

Basic RF Technic and Laboratory Manual - Impedance Matching.

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Chapter 1

PRELAB EXERCISE

1. Define of the following terms: DC resistance, AC resistance, impedance matching (what are its usages?) and Q factor (what are its usages?).

2. For a load impedance $Z_L = 66 + j62.8\Omega$, calculate what should be the two lumped elements network (L section) to match this load to a 50Ω transmission line (two solutions). Assume that the load is matched at 10 MHz and the load consists of a resistor and a series inductor.

3. For a load impedance $Z_L = 25\Omega$, calculate the distance from the load and the value of a single lumped element network to match this load to a 50Ω line.

Assume that the load is matched at 200 MHz.

Chapter 2

BACKGROUND THEORY

Impedance matching is defined as: "The connection of an additional impedance to an existing one in order to achieve a specific effect, such as maximum power transfer from the output of one circuit to the input of another, or to reduce reflection in a transmission line, or to balance a circuit". In order to achieve these goals, we will define:

- **Conjugate Matching** - The matching of a load impedance to a generator for maximum power transfer (assuming $Z_G = Z_0$).
- **Characteristic impedance matching** - The matching of a load impedance to a transmission line to minimize reflection wave.

2.0.1 *Impedance matching is important for the following reasons:*

- For dissipation-less matching network - for low loss transmission line, maximum power is delivered from the generator to the load, when the load is matched to the line (assuming the generator is matched to the line).
- For a high power system, the peak voltage along the line is minimized when the SWR is close to unity. This is important when dielectric breakdown or corona loss problem may encountered.
- If neither the load nor the generator matched to the line, the transmission line can cause non linearity of phase versus frequency which results in modulation distortion, which limits the information rate capability.
- For low loss transmission line, the load power is independent of line length and frequency.
- For a lossy line, power transfer is most efficient, with no reflected wave on the line (characteristic impedance matching).
- Impedance matching reduce the insertion loss of the system, therefore a noise figure of the system is improved.

For the mentioned reasons, many systems and components are designed to minimum SWR over their operating frequency range (typically for $\text{SWR} < 1.25$).

2.1 Matching using Two Lumped Elements (L Section)

A simple way to match an arbitrary load, Z_L , to a transmission line is the L section, which uses two reactive elements, jX and jB , to match an arbitrary load Z_L . For the case for $R_L > Z_0$. The L section is shown in Figure 1.

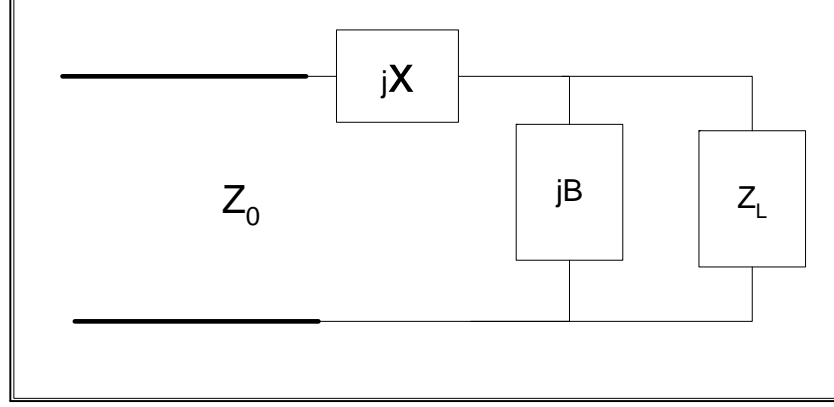


Figure 1 - LC matching network - $R_L > Z_0$.

We assume that jX is the imaginary part of the impedance, and jB is the admittance of the L section. For a match, the impedance seen toward the load has to be equal to Z_0 .

$$Z_0 = jx + \frac{1}{jB + \frac{1}{R_L + jX_L}} \quad (2.1)$$

If we separate the real and imaginary parts of equation 1, we get two equations:

$$\begin{aligned} Z_0 &= \frac{R_L}{B^2 X_L^2 - 2BX_L + B^2 R_L^2 + 1} \\ 0 &= X_L^2 X B^2 - BX_L^2 - 2X_L X B + X_L - BR_L^2 + X_L B^2 R_L^2 + X_L \end{aligned} \quad (2.2a)$$

For solving equation 2 for B and X, we get:

$$\begin{aligned} B &= \frac{1}{2(Z_0 R_L^2 + Z_0 X_L^2)} \left(2Z_0 X_L \pm 2\sqrt{-Z_0^2 R_L^2 + Z_0 R_L^3 + Z_0 X_L^2 R_L} \right) \\ X &= \frac{BR_L^2 + BX_L^2 - X_L}{B^2 R_L^2 - 2BX_L + 1 + B^2 X_L^2} \end{aligned} \quad (2.3)$$

Equation 3 indicates that there are two solutions possible for admittance B and for impedance X . The two solutions are physically realizable, since a positive X implies an inductor and a negative X implies a capacitor, while a positive B implies a capacitor and a negative B implies an inductor.

