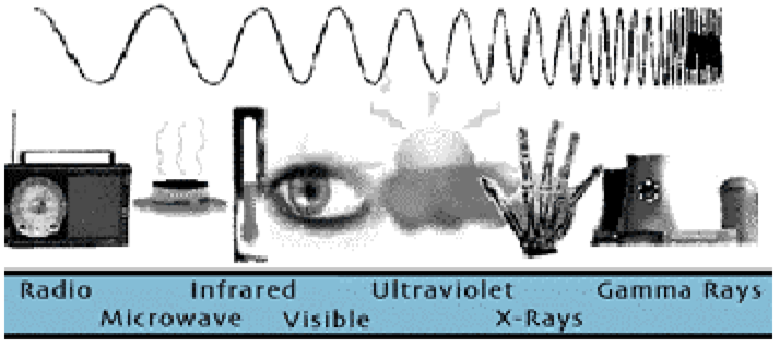
Microwave Engineering

- Microwave Networks
  - What are Microwaves?
  - S-parameters
  - Power Dividers
  - Couplers
  - Filters
  - Amplifiers

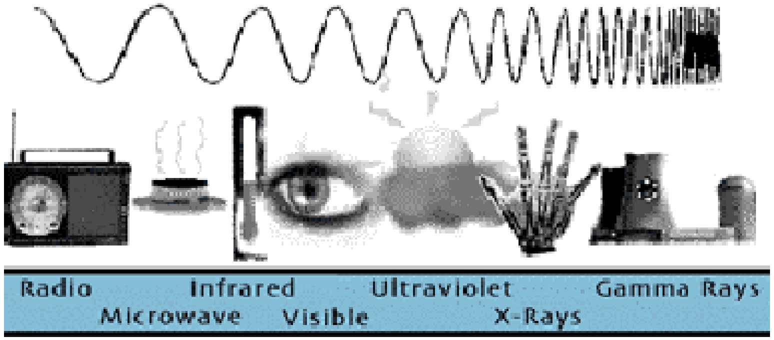
Microwave Engineering

Microwave engineering: Engineering and design of communication/navigation systems in the microwave frequency range.

Applications: Microwave oven, Radar, Satellite communi-cation, direct broadcast satellite (DBS) television, personal communication systems (PCSs) etc.



What are Microwaves?



$$\text{frequency f }(Hz) = \frac{\text{velocity of light c}}{\text{wavelength } \lambda} = \frac{3 \times 10^{8}\,(m/s)}{\lambda\,(m)}$$

Microwaves: 30 cm – 1 cm (centimeter waves)

λ = 30 cm: $f = 3 \times 10^{8} / 30 \times 10^{-2} = 1$ GHz

λ = 1 cm: $f = 3 \times 10^{8} / 1 \times 10^{-2} = 30$ GHz

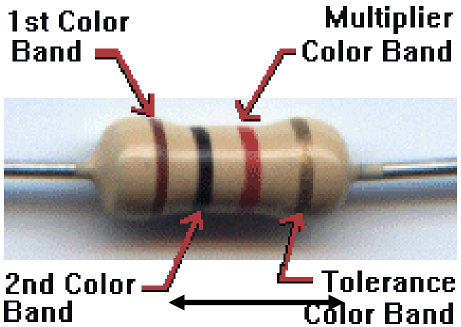
Note: 1 Giga = 10^{9}

Millimeter waves: 10 mm – 1 mm

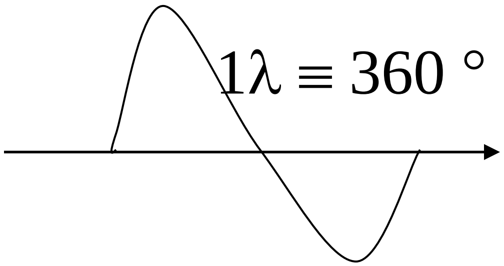
λ = 10 mm: $f = 3 \times 10^{8} / 10 \times 10^{-3} = 30$ GHz

λ = 1 mm: $f = 3 \times 10^{8} / 1 \times 10^{-3} = 300$ GHz

What are Microwaves?



