Impedance Matching using Lumped Elements in ADS

1) Objective:

To design L-section matching networks to match two arbitrary impedances using either the analytical or Smith Chart approach, and characterize impedance matched systems using ADS

2) Theory:

Impedance matching is defined as the connection of additional circuitry between a source and a load to achieve a specific effect such as maximum power transfer from source to load, or to reduce reflections in a transmission line. Impedance matching is important for the following reasons:

a) Maximizes power delivered from generator to load
b) Prevents equipment damage by reducing power reflected back to source
c) Minimizes power loss, thus maximizing battery life and reducing risk of radiation hazard
d) Reduces insertion loss of a system, which in turn improves noise figure of a system
e) Minimizes peak voltage along a transmission line which prevents dielectric breakdown or corona loss
f) Prevents phase nonlinearity and modulation distortion in a transmission line
g) Increases sensitivity of receiver circuitry by maximizing power transfer to load

The factors that are important in the selection of a particular matching network include the following:

a) Complexity: A simpler matching network is usually cheaper, more reliable and incurs less loss than a more complex design.
b) Bandwidth: A matching network should achieve wide bandwidth matching.
c) Ease of Implementation: A matching network should be realizable using available fabrication technology.
d) Adjustability: A tunable matching network is preferred that can perform satisfactorily even when load impedance changes.

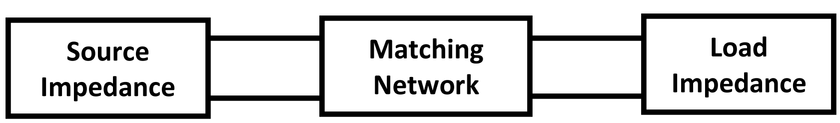


Figure 1: Matching Network between Load and Source Impedances

Consider the case of matching a 100 Ω load to a 50 Ω system at 100 MHz as shown in figure 2. A 100 Ω resistor in parallel with the load will match the load to the 50 Ω system. However, half of the power will be dissipated in the matching network.

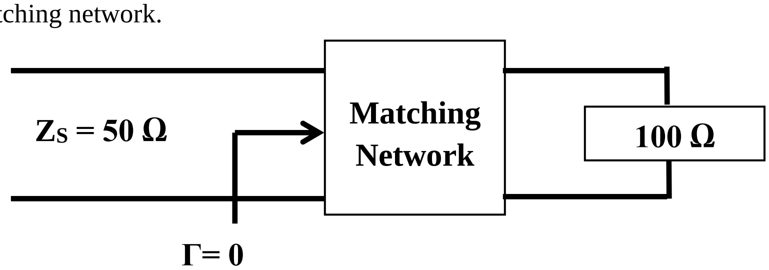


Figure 2: Matching Network between 100 Ω load and 50 Ω Source

To ensure that the available power of the source is delivered to the load, the matching network must not absorb any power, i.e. the matching network must be lossless. This condition can be fulfilled by constructing the matching network entirely using reactive elements. Examples of reactive elements include inductors, capacitors as well as lengths of lossless transmission lines.

Impedance Matching using Lumped Elements in ADS

The simplest type of matching network is the L-section. It uses two reactive elements to match an arbitrary load impedance to a source impedance. This network topology gets its name from the fact that the series and shunt elements of the matching network form an "L" shape. There are two possible configurations for this network depending upon whether the normalized load impedance is inside or outside the unit resistance circle.

Case 1: Normalized Load Impedance Inside Unit Resistance Circle (Re $\{Z_L\} > Z_0$)

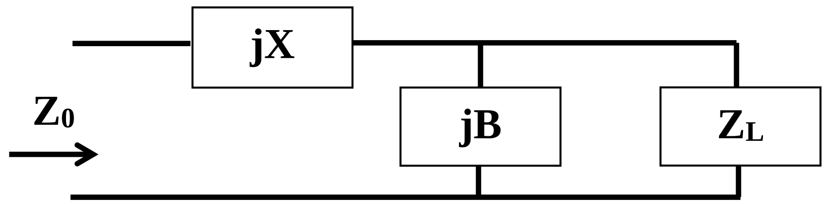


Figure 3: L-Section Configuration when Normalized Impedance is Inside Unit Resistance Circle

