Microwave Simulation of an X-Band RF MEMS Switch

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Abstract

This paper presents the design, simulation and testing of an X-Band, RF Microelectromechanical (MEM) switch. The switch takes the form of a microstrip line with a small gap that can be closed by a conductor that can be moved progressively from "off" to "on" in the vertical direction. The simulation is found to agree with the experimental results for a switch fabricated on RT Duroid giving us confidence in predicting an isolation of ~ 50 dB for a device based on SU-8.

Keywords: RF MEMS Switch, Isolation, Microwave Simulation

Introduction

Compared to the usual semiconductor PIN device, radio frequency MEMS switches have many advantages such as high power handling capacity, high linearity, low power consumption and low fabrication cost. In recent years, many research groups have been working to optimise the physical structure and process flow of MEMS switches for high performance over a wide frequency range [1].

The aim of this project is to design and fabricate a MEMS isolator switch that could be placed in the front end of a radar. In this paper we describe a simple microstrip design fabricated on a RT/Duroid 5880 substrate with a gap in the middle of the transmission line (Fig. 1). A copper contact (also RT/Duroid 5880) is used to close the gap between the two transmission lines. The height of the contact above the substrate was varied by up to 5 mm from the closed "on" state position. The circuit has been simulated in Advanced Design System ADS and S-parameter measurements carried out over a frequency range from 9GHz - 11 GHz. The main interest was in the return loss S_{11} and isolation S_{12}.

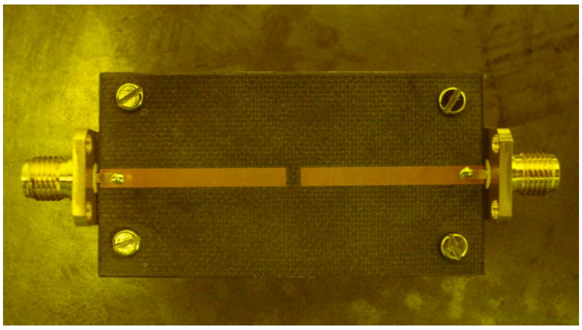

Figure 1. Microstrip transmission line with a gap of 2 mm as fabricated on RT/Duroid 5880 substrate

Microwave switch

The switch element is considered to be part of a circuit that includes an incoming and an outgoing transmission line. This is one of the significant differences between microwave switching and low frequency switching. In general we must consider the impedance of the transmission line that connects to the switch. Frequently, we must also consider the mode of propagation of the signal on the line, because the electric field orientation influences the value of the off state capacitance [2]. The switch can be viewed as a transmission device with some reflection when in the closed state. On the other hand in the off-state, the switch can be viewed as almost fully reflecting with some unwanted transmission

On-state position

Figure 2 is a schematic of a series switch in the down or "on" position. In this state, the contact behaves as a resistance connected in series between the two transmission line sections.

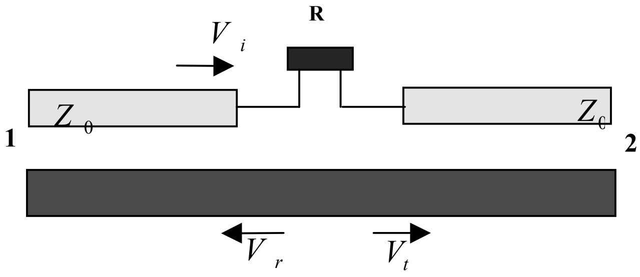

Figure 2. An ideal series switch for the on-state position. The switch is closed while the contact is down. Numbers 1 and 2 indicate the ports where the microwave signal can enter and exit the device.

In this on-state condition a signal is mostly transmitted through the switch with only a small fraction reflected and some absorption. The insertion loss of a network is defined as the ratio of the transmitted power V_t to the difference between the incident V_i and reflected power V_r. If the reflected power is low then S_{12} is the insertion loss. The reflected power under these conditions is the return loss and is represented by S_{11}. In this case it can be shown that:-

$$S_{11} = \frac{R}{R + 2Z_0}, \tag{1}$$

$$S_{12} = \frac{2Z_0}{R + 2Z_0}. \tag{2}$$

Where R is the on-state resistance of the contact and Z_0 is the characteristic impedance (50 Ohm) of the line. From the measured values of $S_{11} \sim 0.1$ and $S_{12} \sim 0.9$. The contact resistance R was calculated to be # 11 Ohm.