1 cm



Electrical length = Physical length/Wavelength (expressed in λ)

Phase delay = $(2\pi$ or $360°)$ x Physical length/Wavelength

RF

f =10 kHz, λ = c/f = 3 x 10^8/ 10 x 10^3 = 3000 m

Electrical length =1 cm/3000 m = $3.3 \times 10^{-6}\lambda$, Phase delay = 0.0012°

Microwave

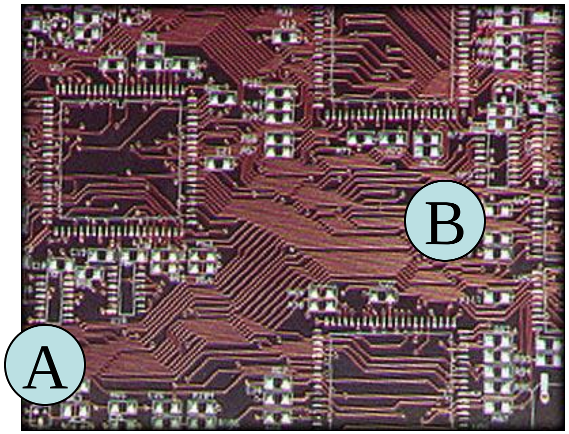
f =10 GHz, λ = 3 x 10^8/ 10 x 10^9 = 3 cm

Electrical length = 0.33λ, Phase delay = 118.8° !!!

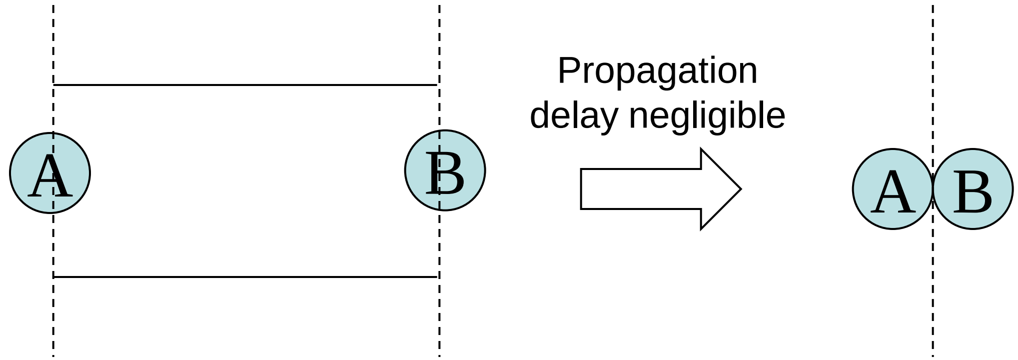
Electrically long - The phase of a voltage or current changes significantly over the physical extent of the device

How to account for the phase delay?

Printed Circuit Trace

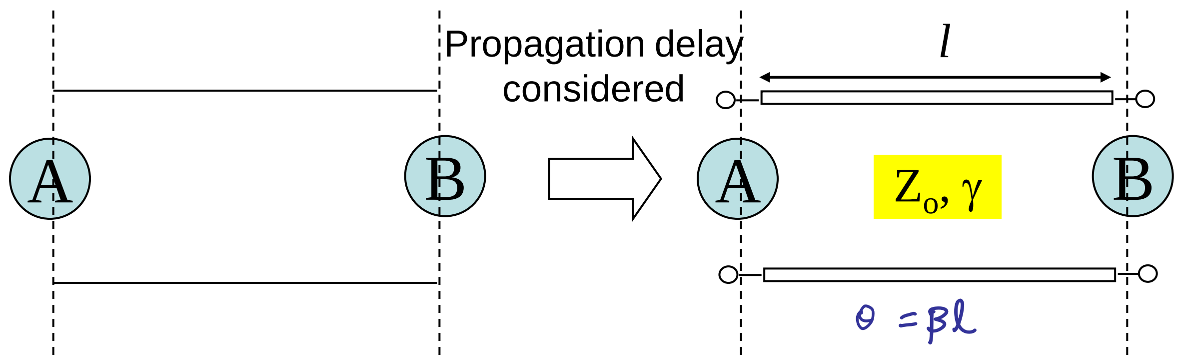


Low Frequency



Microwave

Transmission line section!