It is assumed that the un-normalized load impedance is $Z_L = R_L + jX$, and that the impedance looking into the matching network is Z_0. An analytical solution for the matching network is as follows:

$$B = \frac{X_L \pm \sqrt{\frac{R_L}{Z_0}}\left(R_L^2 + X_L^2 - Z_0 R_L\right)}{R_L^2 + X_L^2} \qquad X = \frac{1}{B} + \frac{X_L Z_0}{R_L} - \frac{Z_0}{B R_L}$$

The requirement that $R_L > Z_0$ ensures that the term under the square root in the numerator is real. Note that two solutions for (B) are possible and both solutions are physically realizable given that (B) can be positive or negative. Positive (X) implies an inductor and negative (X) implies a capacitor, while positive (B) implies a capacitor and negative (B) implies an inductor.

Case 2: Normalized Load Impedance Outside Unit Resistance Circle (Re $\{Z_L\} < Z_0$)

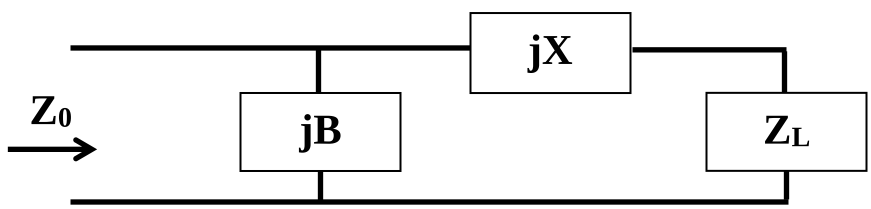


Figure 4: L-Section Configuration when Normalized Impedance is Outside Unit Resistance Circle

It is assumed that the un-normalized load impedance is $Z_L = R_L + jX_L$, and that the impedance looking into the matching network is Z_0. An analytical solution for the matching network is as follows:

$$B = \pm\frac{1}{Z_0}\sqrt{\frac{Z_0 - R_L}{R_L}} \qquad X = \pm\sqrt{R_L(Z_0 - R_L)} - X_L$$

Since $R_L < Z_0$, the arguments of the square roots are always positive. Two solutions for (B) are possible and both solutions are physically realizable given that (B) can be positive or negative. Positive (X) implies an inductor and negative (X) implies a capacitor, while positive (B) implies a capacitor and negative (B) implies an inductor.

