High-Isolation and Low-Loss RF MEMS Shunt Switches

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Abstract **—** This paper presents the design and simulation of a radio frequency (RF) microelectromechanical system (MEMS) shunt switch using a three-dimensional RF simulator, Em3ds10 (2008 version) software for the frequency range of 1-40 GHz. The shunt capacitive switch is electrostatic actuated and designed with a meander beam support to lower the pull-in voltage. Fast simulations of complex structures based on a method-of-moment approach allow for optimal design of MEMS switch. The switch has a simulated pull-in voltage of 2.5 V and the RF performances of insertion loss and isolation are less than -0.2 dB and -50 dB at 12 GHz, respectively.

Index Terms **—** Insertion loss, isolation, low voltage, MEMS, method-of-moment, RF MEMS, shunt switch.

I. INTRODUCTION

Radio frequency (RF) microelectromechanical system (MEMS) technology is an area of MEMS technology that shows great potential. RF MEMS enable the creation of devices and techniques to improve the performance of communication circuits and systems. The RF MEMS switch enables the realization of micro-size mechanical switches to be embedded in electronic devices. The MEMS switch offers the advantages of low actuation, low insertion loss, high isolation, large capacitance ratio, and high-power handling. Thus, a low-voltage, low-insertion loss, and high-isolation MEMS switch is desirable for switch better performance.

A RF MEMS shunt switch is a type of MEMS switch, unlike a series switch, which consists of a suspended movable thin metal bridge over the center conductor. It is fixed and anchored at both ends to the ground line of the transmission line. MEMS switches for RF applications operate through short and open circuits to transmit signals. They operate based on mechanical movement to achieve on and off states.

Figures 1 (a) and 1 (b) show the MEMS shunt switch in the on state and off state conditions. In the on or up state, the DC bias voltage applied to the signal line is 0 V; therefore, the bridge remains up and the signal easily passes through the transmission line due to low capacitance. However, when the DC voltage increases, the center electrode provides an electrostatic force and high RF capacitance between the transmission line and the ground. As a result, the bridge is pulled down onto the dielectric layer placed on top of the signal line. This causes the RF signal to short onto the ground. This state is called the off or down state.

The shunt switch could be integrated in a coplanar waveguide (CPW) or in a microstrip transmission line. In a CPW transmission line, the anchors of the switch are normally connected to the CPW ground planes in the microstrip configuration. One anchor is connected to a quarter-wave open stub, which creates the short circuit at the bridge, and the second anchor is left unconnected or connected to the bias resistor [1].

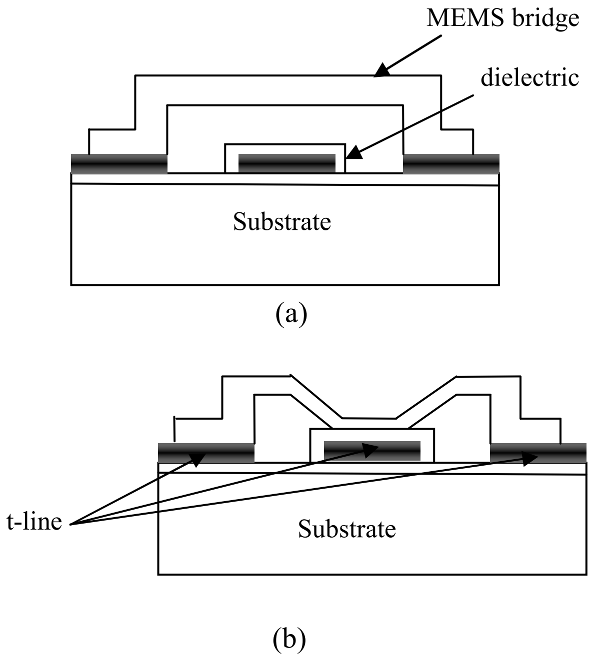

Fig. 1. RF MEMS shunt switch on CPW transmission line: (a) on/up state (b) off/down state.

Obtaining an optimal design of a MEMS shunt switch is best achieved with the aid of a modeling tool for obvious economical advantages. In this work, simulations based on an approach called generalized transverse resonance diffraction (GTRD) have been used. The GTRD method is being implemented in the Em3ds10 software package developed by MEM research. Based on the method of moments, it is a general three-dimensional (3D) integral equation approach for the modeling of passive monolithic microwave integrated circuits (MMICs) involving thick lossy conductors and dielectric discontinuities. The ability of the method to efficiently handle thick lossy conductors and dielectric discontinuities in complex structures is discussed in [2]. It has been shown to successfully model several structures such as the metal–insulator–metal (MIM) capacitor, spiral inductors, and CPWs.

