MEASUREMENT AND MODEL OF A RADIO FREQUENCY MICROELECTROMECHANICAL SWITCH

BY

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THESIS

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A novel process for the fabrication of microelectromechanical systems (MEMS) has been introduced. One potential application of this process is a radio frequency (RF) MEMS switch. This thesis provides an overview of the measurement and modeling techniques used to verify the functionality of an RF MEMS switch that was fabricated using this process. This thesis confirms that this specific RF MEMS design was not fully functioning, but can still be measured, characterized, and modeled.
To Bob, Dawn, Amy, and Jules, for their love and support.
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CHAPTER 1

INTRODUCTION

1.1 Motivation

A new fabrication process for microelectromechanical systems (MEMS) has been introduced. This new process was used to make a radio frequency (RF) MEMS switch. However, the functionality of this device had yet to be verified. The goal and purpose of this thesis was to verify the functionality of this new device. Beyond simply verifying whether or not this device worked, the goal was to characterize, model, and quantify how well the RF MEMS switch performed.

1.2 Outline

This thesis describes the measurement, modeling and corresponding analysis of an RF MEMS switch. The specific measurements used to verify the functionality and characterize the RF MEMS switch were scattering parameter (S-parameter) measurements. Chapter 2 discusses the basic theory behind S-parameters that is necessary to understand the measurement results. The S-parameters of a 2-port network are explained in this section since the RF MEMS switch can be treated as a 2-port device. After the basic theory of S-parameters, chapter 2 explains the specific application of S-parameter measurements for the RF MEMS switch.

Chapter 3 describes the physical setup for taking S-parameter measurements of the RF MEMS switch. This chapter explains the necessary components (network analyzer, probe station, etc.) as well as how they were used in this specific application. Chapter 3 also includes the results of the S-parameter measurements and analyzes these results. The analysis includes
verifying whether or not the switch is working and, if it is working, how well it performs as an RF switch.

Chapter 4 explains the process of devising a lumped element circuit model for the RF MEMS switch based on the S-parameter measurements. The final schematic of the lumped element model as well the comparison between the simulated S-parameters of the model and the S-parameters of the actual RF MEMS switch are shown.

Finally, chapter 5 summarizes the findings of this thesis. Chapter 5 also includes recommendations for how the work in this thesis could be continued.
CHAPTER 2
SCATTERING PARAMETERS

2.1 Theory

Circuits operating in the microwave frequency range are best described and measured using scattering parameters (S-parameters). S-parameters can describe a device in terms of incident and reflected waves [1]. Using a generic 2-port device as an example, shown in figure 2.1, we can define the four S-parameters necessary to fully describe this two port as follows:

\[
S_{11} = \frac{b_1}{a_1}|_{a_2=0}
\]

\[
S_{12} = \frac{b_1}{a_2}|_{a_1=0}
\]

\[
S_{21} = \frac{b_2}{a_1}|_{a_2=0}
\]

\[
S_{22} = \frac{b_2}{a_2}|_{a_1=0}
\]

where \(a_1\) and \(a_2\) are the incident waves at port 1 and port 2 respectively and \(b_1\) and \(b_2\) are the reflected waves at port 1 and port 2 respectively. These

![Figure 2.1: 2-Port network](image-url)
variables, \( a_1, a_2, b_1, \) and \( b_2 \), are the incident and reflected voltage waves at each port normalized with respect to the square root of the reference impedance, \( Z_o \).

\[
a_1 = \frac{V_1 + Z_o I_1}{2\sqrt{Z_o}}
\]

\[
a_2 = \frac{V_2 + Z_o I_2}{2\sqrt{Z_o}}
\]

\[
b_1 = \frac{V_1 - Z_o I_1}{2\sqrt{Z_o}}
\]

\[
b_2 = \frac{V_2 - Z_o I_2}{2\sqrt{Z_o}}
\]

The variables \( a_1, a_2, b_1, \) and \( b_2 \) therefore have units of \([\text{watts}]^{\frac{1}{2}}\). This means that \( |a_1|^2, |a_2|^2, |b_1|^2, \) and \( |b_2|^2 \) have units of watts and can be thought of as power waves [2]. \( |a_1|^2 \) and \( |a_2|^2 \) are the incident power at ports 1 and 2 respectively and \( |b_1|^2 \) and \( |b_2|^2 \) are the reflected power at ports 1 and 2 respectively.