Impedance Matching using Lumped Elements in ADS

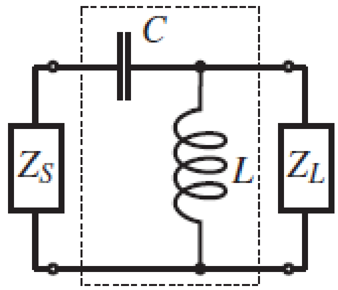


Figure 5: Shunt L, Series C Matching Network

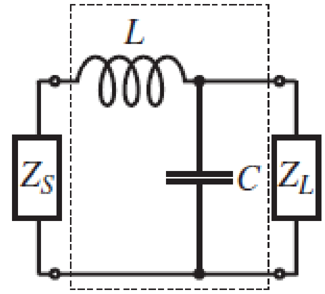


Figure 6: Shunt C, Series L Matching Network

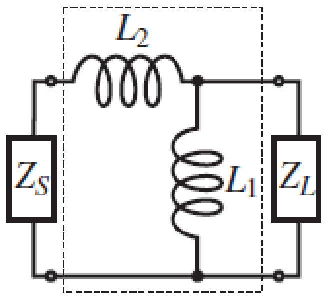


Figure 7: Shunt L, Series L Matching Network

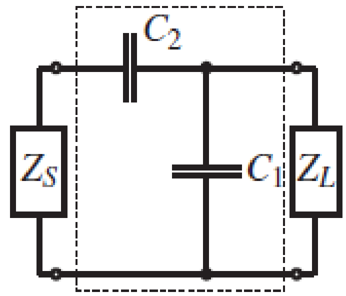


Figure 8: Shunt C, Series C Matching Network

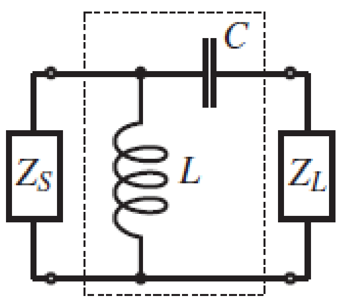


Figure 9: Series C, Shunt L Matching Network

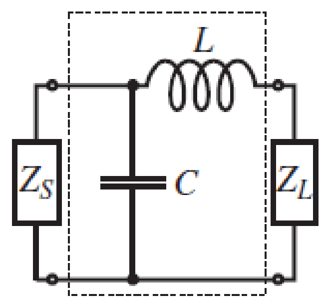


Figure 10: Series L, Shunt C Matching Network

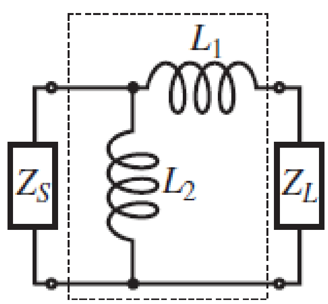


Figure 11: Series L, Shunt L Matching Network

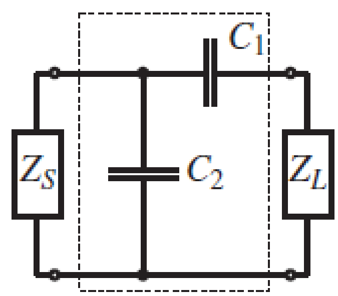
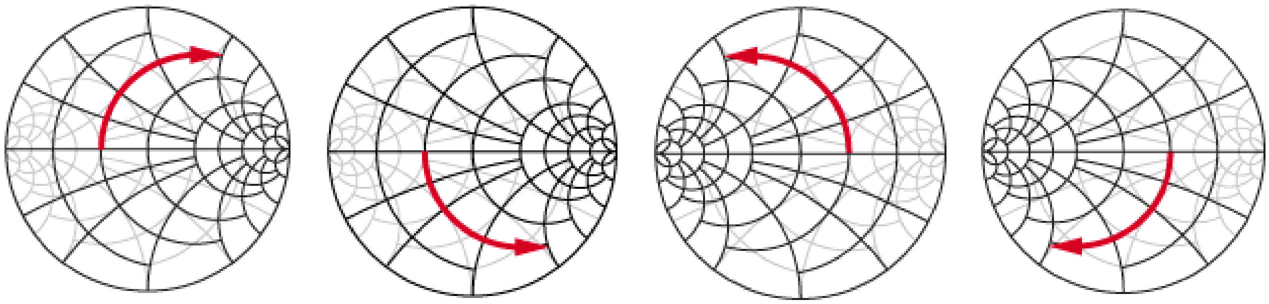


Figure 12: Series C, Shunt C Matching Network

The ultimate goal of a matching network is to arrive at the origin of the Smith Chart. It should be apparent that when a point lies on the unit resistance circle or unit conductance circle, the origin of the Smith Chart can be

Impedance Matching using Lumped Elements in ADS

reached by adding a single reactive element in series or in parallel with the load. Otherwise, a two-element L-section network is needed to provide the necessary degree of freedom to match an arbitrary load to a characteristic impedance Z_0.



(a) Increasing Series L **(b) Decreasing Series C** **(c) Decreasing Shunt L** **(d) Increasing Shunt C**

Figure 13: Effect of Reactive Elements on the Smith Chart

From figure 13, the following observations can be made:

(a) Series inductor causes clockwise rotation along circles of constant resistance
(b) Series capacitor causes counter-clockwise rotation along circles of constant resistance
(c) Shunt inductor causes counter-clockwise rotation along circles of constant conductance
(d) Shunt capacitor causes clockwise rotation along circles of constant conductance

While matching a complex load to a complex source as shown in figure 14, the following points need to be considered:

(a) The input impedance looking into the matching network from the source side must be equal to the complex conjugate of the source impedance. If the source impedance is $Z_S = R_S + jX_S$, then for maximum power transfer into the matching network from the source, the required condition is $Z_{IN} = Z_S^* = R_S - jX_S$.

(b) The output impedance looking into the matching network from the load side must be equal to the complex conjugate of the load impedance. If the load impedance is $Z_L = R_L + jX_L$, then for maximum power transfer into the load from the matching network, the required condition is $Z_{OUT} = Z_L^* = R_L - jX_L$.