II. RF PARAMETERS

As the parameters of RF performance are essential, microwave parameters other than the actuation voltage should, also, be considered and optimized when designing RF MEMS switches. In the on state, the RF switch connects the input port to the output port. In the off state, the switch is configured to disconnect the two ports. The measureable parameters for RF performance are insertion loss in the on state, isolation in the off state, and return loss in both states. Achievements of the design include the RF insertion loss and isolation at less than -0.5 dB and approximately 26 dB, respectively, obtained at 40 GHz [3].

The MEMS shunt switch is modeled by two short sections comprising a transmission line and a lumped capacitance, inductance and resistance (CLR) model of the bridge with the capacitance with up state/down state values as shown in Fig. 2 [4].

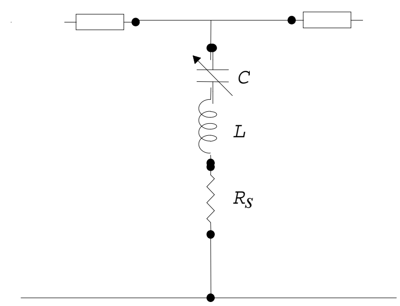

Fig. 2. Circuit model of a MEMS shunt switch.

The switch shunt impedance is given by (1).

$$Z_s = R_s + j\omega L + \frac{1}{j\omega C} \quad , \tag{1}$$

where C is Cu or Cd depending on the position of the switch. The inductance and capacitance (LC) series resonant frequency of the shunt switch is:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad . \tag{2}$$

In the up state position, $Zs >> Zo$, and the loss becomes

$$\text{Loss}=\omega^2 C_u^2 R_s Z_o \quad . \tag{3}$$

In the down state position, $Zs << Zo$, and the loss is [4]

$$\text{Loss}=\frac{4R_s}{Z_o} . \tag{4}$$

The insertion loss is caused by the mismatch between the characteristic impedances of the line and the switch [5]. The contact resistance and the beam metallization loss will also contribute to the insertion loss. Hence, it is essential to design RF MEMS switches with transmission line structures that are circuit elements in a microwave integrated circuit.

Low-insertion loss MEMS shunt switches are one of the design goals for most MEMS switches. The ratio between the C_u and C_d is a key parameter for the capacitive coupling shunt switch as it is a determining factor for both insertion loss and isolation. A small C_u is necessary for maintaining low insertion loss. This requires a large gap between the membrane and the bottom electrode, which is traded off by achieving a low pull-down voltage [5].

When the membrane is in the unactuated or up state, the capacitance of the system is approximated using (5) by considering the dielectric layer between the two plates.

$$C_u = \varepsilon_0 w W \left(g_0 + \frac{t_d}{\varepsilon_r} \right)^{-1}, \tag{5}$$

where w is the width of the membrane, W is the width of the center conductor of the CPW line, g_0 is the gap height between the membrane and the bottom transmission line, ε_0 is air permittivity, t_d is the thickness of the dielectric layer and ε_r is the relative permittivity.

The MEMS switch capacitance in the down state position can be calculated using (6).

$$C_d = \frac{\varepsilon_o \varepsilon_r A}{t_d}, \tag{6}$$

where A is the area of pull-down electrode ($w \times W$). In this case, the thickness of the dielectric is so small that the fringing capacitance is negligible [5]. Thus, the down state/up state capacitance ratio is

$$\frac{C_d}{C_u} = \frac{\dfrac{\varepsilon_o \varepsilon_r A}{t_d}}{\dfrac{\varepsilon_o A}{g + \dfrac{t_d}{\varepsilon_r}} + C_f}, \tag{7}$$

with $C_f = 0.3 - 0.4C_u$.

High isolation is a desirable parameter of RF switches in the off or down state condition. In this state, a capacitance causes undesired coupling. The gap between the membrane and the signal line could be increased for greater isolation (> 20 dB is desirable). However, a high gap will result in an even greater actuation voltage. Therefore, a large Cd is necessary to maintain high isolation. This requires intimate contact between the membrane and the dielectric film over the bottom electrode in the down state [5]. The increment of Cd/Cu can effectively improve isolation performance.