Combining the definitions of the four S-parameters with the definitions for \( a_1, a_2, b_1, \) and \( b_2 \) leads to the following:

\[
S_{11} = \frac{b_1}{a_1} \bigg|_{a_2=0} = \frac{\frac{V_1 - Z_o I_1}{2\sqrt{Z_o}}}{\frac{V_1 + Z_o I_1}{2\sqrt{Z_o}}} = \frac{V_1 - Z_o I_1}{V_1 + Z_o I_1}
\]

And similarly,

\[
S_{12} = \frac{V_1 - Z_o I_1}{V_2 + Z_o I_2}
\]

\[
S_{21} = \frac{V_2 - Z_o I_2}{V_1 + Z_o I_1}
\]

\[
S_{22} = \frac{V_2 - Z_o I_2}{V_2 + Z_o I_2}
\]

With these basic definitions we can gain some insight into the meaning of
the four S-Parameters. $S_{11}$ is ratio of the reflected wave to the incident wave at port 1, which is really just a reflection coefficient. $S_{11}$ can be thought of as the fraction of the incident voltage on port 1 that is reflected back from port 1, while making sure there is no incident wave at port 2. $S_{22}$ can be thought of in the exact same manner, but at port 2, with no incident wave on port 1. $S_{21}$ can be thought of as either the reflected wave at port 2 due to the incident wave at port 1 or the fraction of the incident voltage on port 1 that is transferred to port 2, while making sure there is no incident wave at port 2. This is simply a transfer function that describes the gain or loss of a signal traveling from port 2 to port 1. Again, $S_{12}$ can be thought of in the same manner, but as a ratio of the reflected wave at port 1 to the incident wave at port 2 or as the fraction of the incident voltage wave at port 2 that is transferred to port 1 while there is no incident wave at port 1. These four S-parameters can be used to fully describe the behavior of linear 2-port networks. Using the same logic shown above, the S-parameter formalism can be expanded to represent an n-port device [3]. For the purposes of this thesis, we will focus on a 2-port device and $S_{11}$ and $S_{21}$ specifically.

2.2 Application

The specific application addressed in this thesis is the measurement and characterization of a radio frequency (RF) microelectromechanical system (MEMS) switch. The design of this specific RF switch is shown in figures 2.2 and 2.3. The switch consists of a center conductor (the signal line) and two large ground planes that create a coplanar waveguide. The signal line and ground planes have a 150 $\mu$m pitch for compatibility with 150 $\mu$m pitch microwave probes. Connecting the two ground planes is a flexible conducting bridge that spans across the signal line. As seen in figure 2.3, the bridge is fabricated out of silicon and then coated in gold. The same is true for the signal line and ground planes. The gap between the bridge and the signal line is 12 $\mu$m when the switch is unbiased, or in the “open” state. When the switch is biased, or in the “closed” state, the bridge can deflect to a maximum of 9 $\mu$m. This corresponds to a gap distance of 3 $\mu$m.

We can model the gap between the bridge and signal line as a parallel plate capacitor [4]. The capacitance of a parallel plate capacitor is defined by the
following function:

\[ C = \epsilon_r \epsilon_0 \frac{A}{d} \]

where \( C \) is the capacitance in farads, \( \epsilon_r \) is the relative permittivity, \( \epsilon_0 \) is the permittivity of free space \( (\epsilon_0 \approx 8.854 \times 10^{-12}[\text{F/m}]) \), \( A \) is the overlap area of the two plates in \( m^2 \), and \( d \) is the distance between the two plates.