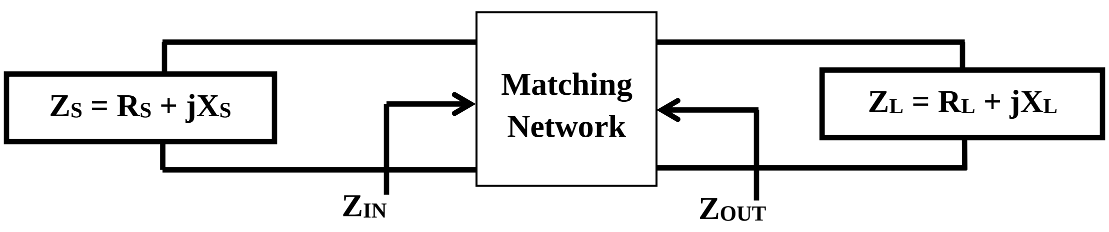


Figure 14: Matching Complex Load to Complex Source

Impedance Matching using Lumped Elements in ADS

Example:

Design an L-section matching network to match a series RC load having an impedance of $Z_L = (200 - j100)\Omega$ to a 100 Ω line at a frequency of 500 MHz.

Since, (Re $\{Z_L\} > Z_0$), the normalized load impedance lies within the constant resistance circle. The normalized load impedance is: $Z_n = (2 - j)\Omega$

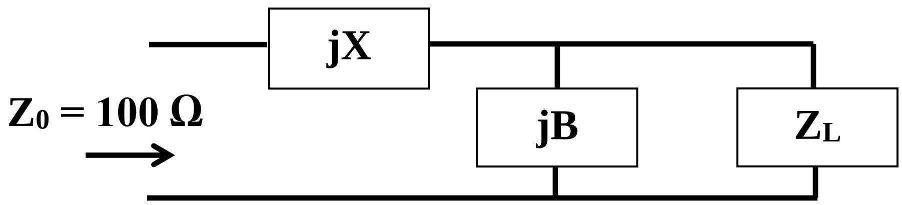


Figure 15: L-Section Matching Network Configuration for $R_L = 200\ \Omega > Z_0 = 100\ \Omega$

The reactive component values for solution 1 (B1 and X1) are:

$$B1 = \frac{X_L + \sqrt{\frac{R_L}{Z_0}(R_L^2 + X_L^2 - Z_0 R_L)}}{R_L^2 + X_L^2} = 2.899 \times 10^{-3} \qquad X1 = \frac{1}{B1} + \frac{X_L Z_0}{R_L} - \frac{Z_0}{(B1)R_L} = 122.474$$

Since (B1) is positive it represents a capacitor and its value is calculated as follows:

$$j\omega C = jB1 \qquad C = \frac{B1}{2\pi f} = 0.92\ pF$$

Since (X1) is positive it implies an inductor and its value is calculated as follows:

$$j\omega L = jX1 \qquad L = \frac{X1}{2\pi f} = 38.8\ nH$$

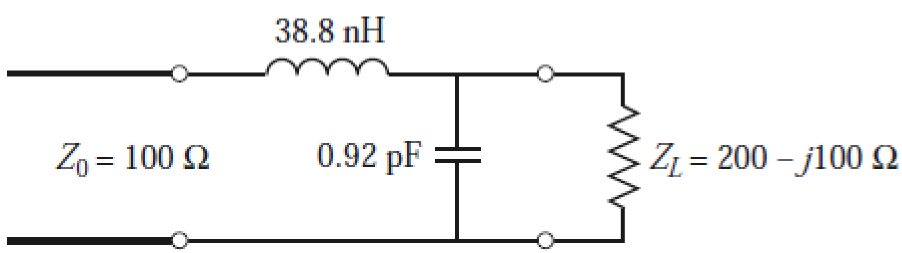


Figure 16: Shunt Capacitor and Series Inductor Matching Network (solution 1)

The second analytical solution is:

$$B2 = \frac{X_L - \sqrt{\frac{R_L}{Z_0}(R_L^2 + X_L^2 - Z_0 R_L)}}{R_L^2 + X_L^2} = -6.899 \times 10^{-3} \qquad X2 = \frac{1}{B2} + \frac{X_L Z_0}{R_L} - \frac{Z_0}{(B2)R_L} = -122.474$$