2.2 Matching using Single Lumped Element

The simplest matching technique which uses a single reactive element connected either in parallel or in series with the transmission line at a certain distance from the load, is shown in Figure 2.

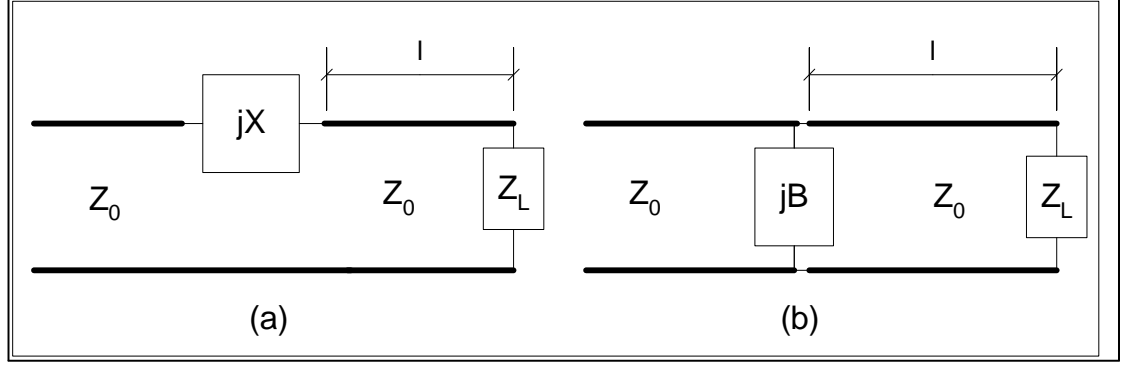


Figure 2 - Single element matching (a) Serial element (b) Shunt element.

In single-element matching, the two adjustable parameters are the distance, l and the value of susceptance or reactance provided by the shunt or series element. Distance l is measured from the load to element position.

2.2.1 Series Element Matching

For the series element case, the distance l is selected, so that the impedance Z , seen toward the load at a distance l is equal to $Z_0 + jX$. In this case, the element reactance is selected as $-jX$, resulting in conjugate matching.

For a load impedance of $R_L + jX_L$, the impedance Z_{in} at distance l from the load is:

$$Z_{in} = Z_0 \frac{(R_L + jX_L) + jtZ_0}{Z_0 + (R_L + jX_L)jt} \quad (2.4)$$

Where $t = \tan\beta l$. By separating the impedance Z into real and imaginary parts, $Z = R + jX$, we get:

$$R = Z_0^2 R_L \frac{1 + t^2}{Z_0^2 - 2Z_0 t X_L + t^2 X_L^2 + t^2 R_L^2} \quad (2.5)$$

and

$$X = Z_0 \frac{Z_0 X_L - t X_L^2 + t Z_0^2 - t^2 Z_0 X_L - R_L^2 t}{Z_0^2 - 2Z_0 t X_L + t^2 X_L^2 + t^2 R_L^2} \quad (2.6)$$

For $R = Z_0$, we get:

$$\begin{aligned} t_1 &= -\frac{Z_0 X_L - \sqrt{Z_0} \sqrt{R_L} \sqrt{X_L^2 - 2Z_0 R_L + R_L^2 + Z_0^2}}{-X_L^2 - R_L^2 + Z_0 R_L} \\ t_2 &= -\frac{Z_0 X_L + \sqrt{Z_0} \sqrt{R_L} \sqrt{X_L^2 - 2Z_0 R_L + R_L^2 + Z_0^2}}{-X_L^2 - R_L^2 + Z_0 R_L} \end{aligned} \quad (2.7)$$

By knowing the value of t , one can extract the value of l , by solving the equation $t = \tan \beta l$. If $l < 0$, $\lambda/2$ has to be added to the value of l .