Z_o: characteristic impedance

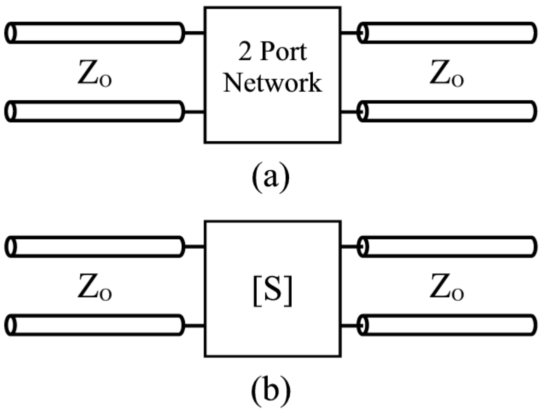
γ ($=\alpha+j\beta$): Propagation constant

Scattering Parameters (S-Parameters)

Consider a circuit or device inserted into a T-Line as shown in the Figure. We can refer to this circuit or device as a two-port network.

The behavior of the network can be completely characterized by its scattering parameters (S-parameters), or its scattering matrix, [S].

Scattering matrices are frequently used to characterize multiport networks, especially at high frequencies. They are used to represent microwave devices, such as amplifiers and circulators, and are easily related to concepts of gain, loss and reflection.

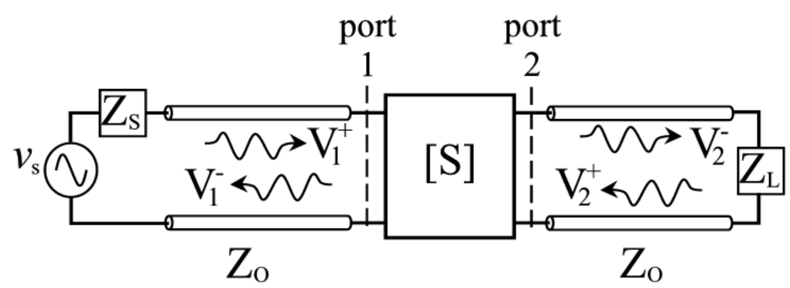


Scattering matrix

$$[S] = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

Scattering Parameters (S-Parameters)

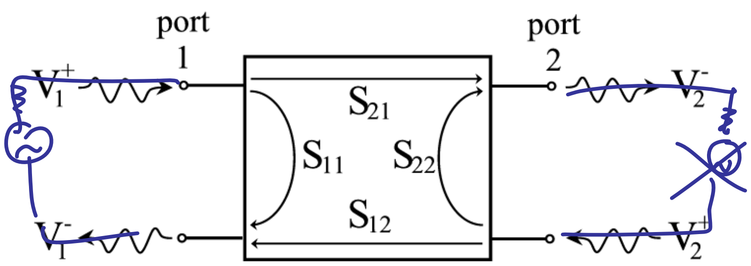
The scattering parameters represent ratios of voltage waves entering and leaving the ports (If the same characteristic impedance, Zo, at all ports in the network are the same).



$$V_1^- = S_{11}V_1^+ + S_{12}V_2^+.$$

$$V_2^- = S_{21}V_1^+ + S_{22}V_2^+.$$

$V_2^- = S_{22}V_2^+ + S_{21}V_1^+$



In matrix form this is written

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}, \quad [V]^- = [S][V]^+.$$