Impedance Matching using Lumped Elements in ADS

Since (B2) is negative it represents an inductor and its value is calculated as follows:

$$jB2 = \frac{1}{j\omega L} \qquad L = \frac{1}{2\pi f B2} = 46.1\ nH$$

Since (X2) is negative it implies a capacitor and its value is calculated as follows:

$$jX2 = \frac{1}{j\omega C} \qquad C = \frac{1}{2\pi f X2} = \ 2.61\ pF$$

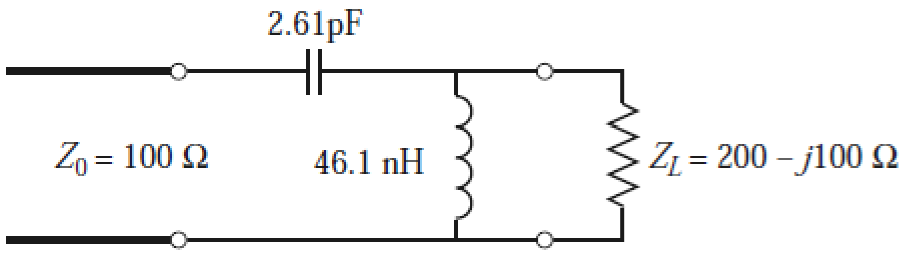


Figure 17: Shunt Inductor and Series Capacitor Matching Network (solution 2)

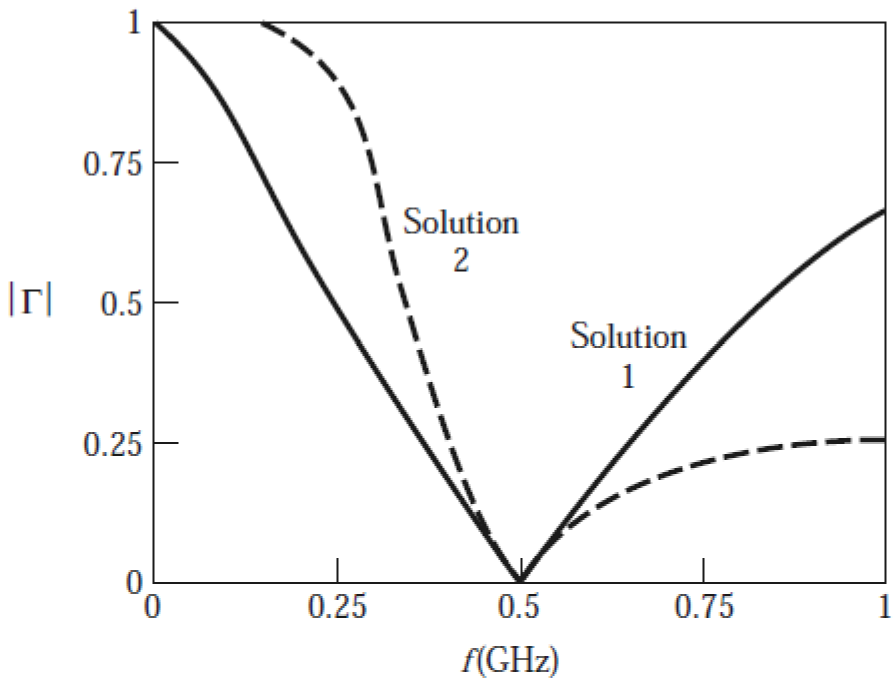


Figure 18: Reflection Coefficient Magnitude versus Frequency for Matching Circuits

Impedance Matching using Lumped Elements in ADS

3) Lab Exercises:

1) Obtain two L-section matching networks to match a 50 Ω line to a load impedance of $Z_L = (70 + j100)\Omega$ at a frequency of 700 MHz.

→ Obtain the analytical solutions

→ Before Matching
- ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
  - Choose a frequency range from 100 MHz to 2 GHz with a step size of 50 MHz
  - Use rectangular plot, list plot and smith chart
- ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

→ After Matching (for both solutions)
- ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
  - Choose a frequency range from 100 MHz to 2 GHz with a step size of 50 MHz
  - Use rectangular plot, list plot and smith chart
- ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

2) Design two L-section matching networks that transform a complex load of resistance 80 Ω and capacitance 2.65 pF into 50 Ω input impedance at 1GHz.