2.2.2 Shunt Element Matching

For the shunt-element case, the basic idea is to select l , so that the admittance, Y , seen toward the load at a distance l from the load is equal to $Y_0 + jB$. Then the element suscepance is chosen to be $-jB$, resulting in conjugate match condition:

$$Y_{in} = Y_0 \frac{Z_0 + (R_L + jX_L) jt}{(R_L + jX_L) + jtZ_0}$$

Where $t = \tan \beta l$.

Separating the admittance Y into real and imaginary parts, $Y_{in} = G + jB$, we get:

$$\text{Re } Y_{in} = G = \frac{R_L (1 + t^2)}{R_L^2 + X_L^2 + 2X_L t Z_0 + t^2 Z_0^2}$$

By substituting $G = Y_0 = \frac{1}{Z_0}$, t becomes:

$$t = \frac{1}{(R_L Z_0 - Z_0^2)} \left(X_L Z_0 \pm \sqrt{-2Z_0^2 R_L^2 + R_L^3 Z_0 + R_L Z_0 X_L^2 + Z_0^3 R_L} \right) \text{ for } R_L \neq Z_0$$

By knowing the value of t , one can extract the value of l , by solving the equation $t = \tan \beta l$. If $l < 0$, $\lambda/2$ has to be added to the value of l .

The imaginary part of Y_{in} , B , is the susceptance of input and can be calculated by:

$$\text{Im } Y_{in} = B = Y \frac{t R_L^2 - X_L Z_0 - t Z_0^2 + X_0^2 t + X_L t^2 Z_0}{R_L^2 + X_L^2 + 2X_L t Z_0 + t^2 Z_0^2}$$

2.3 Air-core solenoids

Although today focus is on planar components, more inductance per volume can be obtained with a classic 3 dimensions structure. The single-layer solenoid, which is widely used at high frequencies, where the inductance of the solenoid is relatively small.

Assuming that the turns are tightly packed ("close-wound"), the inductance in microhenries is given by the famous formula:

$$L (\mu H) = \frac{d^2 n^2}{l + 0.45d}$$

Where $d(\text{meter})$ is the diameter of the coil, $l(\text{meter})$ is the length of it and n is the number of turns of the solenoid. Here a free-space permeability is assumed. These formulas provide remarkable accuracy (typically better than 1 %) for close-wound single-layer coils, as long as the length is greater than the radius.

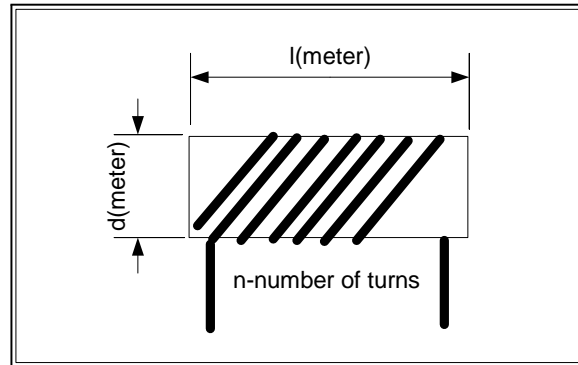


Figure 3 - Air coil solenoid.

Chapter 3

EXPERIMENT PROCEDURE

3.1 Required Equipment

1. Network Analyzer *HP – 8714B*.
3. Termination - 50Ω .
4. Standard 50Ω coaxial cable.
5. Simulation Software ADS.

3.2 Matching using Two Lumped Elements (L Section)

In this part of the experiment you will match a microstrip line ending with the load $Z_L = 66 + j62.8\Omega$. The matching frequency is 10MHz .

1. Simulate the microstrip line connected to the load without any matching, as shown in Figure 4.

The parameters of the microstrip are: line length 10cm, line width 3mm, dielectric substrate high 1.6 mm and dielectric material FR4 $\epsilon_r = 4.7$.