$V_1^- = S_{11}V_1^+ + S_{12}V_2^+$

Reflected signal

$$S_{11} = \left.\frac{V_1^-}{V_1^+}\right|_{V_2^+=0}$$: Reflection coefficient

input signal

$0 \le |S_{11}| \le 1$

o/p @ ①

$$S_{12} = \left.\frac{V_1^-}{V_2^+}\right|_{V_1^+=0}$$ Transmission coefficient from Port ② to ①

i/p @ ②

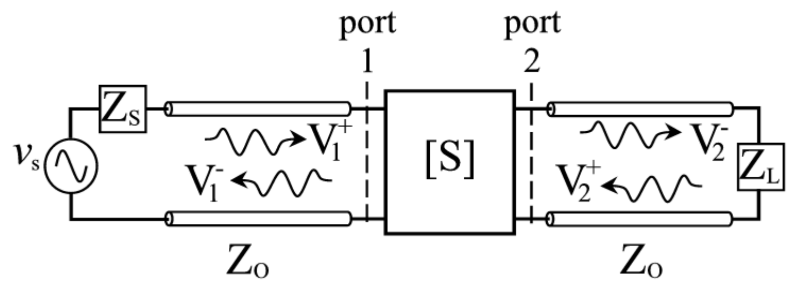
$$S_{21} = \left.\frac{V_2^-}{V_1^+}\right|_{V_2^+=0}$$: Transmission coefficient from Port ① to ②

$$S_{22} = \left.\frac{V_2^-}{V_2^+}\right|_{V_1^+=0}$$: Reflection coefficient at Port ②

Scattering Parameters (S-Parameters)

Properties:

1) Reciprocity



The two-port network is reciprocal if the transmission characteristics are the same in both directions (i.e. $S_{21} = S_{12}$).

It is a property of passive circuits (circuits with no active devices or ferrites) that they form reciprocal networks.

A network is reciprocal if it is equal to its transpose. Stated mathematically, for a reciprocal network

$$[S] = [S]^t,$$

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}^t = \begin{bmatrix} S_{11} & S_{21} \\ S_{12} & S_{22} \end{bmatrix}.$$

Condition for Reciprocity: $S_{12} = S_{21}$

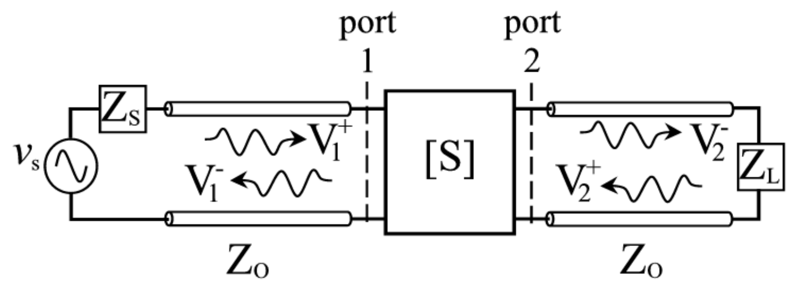
By inspection :

If the network is symmetrical $\Longrightarrow$ Reciprocal

Scattering Parameters (S-Parameters)

Properties:

2) Lossless Networks



A lossless network does not contain any resistive elements and there is no attenuation of the signal. No real power is delivered to the network. Consequently, for any passive lossless network, what goes in must come out!

In terms of scattering parameters, a network is lossless if

$$[S]^t [S]^* = [U],$$ where [*U*] is the unitary matrix $$[U] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

For a 2-port network, the product of the transpose matrix and the complex conjugate matrix yields

$$[S]^t [S]^* = \begin{bmatrix} \left(|S_{11}|^2 + |S_{21}|^2\right) & \left(S_{11}S_{12}^* + S_{21}S_{22}^*\right) \\ \left(S_{12}S_{11}^* + S_{22}S_{21}^*\right) & \left(|S_{12}|^2 + |S_{22}|^2\right) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

