1 Purpose and Learning Objectives

The purpose of this lab is to apply transmission line theory learned in class to implement a high-frequency electronic circuit. Students will first work on understanding the function of the filters, Bode Plots, and decibels. Then given a transmission-line filter design, they will implement the filter in ADS using ideal and microstrip lines. The objectives of the lab are for students to be able to:

1. Explain a basic function of a filter
2. Relate decibels to a fraction of powers for multiples of 2, 10, 1/2 and 1/10.
3. Read and Analyze Rogers Corporation PCB datasheets.
4. Use ADS LineCalc utility to design microstrip lines.
5. Use microstrip equations to design microstrip lines.
6. Implement and simulate a microstrip filter.
7. Describe different PCB (height, $\epsilon_r$, $\tan \delta$, etc) parameters affect the microstrip circuit.
8. Describe how transmission line impedance and electrical length affect width and length of the transmission line.

2 Filters

This section introduces filters, Bode Plots and how to read decibels. You do not have to simulate this circuit, just read through the section, and ensure you understand what is a filter, how to read a Bode Plot, and what -3dB, -10dB, -23dB, etc mean.

Filters are two-port electronic circuits that selectively pass frequencies from input to output. For example, a low-pass filter will only pass low frequencies to its output and reject high frequencies. A high-pass filter will only pass high frequencies to its output and reject low frequencies. We use Bode Plots to describe how different frequencies are passed or rejected by the filter. In your circuits and electronics classes, lower you used to plot the magnitude of the transfer function, or magnitude of the gain $H(j\omega) = V_{out}/V_{in}$ as a function of frequency. In electromagnetics and microwave engineering, we plot the magnitude of the transmission coefficient $S(2,1)$, which is essentially the gain of a circuit.

The circuit in Figure 1 shows an example of a low-pass lumped-element filter designed to have a corner frequency of 8 GHz. The corner frequency is a term that describes at which frequency the output power from the filter is halved.
Figure 1: Example of a lumped-element filter. Specifications: corner frequency $f_0=8\,$GHz, order $N=4$, Maximally-flat (Butterworth) filter.
\[ P_{\text{out}} = \frac{P_{\text{in}}}{2} \]  
(1)

\[ \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1}{2} \]  
(2)

When you look at Figure (b), you see that the gain \( S(2,1) \) is given in terms of dB or Decibels. The gain is -3dB at the corner frequency \( f_c = 8 \, \text{GHz} \). Another specification related to filters is Stopband frequency and attenuation at that frequency. This specification together with corner frequency determines the steepness of the slope on Bode Plot and order of the filter. Order of the filter is the number of elements (inductors, capacitors) in the filter. In the example above, stopband can be specified to be -13dB at 12 GHz.

2.1 Decibels

We use decibels to describe gain at a certain frequency. Corner frequency in a filter is usually defined at the point where the gain is -3dB:

\[ 10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = 10 \log \frac{1}{2} = -3 \, \text{dB} \]  
(3)

We can also use ratio of voltages, because power is proportional to voltage squared, and if the impedances are the same, the equation then becomes:

\[ 10 \log \frac{V_{\text{out}}^2}{V_{\text{in}}^2} = 10 \log \frac{1}{2} = -3 \, \text{dB} \]  
(4)

\[ 10 \log V_{\text{out}} = -3 \, \text{dB} \]  
(5)

\[ 20 \log \frac{|S(2,1)|}{V_{\text{in}}} = -3 \, \text{dB} \]  
(6)

Sometimes the above Equations (5) and (6) are confused when displayed in the simulators or calculated by hand. \( S(2,1) \), the transmission coefficient is the ratio of voltage at the output of the filter over the voltage at the input of the filter. \( S(2,1) = \frac{V_{\text{out}}}{V_{\text{in}}} \), so the equations (5) and (6) can be re-written as

\[ 10 \log |S(2,1)|^2 = -3 \, \text{dB} \]  
(7)

\[ 20 \log |S(2,1)| = -3 \, \text{dB} \]  
(8)

In ADS if you display the magnitude of gain \( |S(2,1)| \) as a function of frequency, and select a dB, ADS will display \( dB(S(2,1)) = 20 \log |S(2,1)| \). When you read the frequency at which the magnitude of \( S(2,1) \) in decibels is -3dB, this is the point where the output power is halved, and also where the output voltage is \( 1/\sqrt{2} = \frac{\sqrt{2}}{2} = 0.707 \) of the input voltage.
2.2 Reading Decibels

Above we saw that the ratio of two powers is represented in Decibels $10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = \text{Ratio}[dB]$. Therefore, the ratio of two powers in Watts is $P_{\text{out}}[W]/P_{\text{in}}[W] = 10^{\text{Ratio}[dB]/10}$.