Figure 2.2: View of the RF MEMS switch using a microscope

Figure 2.3: Diagram of bridge and materials for RF MEMS switch

Ideally, a DC bias applied between the ground planes and the signal line should cause the bridge to flex downward toward the signal line [5]. This, of course, decreases the distance between the signal line and bridge, causing an increase in the capacitance. The impedance of a capacitor, which is frequency
dependent, is defined as follows:

\[
Z_C = \frac{1}{j\omega C}
\]

where \(Z_C\) is the impedance of the capacitor in ohms, \(\omega\) is the angular frequency \((2\pi f)\), and \(C\) is the capacitance in farads. Clearly, the capacitance and impedance are inversely proportional and as the capacitance increases, the impedance decreases. Therefore, when a bias is applied and the bridge moves closer to the signal line, the impedance across the gap between the bridge and the signal line should decrease. This can be interpreted as the switch “closing” at microwave frequencies. The switch will never fully close physically as this would cause a DC short between the ground and signal line and therefore negate the bias voltage. As shown in figure 2.3 there is a layer of SU-8 that prevents the bridge from making electrical contact with the signal line.

One way to measure this expected impedance change, and in turn find the capacitance change, is to treat the switch as a 1-port device and measure \(S_{11}\). \(S_{11}\) can be measured and then compared for the unbiased and biased conditions. This comparison should show whether or not the switch is physically closing and whether or not the switch actually behaves as an RF switch.

\(S_{11}\) of a one port gives the input reflection coefficient. From this information we can find the impedance of the RF MEMS switch using the following equation:

\[
S_{11} = \Gamma_{in} = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} = \frac{Z_{\text{switch}} - Z_o}{Z_{\text{switch}} + Z_o}
\]

Which in turn leads to:

\[
Z_{\text{switch}} = Z_o \frac{1 + S_{11}}{1 - S_{11}}
\]

Using the equation for the impedance of a capacitor shown above, and ignoring the real component and other parasitic contributions to the RF MEMS switch impedance, we can calculate an approximate value for the equivalent capacitance of the RF MEMS switch.

As explained above, with the measurements and calculations for the equivalent capacitance of the RF MEMS switch, we should be able to verify functionality by comparing the biased and unbiased cases. In order to show that the switch is functioning, we can verify that the capacitance changes as the DC bias across the switch changes. Specifically, we expect that the
capacitance should increase as the bias voltage increases.

The functionality of the RF MEMS switch can also be verified by treating the switch as a 2-port device and looking at $S_{21}$. Alternatively, $S_{12}$ could be used to verify the functionality of the switch in the same manner since the switch is symmetric and reciprocal (see section 3.3.1). Ideally, when the switch is unbiased and the bridge is the full 12 µm away from the signal line, the signal should be uninterrupted and $S_{21}$ should have a magnitude of 1. When the switch is biased, ideally any RF signal on the signal line should be shorted to RF ground and $S_{21}$ should approach magnitude 0.

As will be shown in the next section, this is the ideal case. In reality, there will be some impedance mismatch between the switch and the characteristic impedance of the system (50 Ω). This will cause $S_{11}$, the input reflection coefficient in this case, to have a non-zero value. This means that in the unbiased, or “open” state, $S_{21}$ can never be 1. In the best possible case, $|S_{21}| = \sqrt{1 - |S_{11}|^2}$. 
CHAPTER 3

S-PARAMETER MEASUREMENTS

3.1 Measurement Setup

To take S-parameter measurements of the RF MEMS switch, an HP8510C Network Analyzer was used in conjunction with a Cascade Microwave Probing Station [6]. As described in section 2.2, the probe tips, which use a ground-signal-ground (GSG) configuration, and the GSG lines on the actual switch both had a 150 µm pitch [7]. In order to bias the RF MEMS switch, an Agilent E3612A DC Power Supply was used along with a Mini-Circuits ZFBT-6G+ Bias-Tee [8]. The diagram of the complete setup is shown in figure 3.1. Figure 3.2 shows that the “RF Data” connection for the bias tee is connected to Port 1 of the network analyzer. Then, the “RF Data + DC Bias” connection for the bias tee is connected to the probe tips on the microwave probe station. And, of course, the DC connection on the bias tee is connected to the DC power supply.