If the network is reciprocal and lossless

$$|S_{11}|^2 + |S_{21}|^2 = 1$$

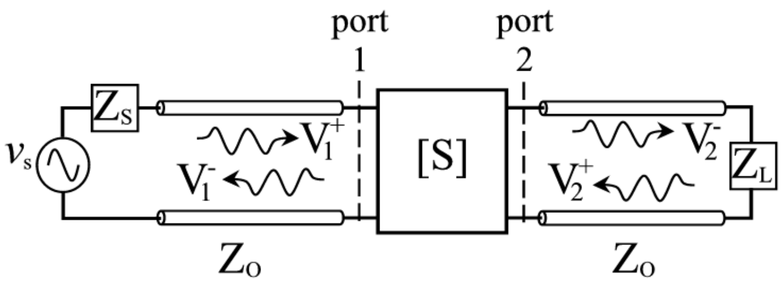
$$S_{11}S_{12}^* + S_{21}S_{22}^* = 0$$

Scattering Parameters (S-Parameters)

Return Loss and Insertion Loss

Two port networks are commonly described by their return loss and insertion loss. The return loss, RL, at the ith port of a network is defined as

$$RL_i = -20\log\left|\frac{V_i^-}{V_i^+}\right| = -20\log\left|\Gamma_i\right|.$$

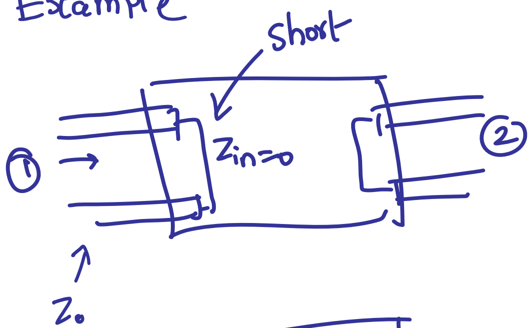


The insertion loss, IL, defines how much of a signal is lost as it goes from a jth port to an ith port. In other words, it is a measure of the attenuation resulting from insertion of a network between a source and a load.

$$IL_{ij} = -20\log\left|\frac{V_i^-}{V_j^+}\right|.$$

Scattering Parameters (S-Parameters)

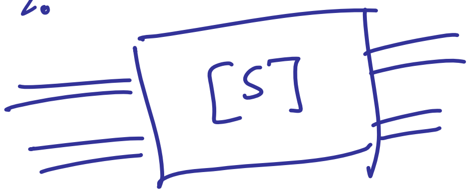
Example



$S_{12} = S_{21} = 0$ (Reciprocal) ✓

$$S_{11} = \Gamma_{in,1} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \frac{0 - Z_0}{0 + Z_0} = -1$$

$$S_{22} = \Gamma_{in,2} = -1 = 1\angle 180^\circ$$

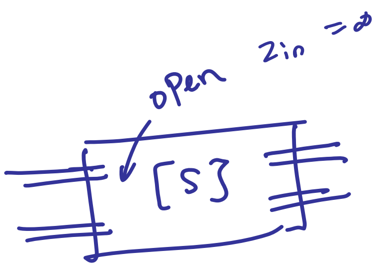


$$[S] = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$$

Lossless condition check ✓

$$|S_{11}|^2 + |S_{21}|^2 = 1$$

$$|-1|^2 \quad 0 \quad = 1$$

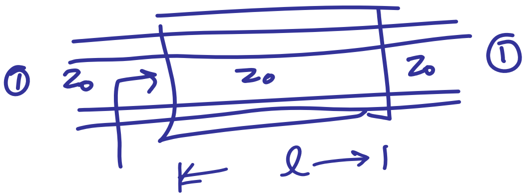


$$[S] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$S_{11} = \Gamma_{in,1} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \frac{1 - \frac{Z_0}{Z_{in}}}{1 + \frac{Z_0}{Z_{in}}} = \frac{1 - \frac{Z_0}{\infty}}{1 + \frac{Z_0}{\infty}} = 1\angle 0^\circ$$

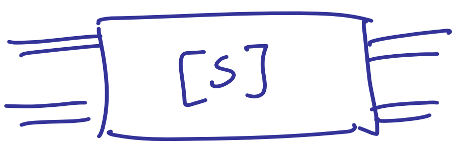
Scattering Parameters (S-Parameters)