So, what does it mean when you read on a Bode Plot that gain is $0dB$? It means that the output power is equal to input power.

$$10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = 0dB \quad (9)$$
$$P_{\text{out}}[W]/P_{\text{in}}[W] = 10^0 = 1 \quad (10)$$
$$P_{\text{out}}[W] = P_{\text{in}}[W] \quad (11)$$

What if this ratio is $-10\, dB$? It means that the output power is one-tenth of the input power.

$$10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = -10\, dB \quad (12)$$
$$P_{\text{out}}[W]/P_{\text{in}}[W] = 10^{-1} = \frac{1}{10} \quad (13)$$
$$P_{\text{out}}[W] = P_{\text{in}}/10[W] \quad (14)$$

What if this ratio is $-30\, dB$? It means that the output power is $-10\, -10\, -10\, dB$, one-thousandth of the input power. Every time we subtract 10dB, we divide input power by 10.

$$10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = -30\, dB \quad (15)$$
$$10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = -10dB - 10dB - 10dB \quad (16)$$
$$\frac{P_{\text{out}}}{P_{\text{in}}} = 10^{-3} = 10^{-1}10^{-1}10^{-1} = \frac{1}{10} \frac{1}{10} \frac{1}{10} = \frac{1}{1000} \quad (17)$$
$$P_{\text{out}}[W] = P_{\text{in}}/1000[W] \quad (18)$$

What if this ratio is (positive) $30\, dB$? It means that the output power is $1000$ times the input power. Every time we add another 10dB, we multiply input power by 10.

$$10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = +30\, dB \quad (19)$$
$$10 \log \frac{P_{\text{out}}}{P_{\text{in}}} = +10dB + 10dB + 10dB \quad (20)$$
$$\frac{P_{\text{out}}}{P_{\text{in}}} = 10^3 = 10^110^110^1 = 1000 \quad (21)$$
$$P_{\text{out}}[W] = 1000P_{\text{in}}[W] \quad (22)$$
What if this ratio is -3dB? It means that the output power is 1/2 of the input power.

\[
10 \log \frac{P_{out}}{P_{in}} = -3
\]  
(23)

\[
P_{out} = 10^{-0.3} = \frac{1}{2}
\]  
(24)

\[
P_{out}[W] = \frac{P_{in}}{2}[W]
\]  
(25)

What if this ratio is -6dB? It means that the output power is -3dB, or 1/4 of the input power. Every time you subtract -3dB you divide the input power by 2.

\[
10 \log \frac{P_{out}}{P_{in}} = -6 dB
\]  
(26)

\[
10 \log \frac{P_{out}}{P_{in}} = -3dB - 3dB
\]  
(27)

\[
P_{out} = 10^{-0.6} = 10^{-0.3} \cdot 10^{-0.3} = \frac{1}{22} = \frac{1}{4}
\]  
(28)

\[
P_{out}[W] = \frac{P_{in}}{4}[W]
\]  
(29)

What if this ratio is -13dB? It means that the output power is -10dB, or one-twentieth of the input power. When we subtract 10dB we divide by 10, and subtract another 3dB, divide by 2.

\[
10 \log \frac{P_{out}}{P_{in}} = -13 dB
\]  
(30)

\[
10 \log \frac{P_{out}}{P_{in}} = -10dB - 3dB
\]  
(31)

\[
P_{out} = 10^{-1.3} = 10^{-1} \cdot 10^{-0.3} = \frac{1}{10} \cdot \frac{1}{2} = \frac{1}{20}
\]  
(32)

\[
P_{out}[W] = \frac{P_{in}}{20}[W]
\]  
(33)

**Question** Look at the gain as a function of frequency in Figure [I] and describe what are the ratios of power for the two frequencies given in the graph.

### 3 Implementation of the low-pass maximally-flat filter with Ideal Transmission Lines in ADS

In this section, we will simulate a transmission-line filter. To do that we will first use ideal transmission lines. You can find them under "Transmission Lines Ideal" components in ADS. Once we confirm that the circuit acts as a low-pass filter with desired corner frequency, we will proceed to implement the filter in microstrip line technology, as shown in the subsequent section. You could make this filter using different kinds of transmission lines as well: coaxial cables (although it would
be difficult to make specific transmission line impedances as given below - this would require specific radii of inner and outer conductor), microstrip lines, or waveguides.