The Mini-Circuits bias tee allowed measurements to be taken with voltages over the 40 V limit for the internal bias tee on the HP8510C Network Analyzer shown in figure 3.3. The ZFBT-6G+ is only rated for 30 V, but with this switch design, there is no current drawn from the DC supply. This means there is no DC power on the signal line, just the DC voltage. This allowed us to use the bias tee and Agilent E3612A power supply shown in figure 3.4 to bias the switch with voltages as high as 100 V.

3.1.1 Calibration

Calibration is an important step for any microwave measurements using a network analyzer [9]. For these measurements the calibration accounts for the cables, connectors, bias-tee, and probe tips. The calibration moves the
Figure 3.1: Diagram of the complete setup that was used to take S-parameter measurements

reference plane from the measurement port of the network analyzer to the tips of the microwave probes (figure 3.5). In order to calibrate the network analyzer, SOLT (short, open, load, thru) standards made by GigaTest Labs were used (figure 3.6).
Figure 3.2: Mini-Circuits ZFBT-6G+ Bias Tee that was used to bias the switch while preventing any high voltage DC bias across the network analyzer’s measurement port.
Figure 3.3: HP8510C Network Analyzer that was used to measure S-parameters for the RF MEMS switch
Figure 3.4: Agilent E3612A DC Power Supply that was used to bias the RF MEMS switch
Figure 3.5: Cascade Microwave Probing Station that was used to hold the switch and control probe tips in order to make S-parameter measurements
Figure 3.6: GigaTest Labs SOLT standards for 150 $\mu$m pitch microwave probes
3.2 Results

After measuring the S-parameters of the RF MEMS switch using the procedure described in the previous section, the unbiased, $V_{bias} = 0V$, and fully biased, $V_{bias} = 100V$, states were compared to verify the functionality of the switch. The results are shown in figures 3.7, 3.8, 3.9, and 3.10. Figure 3.7 compares $S_{11}$ of the RF MEMS switch for the biased and unbiased case on a Smith chart, where “S1.100V..S(1,1)” (in blue) is the fully biased measurement and “S(1,1)” (in red) is the unbiased measurement. Similarly, figure 3.8 compares the magnitude of $S_{11}$ for the biased and unbiased cases. Finally, figures 3.9 and 3.10 are the Smith chart and magnitude plots for the comparison between the biased and unbiased measurements of $S_{21}$.

Figure 3.7: Smith chart comparison of $S_{11}$ for the unbiased and biased case
3.3 Analysis

Clearly from figures 3.7, 3.8, 3.9, and 3.10 it can be seen that the biased and unbiased cases are almost identical. As was discussed in section 2.2, a change in the bias voltage is expected to move the bridge. This changes the capacitance between the signal line and bridge, which means the RF MEMS switch will have a different impedance. Again, as discussed in section 2.2, this impedance change should be reflected in the S-parameter measurements.

The fact that no change in the impedance of the RF MEMS switch is seen when comparing the biased and unbiased cases leads to the conclusion that the switch is not functioning properly. There are multiple possible reasons why the switch may not be functioning: the bias voltage may insufficient, the bridge might not move far enough to change the capacitance/impedance of the device by any significant amount, or the switch may be stuck in the “open” or “closed” state.

The first two possibilities as to why the RF MEMS switch is not functioning can be tested using an optical profilometer and comparing the biased and unbiased cases. Before taking S-parameter measurements of the RF MEMS switch, the mechanical functionality of the switch was verified using an optical profilometer. The optical profilometer measurements showed that...
somewhere between $V_{bias} = 60\, \text{V}$ and $V_{bias} = 70\, \text{V}$, the bridge would deflect as far $9\, \mu\text{m}$. This corresponds to the distance between the bridge and signal line changing from $12\, \mu\text{m}$ to $3\, \mu\text{m}$. This means that a bias voltage of $100\, \text{V}$ is more than sufficient to bias the RF MEMS switch.

