A PARAMETRIC MODEL OF LOW-LOSS RF MEMS CAPACITIVE SWITCHES

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This paper is focused on the creation of an efficient electromagnetic model of MEMS switches which operates at microwave frequencies. The switches are first characterized using a full wave analysis based on a finite element method to extract the S-parameters of the switches for different geometrical dimensions. From the S-parameter database, a scalable lumped circuit model is extracted to allow easy implementation of the switch model into commercial microwave CAD software. The lumped circuit model results are compared with published measured data as validation of our model.

1 Introduction

The recent developments of microelectromechanical systems (MEMS) switches and their uses at microwave frequencies have promoted exciting advancements in the field of microwave switching. In comparison with other switches, realized by FET's or p-i-n diodes, MEMS switches exhibit low-loss performance, zero power consumption and very low intermodulation distortion [1]. To our knowledge, there is very little work which has been done to accurately describe their behaviors at microwave frequencies [2-4]. Due to the three dimensional geometry of such switches, a full wave analysis is needed to characterize MEMS switches. The result of the full wave analysis will provide scattering parameters for different switch geometries, which will allow constructing an equivalent lumped circuit model for different geometries. Based on this database, the equivalent lumped circuit model of the switch is determined. The values of the circuit elements are related to the physical dimensions of the switch as final result.

2 Electromagnetic model

In this paper, we will focus on the shunt capacitive MEMS switch, which consists of a thin metal membrane bridge suspended over the center conductor of a coplanar waveguide (CPW) and fixed on the ground conductor of the CPW, as schematically shown in Fig. 1(a). The full wave electromagnetic simulation of the switch is done by a finite element method using Ansoft High Frequency Structure Simulator (HFSS) [5]. After the full wave analysis is performed, S-parameters are extracted in the frequency range going from 1 GHz to 60 GHz for different width of the switch. The substrate is assumed to be high-resistivity silicon with relative dielectric constant of 11.9. The thickness of the substrate is 600µm and a 1-µm-thick layer of silicon dioxide is used as a buffer layer. The CPW conductors are treated as aluminum with thickness of 4.0 µm. The bottom electrode of the switches and the metallic membrane consists of a 0.4-µm-thick aluminum. The bottom electrode of the switches is assumed to be coated with silicon nitrate (Si₃N₄) having relative dielectric constant of 7 and thickness of 0.1 µm. Figure 1(b) presents the first order equivalent circuit model obtained for the
capacitive MEMS switch.

Fig. 1(a) Schematic of the capacitive MEMS switch over CPW line  (b) Equivalent circuit model of the capacitive MEMS switch

The parameters of the circuit model are optimized to fit the S-parameter obtained from the full wave electromagnetic simulation. Figure 2 shows the EM simulated and circuit model S-parameters of a 280 µm by 120 µm membrane suspended 3.5 µm over a CPW transmission line having a center conductor width of 120µm and a gap of 80µm. Since the capacitance is very small and it dominates the shunt impedance, it is very difficult to determine the resistance and inductance associated with the model in this state (off-state). The capacitance in the circuit model for this state is 0.075pF. When the switch is in the on-state a similar procedure is used. The S-parameters obtained from the full wave analysis are compared with those obtained using our model in Fig. 3. In the circuit model, the capacitance is 9.31pF, the inductance is 5.03pH and the resistance is 0.034Ω. In both cases excellent agreement is obtained between the simulated data and our lumped circuit model.

By repeating this process for different switch widths, a full set of capacitance, inductance and resistance of the bridge is obtained and used to extract the parametric scalable model as explained in the next section.

3 Parametric scalable model

From the result of the full wave analysis, we observe as in the off-state condition of the switch the capacitance is dominating the total value of the impedance of the circuit in Fig. 1(b). For the parametric fitting we show the dependence of the switch capacitance in the off-state versus the switch width. The width of the switch is varied between 60.0µm and 180.0µm and results of the fitting are reported in Fig.4. Also Fig. 4 shows the computed capacitance corresponding to two overlapping
parallel plates. It is clear from the comparison that the overlap capacitance has lower value compared to the one predicted by our model and by the full wave analysis due to the fringing field effects at the switch edges. From the curve in Fig. 4, a linear fitting for the switch capacitance versus the switch width is obtained, as reported in Eq.(1)

$$C(\text{pF}) = 0.0079 + 6.0 \times 10^{-4} W (\mu \text{m})$$  \hspace{1cm} (1)$$

More results for the lumped circuit parameters for different switch dimensions and states are reported in Table 1.

<table>
<thead>
<tr>
<th>Width (µm)</th>
<th>Switch OFF</th>
<th>Switch in ON-State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C (pF)</td>
<td>C (pF)</td>
</tr>
<tr>
<td>60</td>
<td>0.041</td>
<td>5.02</td>
</tr>
<tr>
<td>90</td>
<td>0.070</td>
<td>7.34</td>
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<tr>
<td>120</td>
<td>0.075</td>
<td>9.31</td>
</tr>
<tr>
<td>150</td>
<td>0.097</td>
<td>11.2</td>
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<tr>
<td>180</td>
<td>0.117</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 1. Circuit model parameters of the MEMS switch

By fitting the switch capacitance, inductance and resistance in ON-State versus the width of switch membrane, the values of the scalable circuit model are obtained, shown in Eq.(2), Eq.(3) and Eq.(4).

$$C(\text{pF}) = 0.96 + 0.069 W (\mu \text{m})$$  \hspace{1cm} (2)$$

$$L(\text{pH}) = 0.47 + 514 / W (\mu \text{m})$$  \hspace{1cm} (3)$$

$$R(\Omega) = 0.1 - 5.53 \times 10^{-4} W (\mu \text{m})$$  \hspace{1cm} (4)$$

Fig. 5 shows when the switch is in ON-State, the capacitance of the lumped circuit model linearly depends on the width of the membrane.

To validate our model a comparison between measured data from C. L. Goldsmith et. al. [3] and our circuit model results is reported in Fig. 6.
4 Conclusions

A parametric model based on full wave analysis capable of predicting the performance in the OFF-State and ON-State of MEMS capacitive switches has been developed in this work. The good agreement between computed and measured data confirms the validity of the model. The obtained lumped elements circuit model has the advantage of being easily implemented into the any commercial microwave CAD.

Acknowledgements

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References