Thruline



$Z_{in} = Z_0$ $\quad \theta = \beta l$

(rad/m) (m)



$$[S] = \begin{bmatrix} 0 & e^{-j\beta l} \\ e^{-j\beta l} & 0 \end{bmatrix}$$

Reflection Coefficient

$$S_{11} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = 0, \qquad S_{22} = 0$$

Transmission Coefficients

$$S_{21} = |S_{21}| \angle S_{21}$$

$$= 1 \angle -\theta$$

$$= 1 \, e^{-j\theta}$$

$$= e^{-j\beta l},$$

$$S_{21} = S_{12}$$

Example

$$[S] = \begin{bmatrix} +\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & +\frac{1}{\sqrt{2}} \end{bmatrix}$$

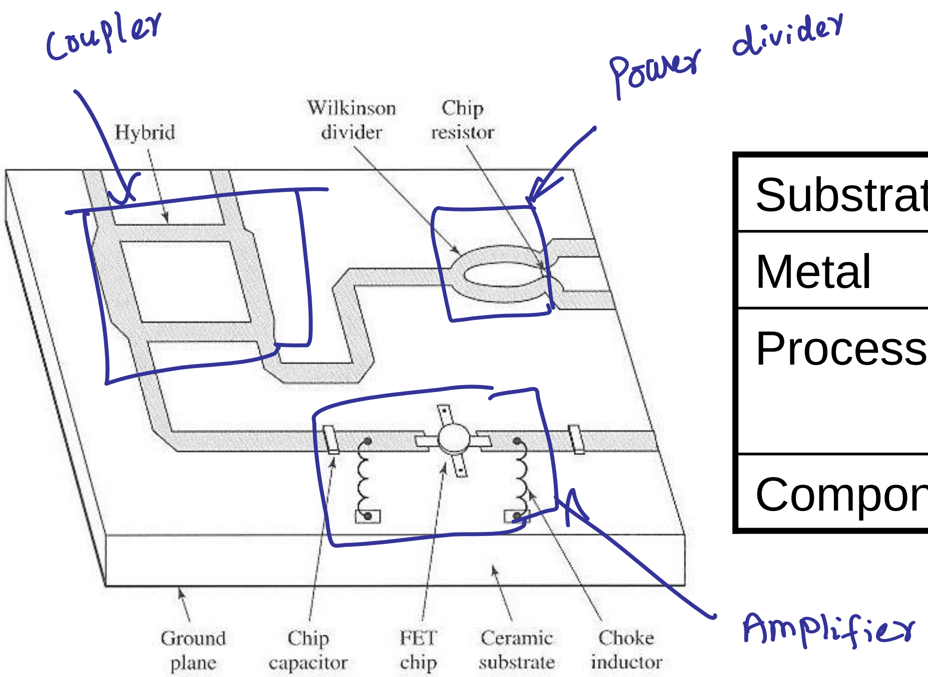
Microwave Integrated Circuits

Microwave Integrated Circuits (MIC):

Traces: transmission lines,

Passive components: resistors, capacitors, and inductors

Active devices: diodes and transistors.

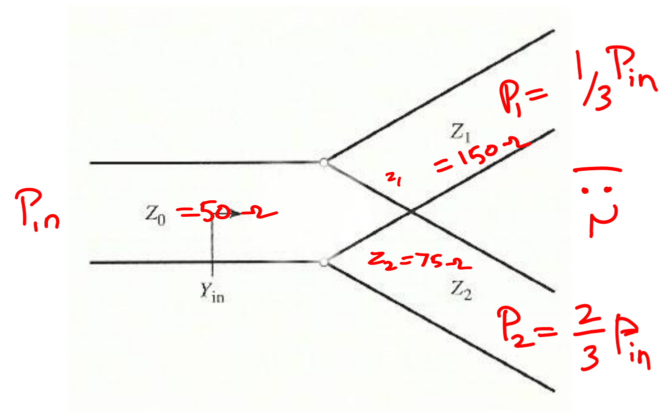


Substrate	Teflon fiber, alumina, quartz etc.
Metal	Copper, Gold etc.
Process	Conventional printed circuit (Photolithography and etching)
Components	Soldering and wire bonding

Power Divider

Lossless T-junction Power Divider

A T-junction power divider consists of one input port and two output ports.