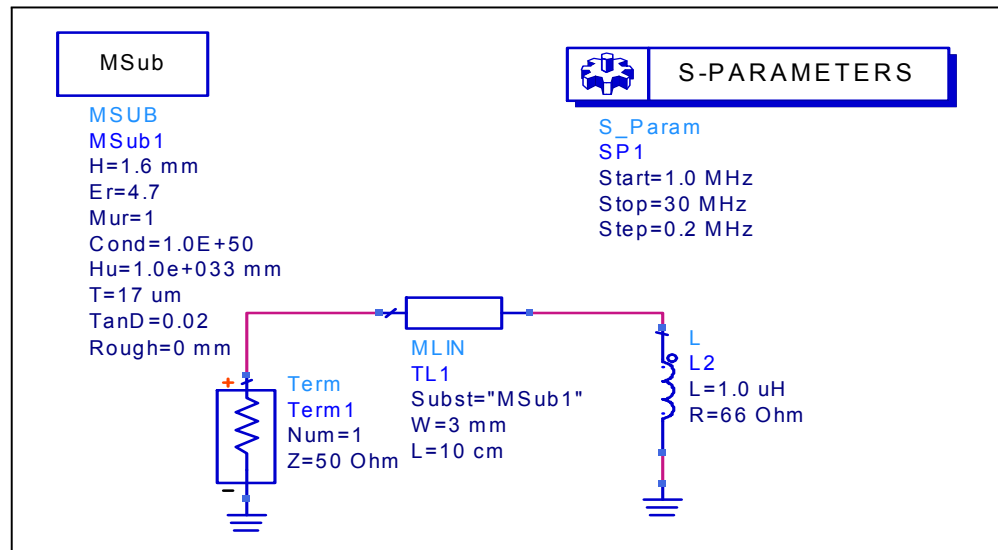


Figure 4 - Simulation without matching.

Draw a graph of S_{11} versus frequency. Frequency range 1-30MHz. **Save the data.**

2. Use the parameters which you calculated in question 2 from the Prelab Exercise and simulate the microstrip line with a L section matching (a series capacitor and a parallel inductor), as shown in Figure 5.

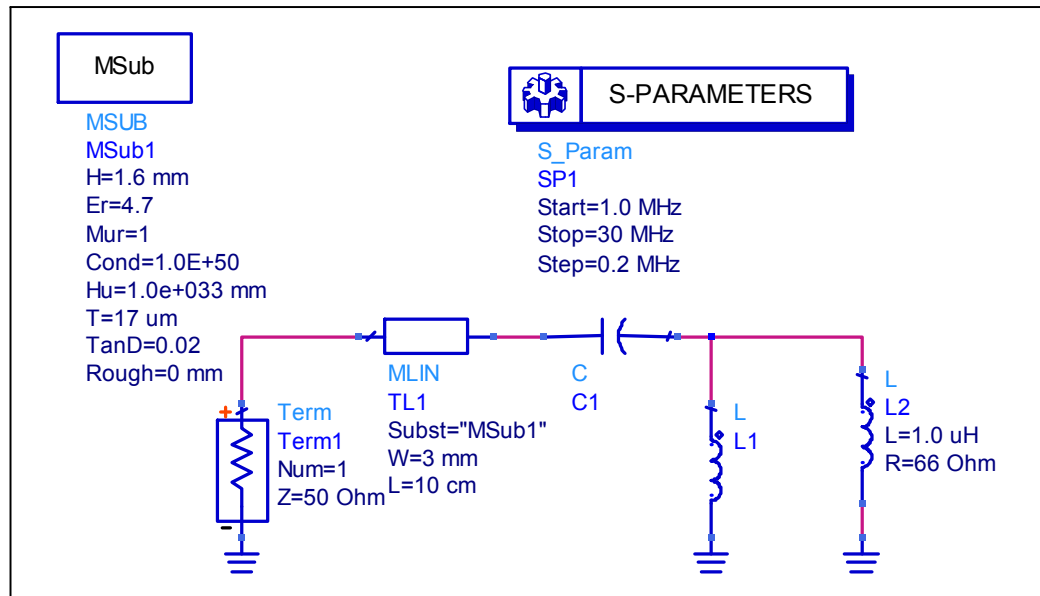


Figure 5 - Simulation of matching using two lumped elements.

Draw a graph of S_{11} versus frequency. Frequency range 1-30MHz. **Save the data.**

Compare this result to the result from question 1.

3. Connect the microstrip line to the network analyzer at one end, and to the load at the other, as indicated in Figure 6.