As shown in section 2.2, the capacitance of a parallel plate capacitor

$$C = \epsilon_r \epsilon_0 \frac{A}{d}$$

is inversely proportional to the distance between the plates. Ideally, changing the gap distance from $12\, \mu\text{m}$ to $3\, \mu\text{m}$ would cause a four-fold increase in capacitance. Again, as shown in section 2.2, the impedance of a capacitor

$$Z_C = \frac{1}{j\omega C}$$

is inversely proportional to the capacitance. This means that changing the gap distance from $12\, \mu\text{m}$ to $3\, \mu\text{m}$ would cause a four-fold decrease in the impedance (again ignoring the real component and parasitics). Clearly, from
the magnitude plots of $S_{11}$ in figure 3.8, we do not see this expected change.

This leaves the possibility that the switch is stuck. Stiction in MEMS switches is a common problem [10, 11]. Stiction occurs when the switch fails to release after the bias voltage has been removed. This corresponds to the RF MEMS switch being stuck in the “closed” state. The magnitude plots of $S_{11}$ and $S_{21}$ in figures 3.8 and 3.10 show that this is the most likely case. Figure 3.8 shows that as frequency increases the magnitude of $S_{11}$ decreases. This means that the magnitude of the input reflection coefficient is decreasing and more of the signal is either transmitted to port 2 or shorted to ground through the switch. If the unreflected power is being transmitted to port 2, then as $S_{11}$ decreases, $S_{21}$ should increase. Ideally, if no power is lost in the switch, then the sum of the squares of the magnitudes of $S_{11}$ and $S_{21}$ would be unity, or $|S_{11}|^2 + |S_{21}|^2 = 1$ [12]. From figure 3.10, it is clear that this is not the case. Not only is $S_{21}$ not increasing as frequency increases, but it is actually decreasing.

This leads to the conclusion that most of the signal that is incident at port 1 is shorted to ground through the switch. This is the ideal functionality of the RF MEMS switch in the “closed” or biased state. Unless the switch already has a large capacitance between the bridge and signal line in the
open state, this shows that the switch is most likely stuck in the “closed” state regardless of whether or not the switch is being biased.

While this means that the switch is not functioning, we can still quantify how well the switch performs in the “closed” state. For the sake of this discussion, it is assumed that the switch is stuck in the equivalent location as a fully biased and functioning switch of the same design and that we can consider this to be fully closed. As previously discussed, this fully closed state corresponds to the bridge and signal line being 3 μm apart.

If the switch were a perfect RF switch, then in the closed state, it would short all of the RF signal to ground. Looking at the S-parameters of the switch, this would correspond to the magnitude of $S_{21}$ being 0. Also, ideally the switch would be impedance matched to the rest of the system and $S_{11}$ would be close to 0 regardless of the state that the switch was in. From figures 3.8 and 3.10, we can see that this is not the case, but as frequency increases, the measurements approach this ideal case.

The amount of power from the input RF signal that is actually shorted to ground when the RF MEMS switch is in the closed state can be calculated using the same logic used to prove that the switch is not lossless. If the switch were lossless, then $|S_{11}|^2 + |S_{21}|^2 = 1$. If we ignore signal attenuation due to losses in the material, radiation, and other paths of loss, we can assume that the only loss is due to the switch shorting the signal to ground. This can be interpreted as

$$1 - (|S_{11}|^2 + |S_{21}|^2) = S_{stg}$$

where $S_{stg}$ is the fraction of the input RF signal that is shorted to ground through the RF switch. $S_{stg}$ can also be interpreted as the amount of power shorted to ground normalized to the input RF signal power. To find the total amount of power shorted to ground through the switch, simply multiply this fraction by the input RF signal power, or

$$P_{stg} = S_{stg} \times P_{in}$$

where $P_{stg}$ is the total power shorted to ground and $P_{in}$ is the input RF signal power.