Off-state position

With the switch contact in the off-state position (Figure 3) C_{off} the off-state capacitance can be approximated as:-

$$C_{off} = \frac{A \times \varepsilon_0 \times \varepsilon_r}{W} \tag{3}$$

Where A is the area of the contact (in this case $9mm^2$), ε_0 is the free space permittivity ($8.854 \times 10^{-12}\ Fm^{-1}$), ε_r is the relative dielectric permittivity of the substrate (2.2) and W is the distance between the contact and the transmission line

Equation 3, illustrates an advantage of MEMS switches in comparison with their PIN counterparts in that the designer has free choice of the height of the switch contact and therefore control of the off-state capacitance.

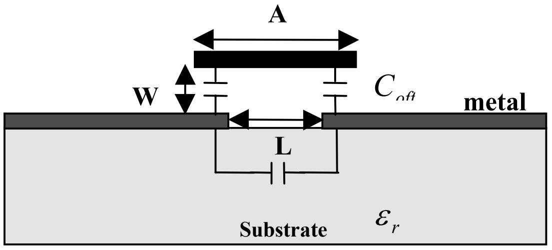

Figure 3. A sketch of two microstrip lines having a gap of length L on a substrate with relative dielectric permittivity ε_r. Also a

metal switch is represented above with a surface area A and a height distance W from the transmission lines.

Consider now the off-state condition where a signal arrives at port 1. The signal should be reflected (ideally with a voltage reflection coefficient of +1) with only a small amount of the wave transmitted through to port 2. The reflected and transmitted signals can be mapped onto S_{11} and S_{12} respectively and are given by the following equations:

$$S_{11} = \frac{1}{1 + j\omega C_{off} \times 2Z_0}, \qquad (4)$$

$$S_{12} = \frac{j\omega\, C_{off} \times 2Z_0}{1 + j\omega\, C_{off} \times 2Z_0}. \qquad (5)$$

ω is the angular frequency, C_{off} the off-state capacitance and Z_0 the characteristic impedance of the line.

Forward transmission is also known as the isolation of the switch under the off-state conditions [2].

For a contact area of 9 mm^2 placed 1 mm above the microstrip line the theoretical off-state capacitance should be roughly $17.5\, nF$. Simulated results for S-Parameters in the off-state position give a magnitude of 0.95 for S_{11} at 10 GHz. Using equation 4, the off-state capacitance is found to be 16.9 *nF*.

Design and fabrication of a simple microstrip transmission line in X-Band frequency

This part outlines two microstrip transmission line fabrication methods. The first is implemented on a conventional RT/Duroid 5880 substrate. The second is based on a SU-8 ultra-thick photoresist and is achieved by exposing and baking the different layers that form microstrip structure. The electrical properties of RT/Duroid 5880 are much better defined than those of SU-8. Because the latter is a relative new material with little published data available in the literature. Some information on the required properties can be found in Dellmann's publication for SU-8 [3] and this has been used in the ADS simulation where available.

Design using RT/Duroid 5880

RT/Duroid 5880 has a substrate thickness of 0.787 mm, a relative dielectric permittivity of 2.2 and a loss tangent of 0.0009. The copper thickness is 17.5 microns. For an ideal 50 Ω transmission line, the width of the microstrip conductor is 2.43 mm at 10 GHz. Simulation results were obtained for a range of frequencies between 9 GHz and 11 GHz, initially with no switch contact to open and close the gap between the two conductors. The simulated S-Parameters for a frequency of 10 GHz are shown in the table below.

Gap (mm)	S_{11}	S_{12}
0	42.1	0.01
0.5	0.35	14.9
1	0.27	19.4
1.5	0.24	22.6
2	0.23	24.94

Table 1. S-Parameters for a simple microstrip line with a variable gap distance fabricated on RT/Duroid 5880 substrate.