III. RF SIMULATIONS

The shunt switch is designed on silicon substrates layers of 280 μm thickness. Then, 1μm aluminum is fabricated on the silicon layer as the transmission line, while silicon nitride is deposited on the electrode (middle transmission line) as the dielectric layer. The switch membrane consists of a thin Au with 1.5 μm thickness over the 2.5 μm gap between the membrane and the electrode. The transmission line metal connects the electrode and the dielectrics materials to form the through path of a shunt switch.

In this research, the CPW was used as the transmission line of the RF MEMS capacitive shunt switch. The characteristics of the CPW line greatly depend on the width, W, conductor spacing, S, substrate permittivity, ε_r, and the height of the substrate, H, to obtain the desired characteristic impedance, Z_o.

The utilized CPW had a signal line width of 100 μm and 60 μm of space. The Z_o of the 60/100/60 μ (S/W/S) CPW was designed with a silicon substrate height of 280 μm approximately 50 Ω.

The Em3ds10 software was used to simulate the RF performances in terms of insertion loss and isolation during the on and off state conditions. Using the software, the switch design can be built and simulated either using 2.5-dimensional (2.5D) or 3D mode. However, the speed is increased in 2.5D mode by a factor varying from 50% up to more than 300% [8]. In other words, the more complex the structure, the larger is the time saved [8].

The switch structure is drawn layer by layer starting from the top layer to the substrate. Few parameters of each layer were defined including y subsection, thickness and the material properties. Figure 3 shows the switch design which consists of five layers for substrate, transmission line,

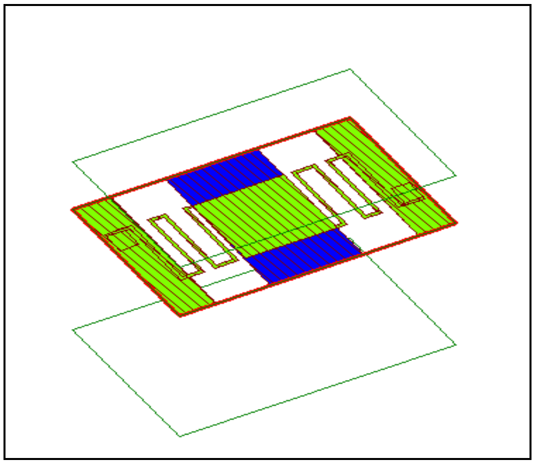

Fig. 3. Switch design using Em3ds in 2.5D mode.

dielectric, bridge, and via. The simulation done was twice for up state and downstate conditions and the design for the two conditions was different depending on the gap height and structure.

This simulator used finite-thickness, finite conductivity real conductors, and dielectrics by using volume mesh currents. The current induced in conductors appears to be oriented of (*Jx*, *Jy* and *Jz)* in the 3D mode [6] as the total current may have arbitrary orientation even over sides of a thick conductor. *Jx* is described by piece-wise sinusoidal (PWS) function with respect to *x* and piece-wise constant (PWC) function with respect to *y* and *z*. Similarly, *Jz* is described by means of PWS function with respect to *z* and PWC with respect to *x* and *y*. However, vertical *y* currents are piecewise constant with respect to any direction [6]. Figure 4 shows the relationship with mesh cells as *Jx* and *Jy* as a function of *x* [8].

In addition, better results can be obtained by setting a fine *y* subsectioning whenever sharp vertical discontinuities are encountered, such as in vias or contacts between conductors lying on different layers. This is due to increasing the number of vertical y or “slices” which may result in a large computational effort [2].

The GTRD approach of modeling with this reduced dimension was first verified by comparing the simulation results of scattering parameters with the experimental data published by [3]. As depicted in Figure 5, the computed insertion loss S_{21} and return loss S_{11} in the down state condition for the switch design in [3] agrees well with the measurements. Of significant interest is the reduction in simulation time is considerable; up to 50 percent of reduction time was observed compared with full three dimensional modeling.