Using these equations allows us to quantify what fraction of input RF signal power is shorted to ground and how well the switch actually functions
as an RF switch. If the switch were a perfect RF switch and impedance matched to the system, then all of the input RF signal power would be shorted to ground when the switch is in the closed state. This corresponds to \( S_{stg} = 1 \). In reality, our switch is not a perfect RF switch and also not impedance matched. For the real switch, the best possible performance of the switch in the closed state would correspond to \( S_{stg} = 1 - |S_{11}|^2 \). This would correspond to \( S_{21} = 0 \) and all of the RF signal power that is actually delivered to the switch (i.e. not reflected back to port 1) being shorted to ground through the switch. Shown in figure 3.11 is the actual \( S_{stg} \) versus \( S_{stg} \) for the ideal case. Figure 3.11 shows that the switch performs very well as an RF switch in the closed state and shorts most of the input signal power, that is not reflected at port 1 due to impedance mismatch, to ground.

In order to show that the RF MEMS switch is actually a fully functioning RF switch, \( S_{stg} \) would need to be verified for the open case. In the ideal case of an impedance matched switch in the open state, \( S_{stg} = 0 \) and \( S_{21} = 1 \). For the real switch, the best possible performance of the switch in the open state would correspond to \( S_{stg} = 0 \) and \( |S_{21}|^2 = 1 - |S_{11}|^2 \). This means that all of the power that is delivered to the switch at port 1 would be delivered to port 2 and no RF signal power would be shorted to ground through the bridge.

3.3.1 Verifying the Switch is Reciprocal

The measured scattering parameters of the RF MEMS switch can be used to characterize more than just the switch performance. The S-parameters can also reveal some traits of the physical design. We assume, based on visual assessments, that the device is physically symmetric about the center of the bridge. Based on this, and the fact that the switch is passive, we assume that the device is reciprocal. If the switch is in fact reciprocal, then \( S_{11} \) and \( S_{22} \) should be equal, and \( S_{21} \) and \( S_{12} \) should be equal [3]. The Smith chart is the best way to compare these measurements because it includes both magnitude and phase information.

The Smith chart plot of \( S_{11} \) and \( S_{22} \) is shown in figure 3.12 and the Smith chart plot of \( S_{21} \) and \( S_{12} \) is shown in figure 3.13. Clearly, these figures verify that the switch is in fact reciprocal. This could be beneficial if we did not
have the means to optically verify that the switch was physically symmetric. For example, if the switch were inside of an enclosure, these measurements allow us to ascertain more information about the physical construction of the switch despite our inability to physically see or measure these features. This result also means that the switch could be placed in either orientation in a circuit, without consequence.

3.3.2 Extracting Capacitance Value

If the switch is approximated as a parallel plate capacitor, then the equivalent capacitance can be found using the following equations from section 2.2:

\[
Z_{\text{switch}} = Z_o \frac{1 + S_{11}}{1 - S_{11}}
\]

\[
Z_C = \frac{1}{j\omega C}
\]
Figure 3.12: Comparison of $S_{11}$ and $S_{22}$ to verify that the switch is reciprocal

where $Z_{\text{switch}}$ and $Z_C$ are the same in this case. From our $S_{11}$ measurement we can determine the impedance, which in turn allows us to determine the equivalent capacitance. Combining these two equations leads to:

$$C = \frac{1 - S_{11}}{j\omega Z_o(1 + S_{11})}$$

Figure 3.14 shows the calculated equivalent capacitance value versus frequency. If the switch truly were a capacitor, then the capacitance value would be constant and not frequency dependent. For this reason, the RF MEMS switch cannot simply be modeled as a capacitor. A description of a more robust model for the RF MEMS switch is given in chapter 4.
Figure 3.13: Comparison of $S_{21}$ and $S_{12}$ to verify that the switch is reciprocal
Figure 3.14: Equivalent capacitance value versus frequency
CHAPTER 4