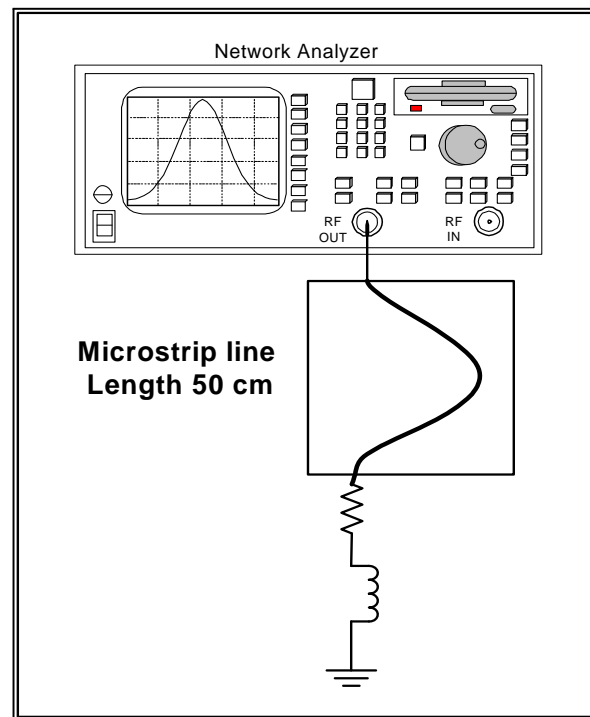


Figure 6 - Microstrip line ending with load $Z_L \neq Z_0$.

Measure S_{11} . **Save the data on magnetic media.**

4. Disconnect the load from the microstrip. Connect the matching circuit, with the series capacitor and the parallel inductor, between the microstrip line and the load.

Measure S_{11} . **Save the data on magnetic media.**

Compare this result to the result from question 3.

5. Compare the measurement results to the simulation results.

6. Simulate the second solution of the matching network (a series inductor and a parallel capacitor), and prove your solution by drawing the graph of S_{11} versus frequency. **Save the data.**

7. Replace the matching circuit with a matching circuit with a series inductor and a parallel capacitor.

Measure S_{11} versus frequency. **Save the data on magnetic media.**

8. Compare the measurement results to the simulation.

3.3 Matching Using a Single Lumped Element

In this part of the experiment you will match at 200 MHz a 25Ω load to a 50Ω microstrip line, using single lumped element (inductor or capacitor).

1. Use the parameters which you calculated in question 3 from the Prelab Exercise and simulate the 50Ω microstrip line, with a single element matching (inductor), as shown in Figure 7.

The parameters of the microstrip are: line length 50cm, line width 3mm, dielectric substrate high 1.6 mm and dielectric material FR4 $\epsilon_r = 4.7$.

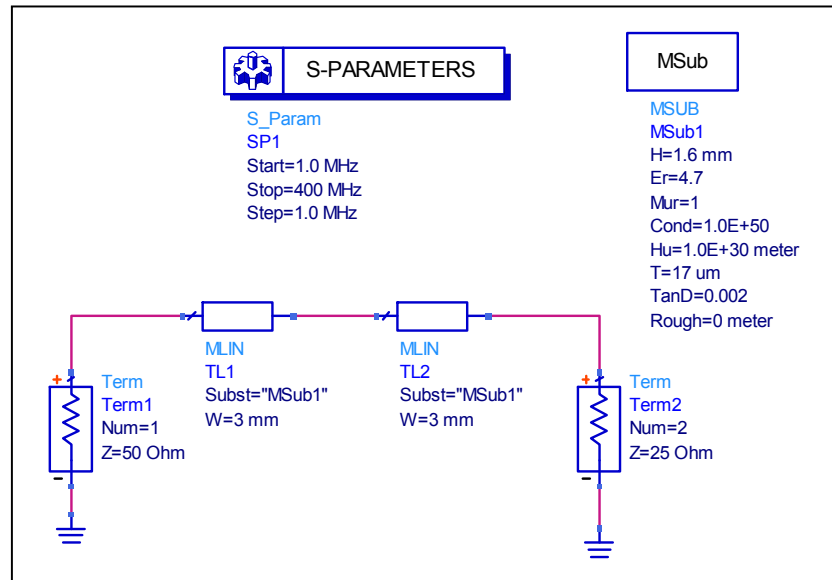


Figure 7 - Simulation without matching.

Draw the graph of S_{11} versus frequency. Frequency range 300kHz-400MHz.

Save the data.