Input Power

$$P_{in} = \frac{1}{2}\frac{V_o^2}{Z_o}$$

Output Power

$$P_1 = \frac{1}{2}\frac{V_o^2}{Z_1} \qquad P_2 = \frac{1}{2}\frac{V_o^2}{Z_2}$$

Design Example

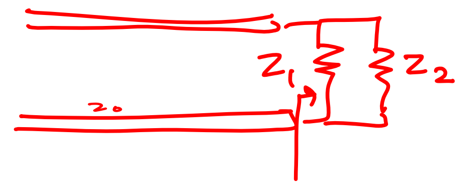
1:2 Power Divider

$Z_o = 50\,\Omega$

$$P_1 = \frac{1}{3}P_{in} \qquad P_2 = \frac{2}{3}P_{in}$$

Solution

$$Z_1 = 3Z_o = 150\,\Omega \qquad Z_2 = \frac{3}{2}Z_o = 75\,\Omega$$



Input Impedance

Input Port

$$Z_{in} = Z_1 \parallel Z_2 = 50\,\Omega$$

Output Port 1

$$Z_{in1} = Z_o \parallel Z_2 = 30\,\Omega$$

Output Port 2

$$Z_{in2} = Z_o \parallel Z_1 = 37.5\,\Omega$$

Reflection Coefficient

$$\Gamma = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} = 0$$

$$\Gamma_1 = \frac{Z_{in1} - Z_1}{Z_{in1} + Z_1} = -0.666$$

$$\Gamma_2 = \frac{Z_{in2} - Z_2}{Z_{in2} + Z_2} = -0.333$$

Input Port is matched

Output Ports are not matched

$Z_{in} = Z_1 \parallel Z_2 = 50\,\Omega$

$\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \frac{50-50}{50+50} = 0$

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

$S_{11} = 0$, $S_{21} =$

COUPLERS

A reciprocal, lossless, matched four-port network behaves as a directional coupler

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{12} & 0 & S_{23} & S_{24} \\ S_{13} & S_{23} & 0 & S_{34} \\ S_{14} & S_{24} & S_{34} & 0 \end{bmatrix}$$

Symmetric Coupler

$$[S]=\begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \alpha & 0 \end{bmatrix}$$

Antisymmetric Coupler

$$[S]=\begin{bmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & -\beta \\ \beta & 0 & 0 & \alpha \\ 0 & -\beta & \alpha & 0 \end{bmatrix}$$

For a lossless network: $\alpha^2+\beta^2=1$

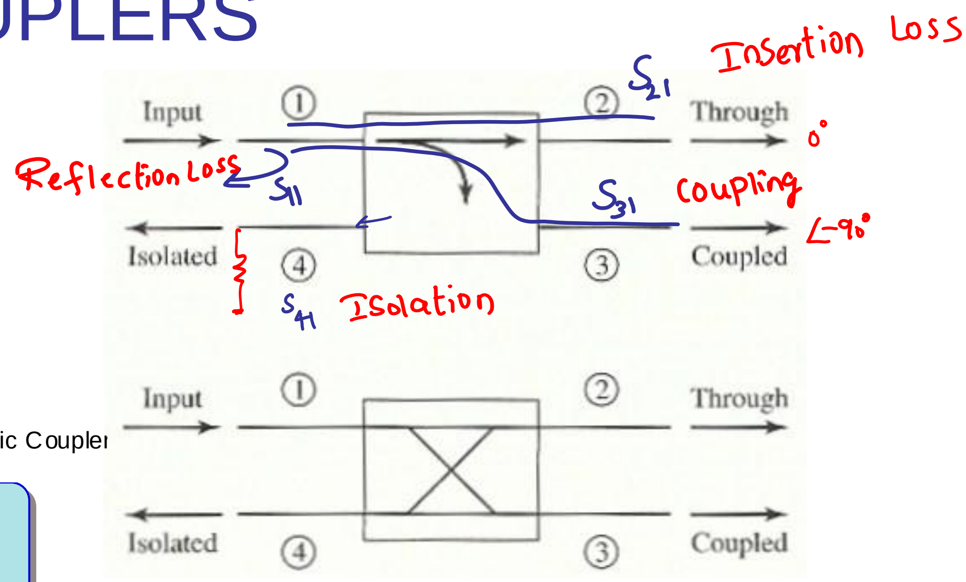
Insertion Loss: $IL=-20\log\left(|S_{21}|\right).$