MODELING RF MEMS SWITCH

4.1 Equivalent Circuit

After taking physical measurement of the RF MEMS switch, the next step was to create a circuit model that would mimic the behavior of the RF MEMS switch. Until this point the RF MEMS switch has been treated as a parallel plate capacitor for simplicity. The measured S-parameters of the switch clearly indicate that simply using a capacitor to model the switch is not sufficient. Another look at the equation for the impedance of a capacitor from section 2.2,

\[ Z_C = \frac{1}{j\omega C} \]

shows that an ideal capacitor would have a purely reactive impedance and infinite impedance for \( \omega = 0 \) which means that the \( S_{11} \) plot for an ideal capacitor would start at the far right of the Smith chart (open, i.e. \( Z_C = \infty \)) and advance on the outer edge (R=0), in the clockwise direction as frequency increases. The actual measurement in figure 3.7 shows that while the switch does look capacitive (i.e., it falls in the bottom half of the Smith chart), it also has some real component to the impedance. The real component is also frequency dependent, which means simply adding a resistor will be insufficient to model the switch since the resistance (real component of impedance) of a resistor is not frequency dependent. For comparison, the unbiased measurement data and a simulation of a 1 pF capacitor are shown together in figure 4.1.

Agilent Advanced Design System (ADS) was used to create a lumped element circuit model of the RF MEMS switch [13]. First, the measurement data was imported into ADS so that it could be compared with the model. Since the measured S-parameters are almost identical for the biased and unbiased states, the model was compared to only the unbiased case for simplicity.
The next step was to actually design a circuit model using only lumped elements that would mimic the behavior of the physical RF MEMS switch. The design originated from a simple lumped element circuit model of a capacitor shown in figure 4.2. After more manipulation, and also using a simple lumped element circuit model of an inductor shown in figure 4.3 as a guide, the final circuit model that was best able to match the behavior of the RF MEMS switch was completed.

The final design of the lumped element circuit model for the RF MEMS switch is shown in figure 4.4. Using the models for a capacitor and an inductor as guides, this model was formed by adding more lumped elements where necessary and varying element values in order to match the measured S-parameters of the RF MEMS switch. When the model started to more
closely match the measured results, the optimization tool in the Advanced Design System software was used to further improve the match between the lumped element circuit model and the measured S-parameters of the RF MEMS switch.

The optimization tool in ADS was utilized by making “goals” to minimize the difference between the S-parameters of the lumped element model and the S-parameters of the measured data. In order to do this, the unbiased ($V_{bias} = 0V$) data was converted into an S2P file. Then a second circuit, shown in figure 4.5, consisting of only S-parameter terminations and an S2P block, was constructed. The S2P file for the unbiased measurement was linked to the S2P block in the second circuit. This allowed the optimization tool to compare the lumped element circuit model with the measured data in order to further optimize the element values for the circuit model.

4.2 Simulation Results

Figures 4.6 and 4.7 show the actual results of the simulation of the lumped element circuit model compared to the measured S-parameters for the RF MEMS switch. These are best shown on a Smith chart because both mag-
Figure 4.4: Complete lumped element circuit model for the RF MEMS switch

Figure 4.5: Circuit used by ADS optimization tool to compare measured S-parameters with those of the lumped element circuit model

Magnitude and phase information is displayed. The Smith chart plots give the best comparison of an actual match between the lumped element model and the actual measured S-parameters of the RF MEMS switch. In figure 4.6, “S1.0V..S(1,1)” (in blue) is the measured $S_{11}$ for the RF MEMS switch and “S(1,1)” (in red) is the simulated $S_{11}$ for the lumped element circuit model. In figure 4.7, “S1.0V..S(2,1)” (in blue) is the measured $S_{21}$ for the RF MEMS switch and “S(2,1)” (in red) is the simulated $S_{21}$ for the lumped element circuit model.

