Modelling of a MEMS Reconfigurable Antenna Using WIPL-D

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Abstract: This paper investigates the feasibility of using a commercial numerical electromagnetic solver to completely model a MEMS reconfigurable patch antenna taking into account not only the switch RF characteristic but also the influence of the MEMS encapsulation and DC actuation circuit on antenna performance in terms of impedance and radiation pattern. To achieve this objective a combined analysis is made using WIPL-D 3D Electromagnetic Solver with WIPL Microwave circuit analysis tool. The MEMS scattering matrix is de-embedded from measurements on a test circuit. The antenna test configuration is based on a square patch with a single slot, the MEMS being used to either short or leave the slot open, enabling to switch between two operating frequencies while maintaining good input impedance match and stable radiation characteristics. This simple antenna structure enables to focus on the modelling of commercial packaged MEMS and on the resulting accuracy of the antenna simulation prediction. An antenna prototype was fabricated and measured. The obtained good agreement between measurements and simulation confirms that the proposed procedure can be used to accurately model and design reconfigurable patch antennas with packaged commercial MEMS switches using a commercial EM solver.

INTRODUCTION

Reconfigurable antennas are very attractive in several wireless communication applications, since they enable to electronically change the operating frequency and/or radiation patterns by adjusting/modifying in some way the shape of the radiating element. In many designs this involves RF switches, which can be either PIN diodes, varactors or, more recently, MEMS switches. Electrostatic actuation RF MEMS switches provide high performance at RF. They are characterized by low insertion loss, very good isolation, and allow easy integration with CMOS circuits and patch antennas. Furthermore, most packaged MEMS have the advantage, when compared with PIN diodes, of much lower power consumption and also having independent DC control and the RF paths. Two approaches can be found when integrating RF MEMS with antennas: either the MEMS is directly constructed and integrated with the antenna wafer during fabrication or a packaged MEMS is attached to the antenna after fabrication. We address the latter approach in this work.

In the literature, the MEMS switches are usually modelled using lumped element circuits for the antenna analysis: in [1]-[2] a resistor or a capacitor, depending of the switch operating state, are used in combination with transmission line sections to model the MEMS. Alternatively, an equivalent RLC circuits is used in [3] to predict the MEMS influence on the antenna performance. In the present work the MEMS is represented by its scattering matrix measured over a broad frequency band, thus enabling more reliable prediction of the antenna frequency behaviour.

Especially when using packaged commercial RF MEMS, the antenna performance is influenced not only by the RF switch characteristic but also by the physical presence of the MEMS package and of the DC control circuit. Therefore, it is desirable to be able to analyse these two aspects altogether, that is, the possibility of performing a 3D modelling of the antenna along with a RF circuit analysis. The objective of this paper is to evaluate how a commercially available electromagnetic solver like WIPL-D Microwave [4] can accomplish this task and predict correctly antenna radiation patterns and input impedance. For this purpose, a commercially available single-pole double throw (SPDT) RF MEMS switch (Teravicta TT712-68CSP) [5] is selected to switch the operating frequency of a reconfigurable antenna. In order to validate the device model, avoiding additional complexity to the antenna, a simple configuration is chosen: a rectangular patch antenna with a single slot cross-connected by a centred MEMS switch.

The 3D Electromagnetic solver core from WIPL-D EM is based on the method of moments, the antenna being modelled by composite wires, metallic plates and dielectric plates structures. This 3D EM module is combined with a microwave circuit analysis code in WIPL-D Microwave. The antenna analysis in the present case follows along three steps. First the scattering matrix of the MEMS switch is obtained experimentally for an accurate RF characterization within the bandwidth of interest using an external test circuit. Then an antenna model is developed and analysed in WIPL-D 3D solver that includes the patch, its RF feeding structure, the MEMS encapsulation geometry including its RF lines, DC control lines and vias. In this model, the MEMS is represented by two RF ports (to be linked in the third step to the measured scattering matrix) and a model of the MEMS package. Finally, in the third step, for each frequency WIPL-D Microwave combines the previously calculated antenna scattering matrix (referred to the MEMS ports) with a RF circuit analysis involving the measured MEMS scattering matrix.
DE-EMBEDDING OF RF MEMS S-MATRIX

The TT712-68CSP RF MEMS encapsulation is a 3.25mmx4.5mmx1.25mm compact hermetic chip-scale package with metallic top-side and RF and DC contacts at the bottom-face (Fig. 1a). Only one of the two output ports of the SPDT switch is used in this application. For optimal performance in the MEMS operation range (1-7 GHz), the manufacturer recommends to use external resistors both at the DC lines and at the RF output lines, to be mounted as close as possible to the MEMS [5]. These resistors were not included in the antenna to avoid clogging the antenna slot with components. It will be seen ahead that this does not degrade much the MEMS performance within the antenna test band.

For the MEMS S-matrix de-embedding procedure, two circuits were fabricated on a 0.254 mm thickness Rogers Duroid 5880 substrate: a reference 50 Ω microstrip transmission line, Fig. 1b; and a test circuit for the RF MEMS, using the same line width and length, including the DC control lines, shown in Fig. 1c. The simplest approach taken for de-embedding the MEMS S-matrix out from the measured S-matrix of the test circuit of Fig. 1c was to normalize it to the measured $s_{21}$ element of Fig. 1b circuit. For the sake of confirmation, an alternative de-embedding approach was also taken, using the WIPL-D Microwave calculated S-matrix for RF Lines 1 and 2 including SMA connectors (Fig. 1c):
- Measured S-matrix from reference line of Fig. 1b was used to tune (by comparison) the WIPL-D connector’s model;
- The obtained SMA connector model was then used in WIPL-D Microwave to calculate the S-matrix of Lines 1 and 2 with connectors included.
- Simple T-matrix manipulation enabled then to extract the desired MEMS S-matrix.