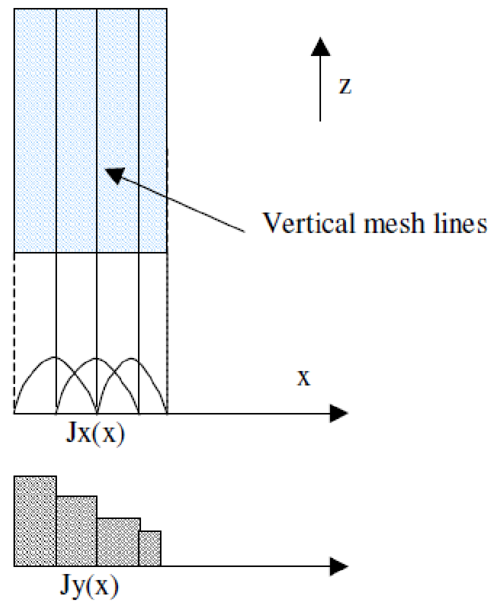

Fig. 4. *Jx* and *Jy* as function of *x*.

IV. RESULTS AND DISCUSSION

The insertion loss and isolation are obtained by the simulation of the *S* parameters when the switch transmits the signal while in the up state, and the signal is capacitively grounded when the beam is in the down state. Figures 6 and 7 illustrate the RF characterization results in the up (on) state condition when the membrane is unactuated. From the *S* parameter, the insertion loss, which is measured as S_{21} in the up state condition is very low (approximately -0.03 dB at 9 GHz or -0.27 dB at 30 GHz). Meanwhile, the return loss measured as S_{11} in the same condition is 13 dB at 29 GHz. The insertion loss is a measure of its efficiency for signal transmission. The return loss is the reflected energy due to the parasitic capacitance caused by the proximity of the transmission path to the grounded metal membrane in the suspended off state [7].

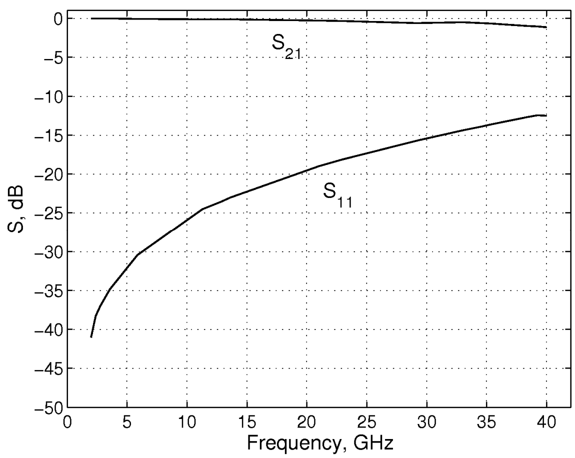

Fig. 5. Insertion loss S_{21} and return loss S_{11} in the down state condition for the switch model in [3].

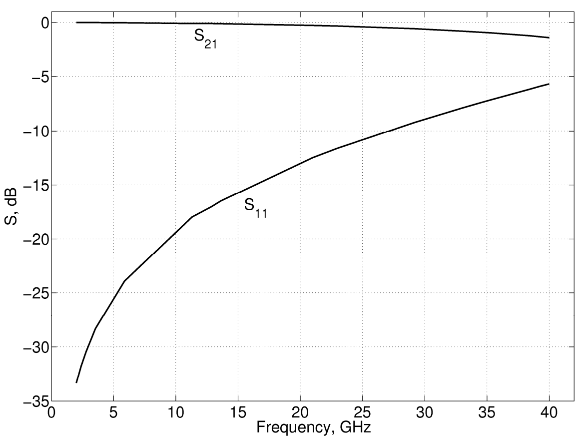

Fig. 6. S parameter showing both insertion loss S_{21} and return loss S_{11} in the up state condition.

A lower insertion loss means a better switch. Resistive losses at lower frequencies and skin depth effects at higher frequencies are the major causes for these losses [5].

