical effort is imposed, the metal bridge grounds the signal line. Figs. 1(a), (b), (c) depict the structure of a capacitive switch on a normal coplanar waveguide (CPW).

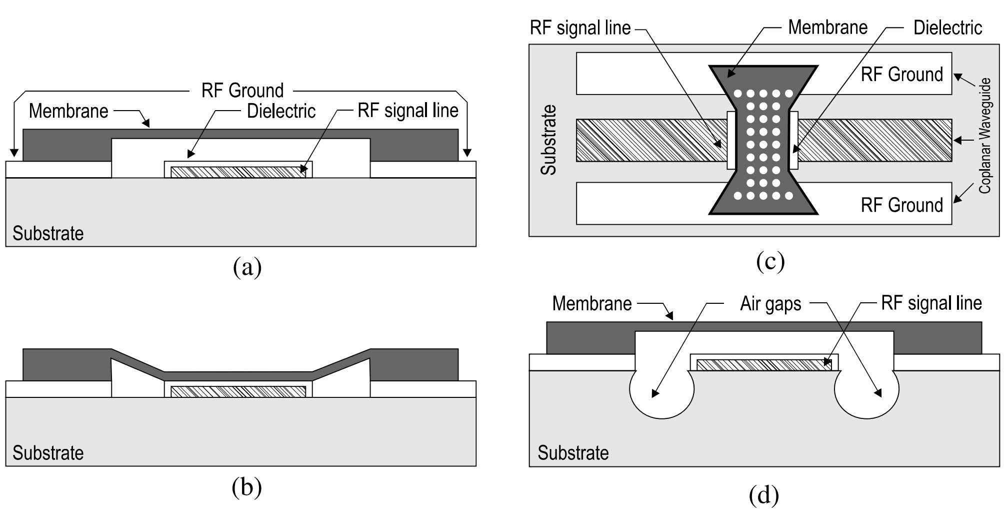


Figure 1: Structure of an RF-MEMS capacitive switch on normal CPW. (a) Up-state. (b) Down state. (c) Top plan view of the capacitive switch. (d) Structure of an implemented RF-MEMS capacitive switch on semi-suspended CPW [6].

3. MODELING AND METHODOLOGY

Normally, passive components degrade the efficiency but MEMS technology offers higher quality factor with less degradation. An electrical model is needed to for simulation with acceptable approximation. In [5] an electrical model was proposed and the study focused on quality factor including parasitic effects. A modified structure for RF-MEMS capacitive switch on semi-suspended CPW has been proposed in [6] (Fig. 1(d)). The switch had two air holes on two sides of the signal line. The study lacked proposing any electrical model for this structure. In this paper, the methodology of [5] is used to propose a novel electrical lumped model for the structure in [6].

According to the basic theory, the quality factor can be defined as [1]:

$$Q = \omega \frac{Aes}{Lss} \tag{1}$$

where A_{es} is the average energy stored, L_{ss} is energy loss/second and ω is the operating frequency.

A physical discrete capacitor can be modeled with 3 basic electrical elements as L_s, C, R_s in series and L_s, C, R_p in parallel configuration which are depicted in Fig. 2. The impedance of the discrete capacitor is:

$$Z = R_s + j\left(\omega L_s - \frac{1}{\omega C}\right) \text{ for series} \quad Z = \frac{1}{\omega^2 C^2 R_P} + j\left(\omega L_s - \frac{1}{\omega C}\right) \text{ for parallel} \tag{2}$$

and the capacitor quality factor is $(1/\omega C R_s)$ and $\omega C R_P$ for series and parallel model respectively when $\omega L_s \ll 1/\omega C$.

The self-resonant f_0 occurs when $\mathrm{Im}(Z) = 0$ and $f_0 = 1/(2\pi\sqrt{LC})$. Series inductance (L_s) has great effect on the capacitor impedance for higher frequency than f_0 [5].