Transmission-line filter design is given in Figure 2 (a). Each transmission line is specified in terms of its transmission-line impedance and electrical length. Your task is to simulate the filter in ADS using the ideal transmission lines, and obtain the gain of the filter as shown in Figure 2 (b). To simulate the gain of the circuit, you will find the "Term 1" and S-parameter simulation blocks under the "Simulation S-Parameter". "Term 1" will send a forward going voltage to the filter and measure the voltages that reflect from the structure and transmit from Term 2. Note that all lines are E=45° long and they have different transmission-line impedances Z (50 Ω, 115.4Ω, etc. There are two types of lines used in this filter: TLIN - Transmission Line IN series, and TLOC - Transmission Line Open Circuit. TLOC has two terminals, one represents the "signal" part of the transmission line and the ground part of the open transmission line. You must ground the skinny part of TLOC.

When you complete the simulation, read the dB from the graph, then calculate the ratio of input and output powers at 2 GHz, 8 GHz and 12 GHz without a calculator.

4 Implementation of the low-pass maximally-flat filter with microstrip transmission lines in ADS

We will now implement the filter from Figure 2 using microstrip lines. This is what an engineer has to do to make the actual filter on a PC Board.

1. The process starts with the selection of a microstrip substrate (a PCB).

2. Then we use either equations from Ulaby, or LineCalc to find width and length of transmission lines on the chosen PCB.

3. Simulate microstrip filter in ADS.

We start with the selection of a microstrip substrate in the next section.

4.1 Select microstrip substrate (PCB)

In this section, your task is to implement the filter above in microstrip technology. To do that you first have to select the substrate (PCB - PC Board) from Rogers Corporation datasheets. Rogers makes high-frequency laminates (aka substrates or PCBs). Low-frequency circuits are usually made on FR4 substrate.

Google "High-Frequency laminates - Product selection guide". The first link should be the datasheet. Find the appropriate substrate parameters (dielectric thickness, copper thickness, $\epsilon_r$, $\tan\delta$) for RT Duroid 5870 and select a standard thickness of the dielectric and electrodeposited copper (EDC). EDC is usually given in ounces, which represent 1oz of copper per (each) square inch.
(a) Transmission-line low pass filter schematic in ADS.

(b) Simulation of transmission-line low pass filter shown in (a).

(c) S-Parameter simulation block settings in ADS

Figure 2: Transmission-line filter design. Specifications: corner frequency $f_0=8$ GHz, order $N=4$, Maximally-flat (Butterworth) filter.
4.2 Use Line Calc and equations from Ulaby to find the width and length of microstrip lines on the selected substrate

1. Start ADS. In the schematic window, click on Tools, Line Calc, Start Line Calc. LineCalc window should open. Choose the microstrip line (MLIN).

2. Design 45°, 50Ω, 115.4Ω, 88.3Ω etc (see Figure 2 (a) ) for the chosen substrate. Hint: The degrees in Line Calc represent the "electrical length" of a line. Electrical length is calculated as $\frac{2\pi l}{\lambda}$, where $\lambda$ is the wavelength, and $l$ is the actual length of the line. $\lambda = \frac{c}{f \sqrt{\epsilon_{eff}}}$, where $c$ is the speed of light, $f$ is the frequency and $\epsilon_{eff}$ is the effective dielectric constant. Remember that the higher the impedance of the line, the thinner the line is. This is because the transmission-line impedance is $Z = \sqrt{L/C}$. For higher $Z$, inductance is higher (thinner line), and capacitance is lower (thinner line) and vice-versa. A rule of thumb to remember is that a 50-Ohm line is usually as wide as the substrate thickness.

3. Use equations for microstrip lines from Ulaby’s book (see Handout or Microstrip Lines section of Ulaby, page 62) and Matlab to calculate transmission line impedances. How do they compare to the ones from LineCalc? Make a table to present data, and calculate relative errors.
Figure 4: Calculating length and width of a microstrip transmission line using Line Calc.
4.3 Simulate the microstrip filter in ADS

To simulate the circuit, follow the steps below:

1. add on the schematic the substrate parameters we’re using as shown in Figure 3(b).

2. Check the values for the substrate parameters you used in the previous step, and update the substrate parameter on the schematics.

3. Layout the microstrip filter lines by using microstrip lines from “Transmission Lines Microstrip” as shown in Figure 3(a). You have to replace each width and length of a microstrip line that you calculated in the previous section. Notice that two types of lines are used: MLIN and MLOC. MLOC here does not have the ground connection, because in microstrip lines, ground is one large, solid metal surface, and there is no uncertainty on how the ground will be connected.

4. Add the S-Parameter simulation block.

5. Plot magnitude of transmission coefficient as a function of frequency.