Isolation is simulated in the down state condition where the RF signal originating from the input is shorted to the ground due to beam reflection. In other words, isolation is measured when no signal transmission occurs. The isolation value may, also, be defined as a result of proximity coupling between the moving part and the stationary transmission line of leakage currents [5]. Thus, greater isolation means better

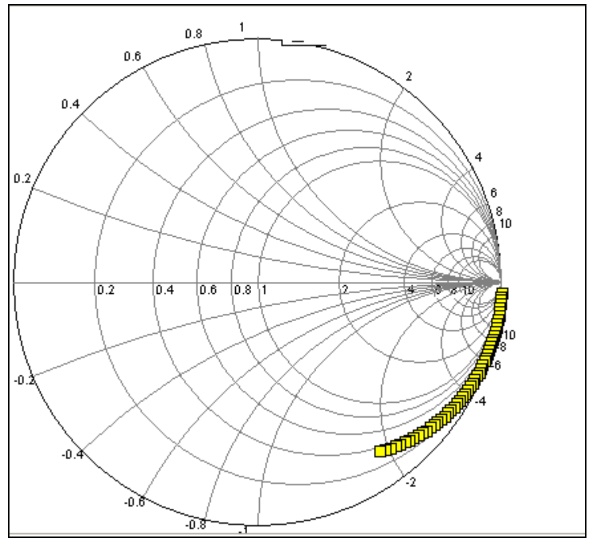

Fig. 7. Insertion loss illustrated in a Smith chart.

performance of the switch. Figure 8 shows that the S parameter for the downstate condition, represented by S_{21}, is -50 dB at 12 GHz, while the isolation illustrated in a Smith chart is shown in Figure 9. From the S parameter, the resulting isolation is high and above the minimum requirement of -20 dB.

One means of obtaining a higher isolation at lower frequencies is to increase the series inductance of the switch to lower the resonant frequency. This is achieved by adding a short section of transmission line between the MEMS bridge and the ground plane. By choosing the appropriate length of the line l, the series resonant frequency can be lowered to the desired frequency range. This gives a high isolation inductively tuned MEMS shunt switch without the use of additional switches or tuned designs [5].

Isolation can, also, be improved by using high dielectric constant materials. It can be further improved by decreasing the thickness of the dielectric between the switch and the center conductor, thus increasing the on capacitance. However, the thin film should be sufficiently thick so that dielectric breakdown and current flow will not occur [3].

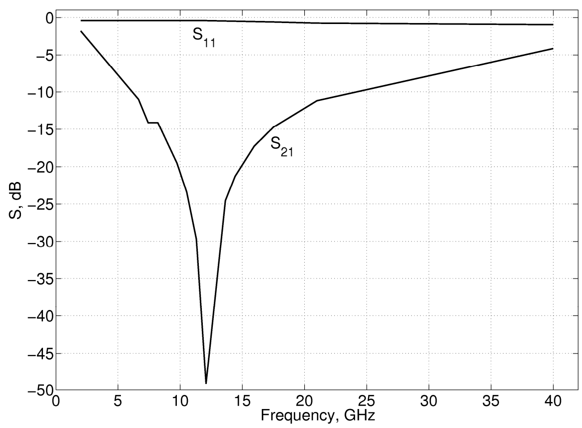

Fig. 8. Isolation S_{21} and return loss S_{11} in the down state condition.

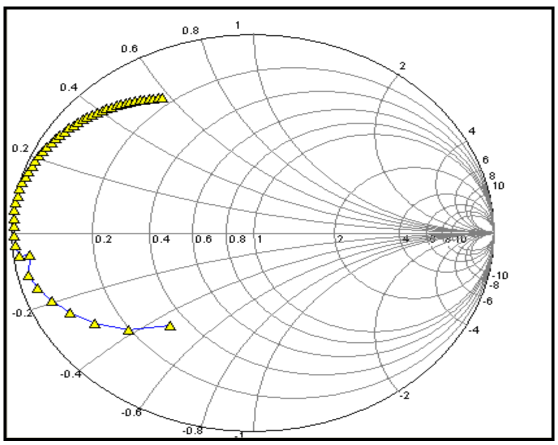

Fig. 9. The isolation illustrated in a Smith chart.

V. CONCLUSION

RF MEMS switches with actuation voltages of 2.5 V and excellent RF characteristics were designed and analyzed. The RF performances of the RF MEMS shunt switch were simulated based on the approach of the generalized transverse resonance diffraction as implemented in the 3D electromagnetic software package Em3ds10. The possibility of reduced order of dimension with this method allows rapid simulations without compromising the accuracies of computed results. The simulated performances were insertion loss, return loss, and isolation. The insertion loss obtained was very low, less than -0.2 dB at 12 GHz, while isolation was high with -50 dB at 12 GHz. These excellent RF characterizations prove that the switch is suitable for microwave applications or space systems where low loss, high isolation, and low power consumption are essential.

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