An electrical model for a normal capacitive shunt switch is depicted in Fig. 2(c). This model is usually referred to as the T-model [1]. C, L, and R_s denote the effective variable capacitor, inductance of the switch, and series parasitic resistance of the suspended membrane respectively. The horizontal section of the T-model represents the $50\,\Omega$ impedance matched of CPW (Z-line). The impedance of the line can be modelled by R_{sl} and L_{sl} [5]. Although this model is acceptable for predicting the quality factor, it fails to determine the quality factor for the frequencies lower than 10 GHz since the substrate effect of switch is not included.

Based on the T-model, the quality factor can be obtained [1]:

$$Q = -\frac{\mathrm{Im}(Z_s)}{R_e(Z_s)} \tag{3}$$

where $Z_s = R_{sl} + j\omega L + (1/j\omega C) + R_s$. C can be in "up" or "down" state but in this paper down-state is studied. The resistance of the line and bridge are the culprits for the device loss [5] and the quality factor is a function of frequency causing the quality factor to rise to its peak and then drops to 0 [7].

Figure 3(a) shows an electrical lump model for the substrate of a normal capacitive shunt switch [5] but the physical description of the implemented switch on the semi-suspended CPW in Fig. 1(d) is slightly different. Fig. 3(b) is proposed to modify the electrical model for this switch since the effect of substrate and air-holes are included.

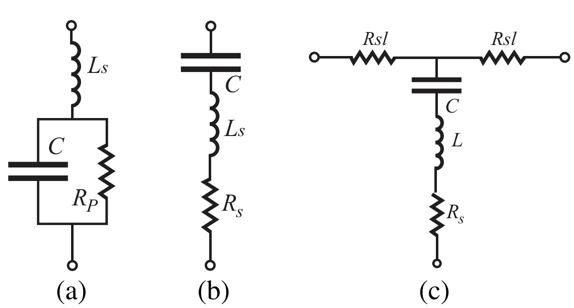


Figure 2: Electrical model for discrete capacitor in (a) parallel and (b) series configurations, (c) T-model for normal capacitive shunt switch [1].

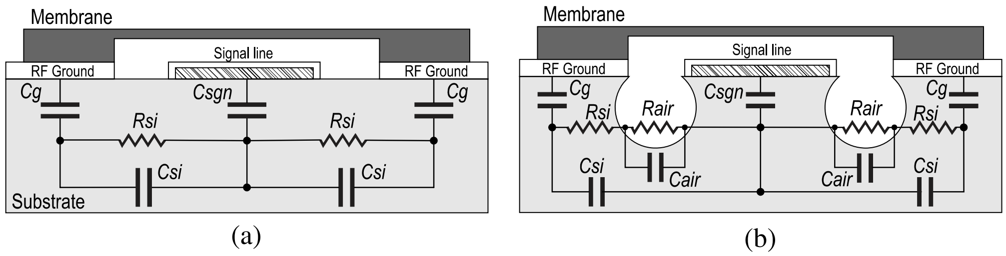


Figure 3: Electrical model for substrate ofanimplemented capacitive shunt switch on (a) normal CPW, (b) semi-suspended CPW.

A comparison between the normal structure and the new structure proposed in [6] shows that the only difference is the air gaps in the CPW which can be model as resistors (R_{air}) and capacitors (C_{air}) in parallel configuration. Therefore, the substrate has resistive and capacitive characteristics, and they are given by:

$$C_C = \frac{2CgC_{sgn}}{2Cg + C_{sgn}} \tag{4}$$

where C_C is the equivalent capacitance of CPW. C_{sub} is $2C_{si}$ and represents the equivalent capacitance of substrate. R_{sa} is $(R_{air} + R_{si})/2$ and denotes the equivalent of both air and substrate resistances. Therefore, a complete lumped electrical model can be proposed and shown in Fig. 4. The highlighted section is equivalent circuit of the substrate effect. The two R_{air} are added to the circuit to model the two holes in the substrate while (C_{air}) is negligible.

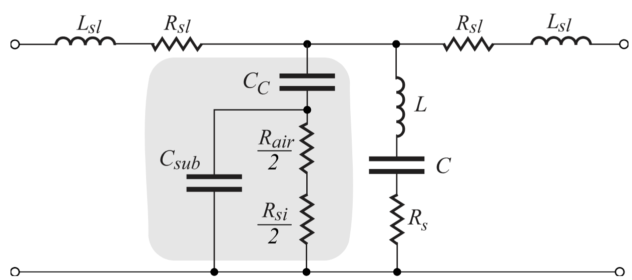


Figure 4: Proposed lumped electrical model for an RF-MEMS capacitive switch on semi-suspended CPW.