2. Add the matching element to your simulation, as shown in Figure 8.

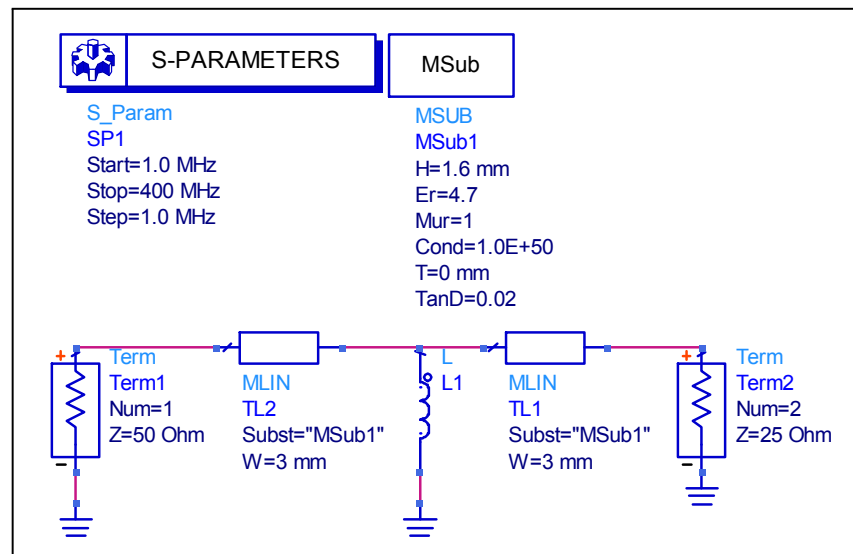
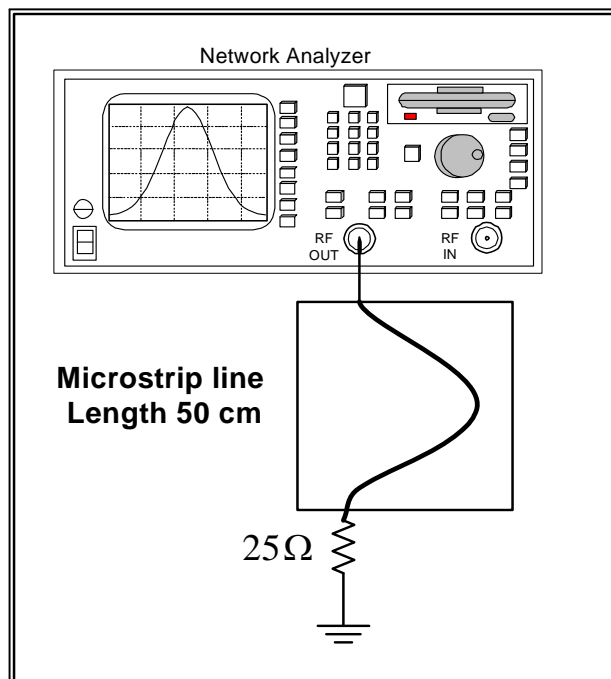


Figure 8 - Simulation of matching real load using a single element.

Draw the graph of S_{11} versus frequency. Frequency range 300kHz-400MHz.
Save the data.

3. Connect the real microstrip line to the network analyzer in one end and to a 25Ω load in the other, as shown in Figure 9.

Figure 9 - 50 cm microstrip line terminated with 25Ω .

Measure S_{11} in the frequency range 300 kHz - 400 MHz. **Save the data on magnetic media.**

4. Connect the inductor at the distance which you calculated in question 3 from the Prelab Exercise from the load.

Measure S_{11} in the frequency range 300 kHz - 400 MHz. **Save the data on magnetic media.**

5. Compare the measurement results to the simulation results.

3.4 Final Report

1. **A single element mathing** - It is known that the radius of the wire is 0.3mm and its length is 8mm.

Compute the following parameters of the wire:

1.
 - Calculate the DC resistance and the Q factor of the inductor (based on the phisical dimension of the wire).
 - Draw a graph of the AC resistance versus frequency DC-300 MHz (use skin depth effect).
 - Using Matlab, draw a graph of the calculated Q factor versus frequency.

2. **A single element matching** - Using your measurement data draw graphs of L and Q factor versus frequency (1 – 300MHz) of the inductor that you wind in the lab, compare your inductor to industrial inductor (typical $Q = 100$ at 150 MHz, DC resistance 10m Ω).

3. Calculate the values of a single element (a capacitor) matching and its distance from a load impedance of $Z_L = 25 + j12\Omega$. The load is matched to a 50 Ω microstrip line at 200MHz.

Simulate your design using ADS.

Draw a graph of S_{11} versus frequency, from 1 to 400MHz.