From figures 4.6 and 4.7, it is clear that the lumped element model better matches the measured $S_{11}$ from the measurement data than it does the $S_{21}$. Obtaining a better match between the simulated $S_{21}$ for the circuit model and the measured $S_{21}$ of the RF MEMS switch exacerbates any mismatch between the simulated $S_{11}$ for the circuit model and the measured $S_{11}$ for the RF MEMS switch, and vice versa. The final element values chosen in figure 4.4 were chosen based on what subjectively looked like the best match between both $S_{11}$ and $S_{21}$. Although a lumped element model that better matches each S-parameter alone could be developed, the goal here is to best match the overall behavior of the RF MEMS switch.
Figure 4.6: Comparison of $S_{11}$ for the lumped element circuit model and the actual measured $S_{11}$ of the RF MEMS switch
Figure 4.7: Comparison of $S_{21}$ for the lumped element circuit model and the actual measured $S_{21}$ of the RF MEMS switch
CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The goal of this thesis was to verify the functionality and create a model of an RF MEMS switch that was designed and created using a new fabrication process. Beyond verifying the functionality and creating a model of the RF MEMS switch, the secondary purpose was to quantify how well this new RF MEMS switch actually functions as an RF switch. From sections 3.2 and 3.3, it is clear that the switch is not currently fully functioning. The most likely cause is stiction, which means that the switch is stuck in the closed, or biased, state even though the DC bias voltage has been removed.

Even though the switch was not functioning, an evaluation of how well the switch performs in the closed state was given. In section 3.3, it was shown that the switch performs well in the closed state. A lumped element circuit model was also shown to match the behavior of the RF MEMS switch.

5.2 Future Work

The first step in any future work should be the verification of the conclusion that the RF MEMS switch is stuck in the closed state even though the DC bias voltage has been removed. In order to do this, an optical profilometer can be used to compare the biased and unbiased states and optically verify whether the bridge is moving or the bridge is stuck in the closed position. Assuming that the switch is in fact stuck, it needs to be redesigned in order to address this reliability issue and stiction. Once a new, and fully functioning, design is complete, the 2-port S-parameters can be measured and compared for the open, $V_{bias} = 0V$, and closed, $V_{bias} > 70V$, states. As shown in
section 3.3, the current switch functions well as an RF switch in the closed state with a small $|S_{21}|$ and large (close to 1) $S_{stg}$. The next step would be to verify that this is not the case for the open state. In the open state, an ideal impedance-matched switch would have $|S_{21}| = 1$ and $S_{stg} = 0$. For the real switch (not impedance matched), the best possible case is $|S_{21}|^2 = 1 - |S_{11}|^2$ and $S_{stg} = 0$. This ideal $|S_{21}|$ value is plotted in figure 5.1. If these values are verified with the measurements and the switch still performs well in the closed state, then the overall functionality of the switch as an RF switch will have been verified.

Once a fully functioning switch has been designed, the lumped element circuit model will also have to be verified. The current model is accurate for the closed state. However, as shown in section 3.3.2, the capacitance will clearly change depending on whether the switch is open or closed. Even if the switch is impedance matched to the system in one state, moving the bridge will change the impedance of the switch and therefore change the capacitance. This will be interpreted in the model as component values changing. Overall, the same layout for the circuit model may hold, but the component values

![Figure 5.1: Best possible value of $|S_{21}|$ for the open (unbiased) case given $|S_{11}| \neq 0$](image-url)
will need to change to mimic the behavior of the switch in the open state.

The lumped element circuit model can also be improved so that the match between the simulated $S_{21}$ of the model and the measured $S_{21}$ of the actual RF MEMS switch better match each other. Ideally, a method of improving this match without diminishing the match between the simulated $S_{11}$ of the model and the measured $S_{11}$ of the switch will be found. In order to do this, it may take more than simply changing component values in the current model. The current model may need to be redesigned by adding lumped element components and changing values of current elements.
REFERENCES