Characteristics of the added parallel section can be determined by $f_{zero} = 1/(2\pi(C_C + C_{sub})R_{sa})$ and $f_{pole} = 1/(2\pi C_C R_{sa})$.

In the frequency range $f_{zero} < f < f_{pole}$ the equivalent resistance of substrate (R_{sa}) shunts the MEMS capacitor. In this condition, the joint effect of series and shunt resistors cause the overall device losse.g. the quality factor is determined by shunt losses at low frequency but higher than f_{zero} while at higher frequency, it is determined by the effect of series parasitic resistance ($R_{series} = R_{sl} + R_S$). The inductive parasitic and the capacitive effects of substrate are negligible. The two sub-quality factors are $Q_{series}(\omega) = 1/(\omega C R_{series})$ and $Q_{shunt}(\omega) = \omega C R_{sa}$. Hence,the total device quality factor is:

$$Q_{SW}(\omega) = Q_{shunt}(\omega) \,||\, Q_{series}(\omega) \Rightarrow Q_{SW}(\omega) = \frac{\omega C R_{sa}}{1 + \omega^2 C^2 R_{sa} R_{series}} \tag{5}$$

and the maximum of quality factor in down-state happens when $\omega = \omega_P$:

$$Q_P = Q_{SW}(\omega_P) = \left(\frac{1}{2}\right)^{\frac{3}{2}} \sqrt{\frac{(R_{si} + R_{air})}{R_{series}}} \tag{6}$$

4. RESULT AND DISCUSSION

Figure 5 represents the performance of the switch over 1–50 GHz by assuming the physical parameters in [5] as $C = 1.8\,\text{pF}$, $L = 170\,\text{pH}$, $R_S = R_{sl} = 275\,\text{m}\Omega$ and $R_{sa} = 1.4\,\text{k}\Omega$.

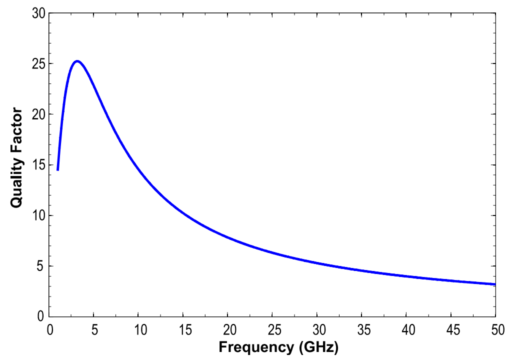
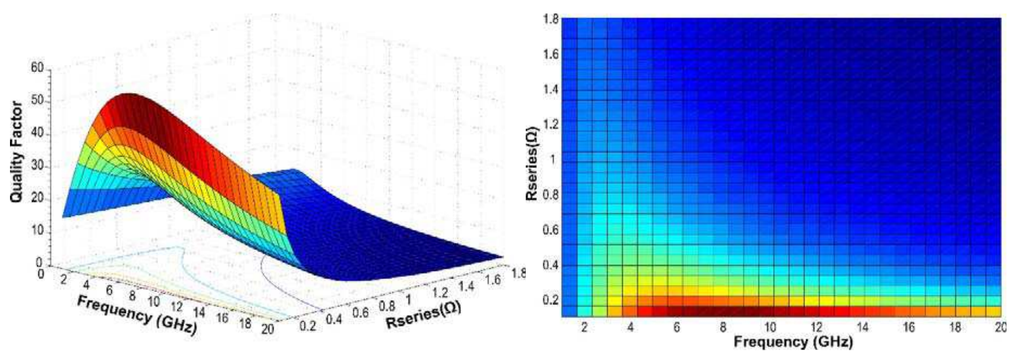


Figure 5: Fluctuation of the quality factor over frequency.