→ Obtain the analytical solutions

→ Before Matching:
- ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
  - Choose a frequency range from 500 MHz to 3 GHz with a step size of 50 MHz
  - Use rectangular plot, list plot and smith chart
- ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

→ After Matching (for all solutions):
- ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
  - Choose a frequency range from 500 MHz to 3 GHz with a step size of 50 MHz
  - Use rectangular plot, list plot and smith chart
- ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

3) The output impedance of a transmitter operating at a frequency of 2 GHz is $Z_T = (150 + j75)\Omega$. Design an L-section matching network as shown in figure 19, such that maximum power is delivered to an antenna whose input impedance is $Z_A = (75 + j15)\Omega$. Assume a characteristic impedance of 75 Ω.

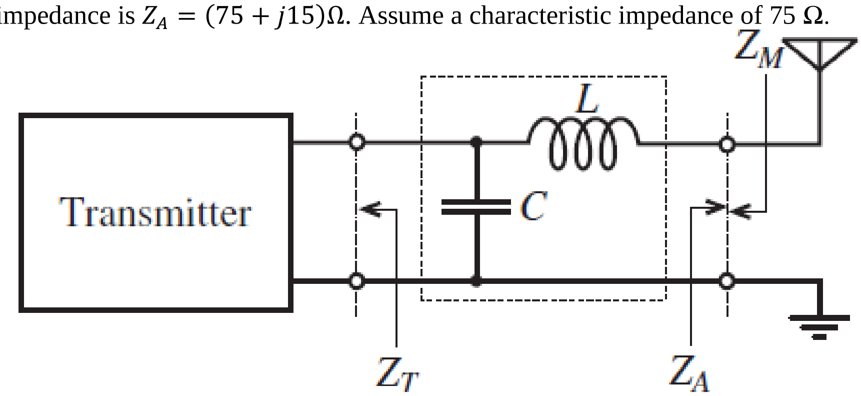


Figure 19: Reflection Coefficient Magnitude versus Frequency for Matching Circuits

Impedance Matching using Lumped Elements in ADS

→ Obtain the analytical solutions

→ Before Matching:
- ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
  - Choose a frequency range from 500 MHz to 4 GHz with a step size of 50 MHz
  - Use rectangular plot, list plot and smith chart
- ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

→ After Matching:
- ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
  - Choose a frequency range from 500 MHz to 4 GHz with a step size of 50 MHz
  - Use rectangular plot, list plot and smith chart
- ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

4) Develop all possible L-section matching network topologies for a load impedance of $Z_L = (30 - j40)\Omega$ and a 50 Ω source at a frequency of 450MHz.

   Repeat the above problem if the source impedance also has an additional parasitic inductance of 2 nH.

   → Obtain the analytical solutions

   → Before Matching:
   - ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
     - Choose a frequency range from 100 MHz to 1 GHz with a step size of 50 MHz
     - Use rectangular plot, list plot and smith chart
   - ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

   → After Matching (for all solutions):
   - ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
     - Choose a frequency range from 100 MHz to 1 GHz with a step size of 50 MHz
     - Use rectangular plot, list plot and smith chart
   - ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

5) Design all possible L-section matching configurations that match the source impedance $Z_S = (50 + j25)\Omega$ to the load impedance $Z_L = (25 - j50)\Omega$. Assume a characteristic impedance of 50 Ω and a frequency of 2 GHz.

   → Before Matching:
   - ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
     - Choose a frequency range from 500 MHz to 4 GHz with a step size of 50 MHz
     - Use rectangular plot, list plot and smith chart
   - ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot

   → After Matching (for all solutions):
   - ✓ Plot the magnitude and phase of the S_{11}, S_{12}, S_{21}, S_{22} parameters versus frequency
     - Choose a frequency range from 500 MHz to 4 GHz with a step size of 50 MHz
     - Use rectangular plot, list plot and smith chart
   - ✓ Plot the magnitude of the voltage standing wave ratio versus frequency on a semi-log plot