Both methods produced similar results. The de-embedded $s_{21}$ curve is shown in Fig. 2, compared to manufacturer values for the 2-3 GHz frequency range. Measured insertion loss for the ON-state ranges from -0.4 to -0.8 dB, which is higher than the manufacturer -0.05 dB value; this is expected since the previously mentioned recommended resistors were not applied in this case. For the OFF-state, isolation ranges between -25 and -22 dB, close to manufacturer value.

PATCH ANTENNA WITH SWITCHABLE SLOT USING MEMS

The simple patch antenna used for validation of the described RF MEMS switch model is shown in Fig. 3a. With the switch at the OFF-state, currents flow around the slot and the average length of the current path is the longest and hence the antenna resonates at the minimum operating frequency. Conversely, when the switch is turned on, most of the electric currents flow through the switch, decreasing the length of the current and increasing the resonance frequency. As previously referred, the antenna configuration is intentionally simple to focus on the MEMS RF modelling. RF and DC contacts from the selected MEMS switch are at the bottom face of the case. In order to minimize the RF path onto the MEMS switch, this was mounted directly on the top of the antenna within the slot metal gap, with the
contacts facing down for direct connection with the RF lines towards the slot edges. In this way, the common flip-chip mounting with bond-wiring was avoided. DC control is fed through vias from the back of the antenna, Fig. 3b. This configuration reduces the influence of the DC circuit on the antenna RF performance.

The antenna in Fig. 3c was fabricated on a 1.5748 mm thickness Rogers DUROID 5880 substrate, with 2.2 permittivity, and fed by a coaxial probe. The patch side dimension is $L=35.1$ mm, the feeding position is at $X_f=14.2$ mm and $Y_f=L/2$ and the slot is positioned at $P_s=27.35$ mm with the width $W_s=4$ mm and length $L_s=22$ mm.

A first study was carried to evaluate the influence of the MEMS encapsulation in the antenna operating frequency and radiation patterns: the antenna input reflection was measured placing the MEMS in the off-state on a patch antenna similar to Fig. 3, except for the DC and the RF paths that connect to the switch. For comparison, a metallic box with exactly the same dimensions of the MEMS was also measured in the same conditions. Both results matched exactly, indicating that a simple model could be used in the simulation to represent the MEMS package. When compared with the antenna results without the RF MEMS, the resonance shifts down by 0.6%, with a slight disturbance of the cross-polarization, in both E and H planes.

As shown in Fig. 4, measured resonances occur at $f_1=2.378$ GHz for the MEMS off-state and at $f_2=2.595$ GHz for the on-state. In the simulations, the corresponding results are $f_1=2.41$ GHz and $f_2=2.63$ GHz, respectively. The shift between measured and simulated resonances is of the order of 1.4% in both states of the switch. It is stressed that if the common lumped elements approach was used to model the MEMS [3], higher discrepancy might result for antenna input return loss characteristic. This is shown in Fig. 4, considering a resistor for the on-state ($R=0.7 \Omega$) and a capacitor ($C=0.065$ pF) for the off-state. These values were calculated from the previously de-embedded scattering matrix of the MEMS at 2.5 GHz (the de-embedded S-matrix shows slow dependence vs. frequency in the band of interest - Fig. 2).

Measured and simulated radiation patterns at both operating frequencies (Fig. 5) show good agreement with the simulations up to 120°. The co-polar components are quite stable at both operating frequencies. The -3 dB beamwidth is about 90° in both planes and at both operating frequencies. Cross-polarization level is excellent at off-state. At the on-state, the peak cross-polarization increases by 10 dB in the E-plane and about 15 dB in the H-plane.

![Fig. 4](image_url)
CONCLUSIONS

This work evaluates the feasibility of using a commercial EM solver (WIPL Microwave) to completely analyse the inclusion of a commercially available packaged RF MEMS into a reconfigurable test antenna. A simple square patch with a MEMS switched slot was used to test the modelling. The experimental radiation patterns and return loss curve showed quite good agreement with simulations, with only 1.4% discrepancy for the return loss. To achieve this agreement, it was fundamental to describe the MEMS (Teravicta) using its measured S-matrix instead of lumped element equivalent circuit and to adopt a 3D EM analysis of the antenna including MEMS package. The agreement between measured and simulated co-polar radiation patterns is quite good. Some discrepancies occurred only for the off-state cross-polar component in the H-plane.

It is stressed that the objective of this work was not to optimize the antenna performance, but rather to evaluate how important is to account the physical presence of the MEMS on top of the antenna and how accurate can be the modelling of MEMS based antennas using a commercial software. Simulations and measurements seem to indicate that, at least for this antenna, the MEMS physical presence can be modelled with a simple metallic box.

The next step for this work will be to validate the described procedure for more complex configurations, involving more than one MEMS, and proceed to antenna optimization for real application specifications.

REFERENCES