R_{series} is the main cause of power loss in the line [8]. Fig. 6 shows the effect of R_{series} on the quality factor. The effect is noticeable in the range of 0.2–0.8 Ω. It also indicates that R_{series} is expected to be as small as possible for operating in high frequency region.

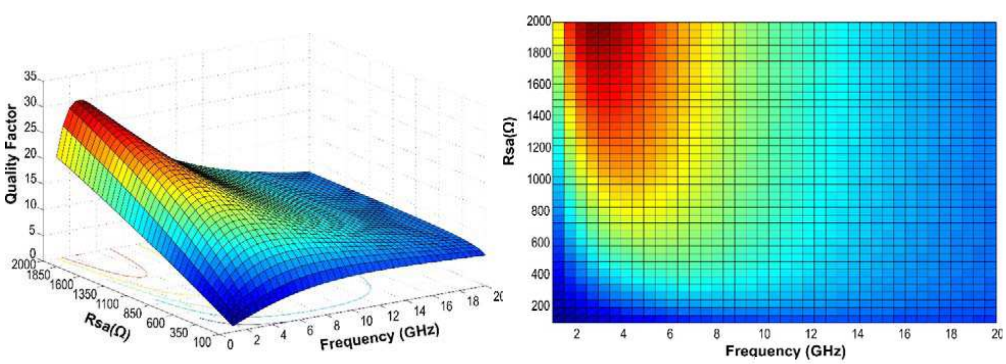
The equivalent resistance of substrate is $R_{sa} = (R_{air} + R_{si})/2$ where R_{si} is resistance of the high resistive silicon. Fig. 7 illustrates the effect of R_{sa} on the quality factor. Increasing the R_{sa} improves the quality factor especially in the lower operating frequency region. R_{sa} also determine the value of maximum quality factor but the frequency of maximum quality factor is independent of R_{sa}.

The value of the switch capacitance in the down-state plays a great role in the switch performance since it is one the influential factors in the isolation [9]. Fig. 8 shows the effect of down-state capacitance. Increasing the C can improve the quality factor in the lower frequency region. The value of the maximum quality factor is independent of C. In addition, the bandwidth of the switch is wider for smaller capacitance comparing to larger capacitance.



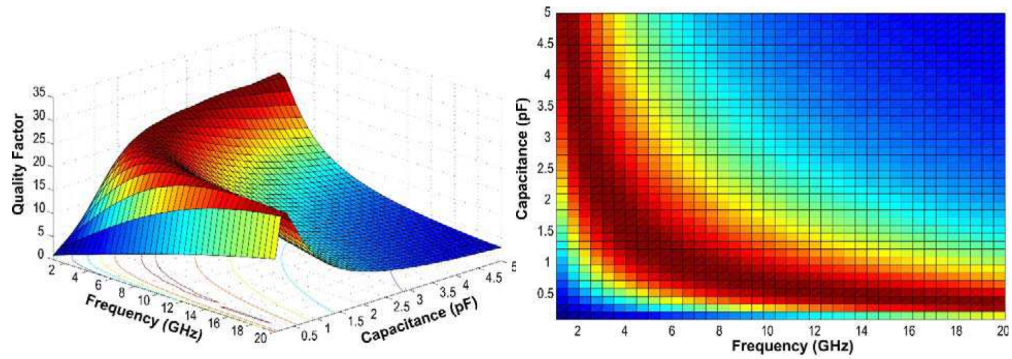
(a) (b)

Figure 6: Effect of R_{series} on the quality factor over frequency.



(a) (b)

Figure 7: Effect of R_{sa} on the quality factor over frequency.



(a) (b)

Figure 8: Effect of C on the quality factor over frequency.

5. CONCLUSION

A new lumped electrical model for RF-MEMS capacitive switch is presented for implemented switch on semi-suspended CPW. An equation for calculating the quality factor is derived. The resistance of T-line and bridge has negative effect on the quality factor while increasing the substrate resistance can improve the quality factor. The capacitance of the switch in down-state does not have any effect on the maximum quality factor amplitude while it has a great role in determining the maximum quality factor frequency. It also has noticeable effecton the bandwidth the switch.

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