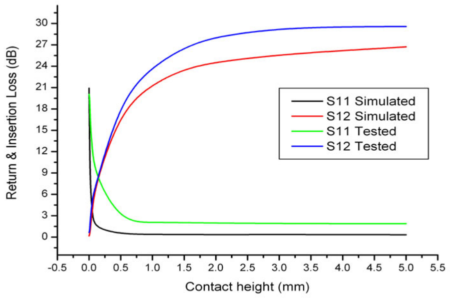

Figure 4. Return and Insertion Loss for the simulated and tested microstrip line on

RT/Duroid 5880 having a copper contact ($9\ mm^2$ area) with variable height from 0-5 mm.

Not unexpectedly the table above shows that the bigger the gap between the lines, the greater is the isolation. Figure 4 compares simulated and measured results for the insertion and return loss for a constant gap length of 2 *mm* as a function of contact height above the switch closed position over a range of 5 *mm*. It can be seen that the results are in reasonable agreement.

Design using SU-8

The second approach is based on a SU-8 structure with a substrate height of 100 microns and a metal thickness of 17.5 microns. The relative dielectric permittivity of SU-8 is taken as 4.2 and the loss tangent as 0.08. Assuming an ideal 50Ω line, the width of the microstrip conductor is 0.183 *mm* at 10 GHz.

Gap (mm)	S_{11}	S_{12}
0	32.53	0.13
0.01	0.25	28.11
0.05	0.23	34.76
0.1	0.23	40.86
0.2	0.23	49.75

Table 2. S-Parameters for a simple microstrip line with a variable gap distance fabricated on SU-8 substrate.

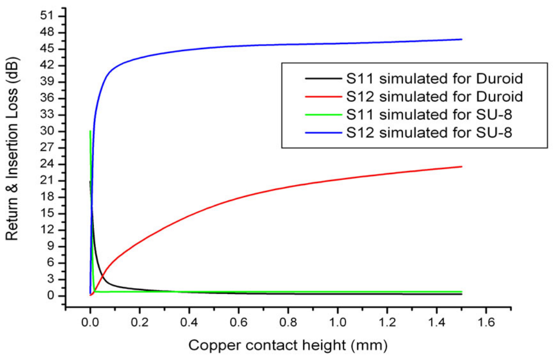

Figure 5. Return and Insertion Loss for the simulated microstrip circuits using RT/Duroid 5880 and SU-8 for substrate.

Table 2 shows the simulation results for the SU-8 device. A comparison with Table 1 shows immediately that the isolation achievable using SU-8 is twice as large as with RT/Duroid. This is due to the much smaller width of the transmission line (i.e. 0.183 *mm* cf 2.43 *mm* respectively) reducing the capacitive coupling between the two sections of line.

Comparing the simulated results between RT/Duroid 5880 and SU-8 (Figure 5), we see that SU-8 can achieve a much better isolation. The significant changes from on to off condition for that material take place within a micron of contact height.

Conclusions

By comparing the simulated results with experimental measurements for a device fabricated on RT/Duroid, we have shown that a simple 2-port model gives a reasonably accurate description of the performance of the proposed microstrip switch. The results show that, for RT/Duroid, a gap width of 2 *mm* and a contact height of 2 *mm* are required to give an isolation of ~ 30 dB. These distances are too large for MEMS type devices. However, when implemented in SU-8, the distances come down to 0.2 *mm* and 0.2 *mm* respectively (also giving an improved isolation loss of 50 dB). These dimensions are easily achievable using microfabrication techniques.

Figure 4 shows that after a height of 5 mm the copper contact has no more effect to the microstrip line. After a height of 700 microns there is a relatively small offset of 1.5 dB for S_{11} and 2.5 dB for S_{12} between the simulated and tested results. One good reason might possibly be that the calibration method used for the network analyser (Open/Short/Load) was not extremely accurate. Future work includes the fabrication, test and optimisation of the microstrip switch using an SU-8 substrate. If necessary, alternative switch architectures will be investigated.

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