Coupling coefficient: $C=-20\log\left(|S_{31}|\right).$

Isolation: $I=-20\log\left(|S_{41}|\right),$

Directivity: $D=20\log\left(\dfrac{|S_{31}|}{|S_{41}|}\right),$

$$D=I-C \text{ (dB)}$$



A coupler will transmit half or more of its power from its input (port 1) to its through port (port 2).

A portion of the power will be drawn off to the coupled port (port 3), and ideally none will go to the isolated port (port 4).

If the isolated port is internally terminated in a matched load, the coupler is most often referred to as a directional coupler.

COUPLERS

Design Example

Example 10.10: Suppose an antisymmetrical coupler has the following characteristics:

Given

C = 10.0 dB
D = 15.0 dB
IL = 2.00 dB
VSWR = 1.30

Voltage standwing wave ratio

VSWR = 1.30 ⟹ $|S_{11}| = \dfrac{VSWR-1}{VSWR+1} = 0.130.$

$|S_{11}| = |S_{22}| = |S_{33}| = |S_{44}|$

Insertion Loss: $IL = -20\log(|S_{21}|).$ ⟹ $|S_{21}| = 10^{-2/20} = 0.794.$

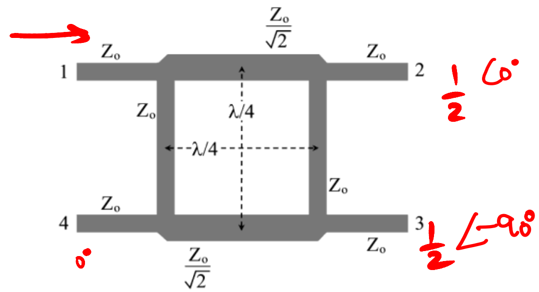
Coupling coefficient: $C = -20\log(|S_{31}|).$ ⟹ $|S_{31}| = 10^{-10/20} = 0.316.$

$I = D + C = 25dB,$ ⟹ $|S_{41}| = 10^{-25/20} = 0.056.$

$$[S] = \begin{bmatrix} 0.130 & 0.794 & 0.316 & 0.056 \\ 0.794 & 0.130 & 0.056 & -0.316 \\ 0.316 & 0.056 & 0.130 & 0.794 \\ 0.056 & -0.316 & 0.794 & 0.130 \end{bmatrix}$$

COUPLERS

Quadrature hybrid Coupler

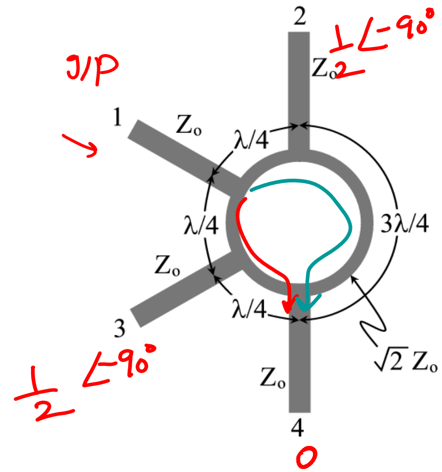


$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix},$$

The quadrature hybrid (or branch-line hybrid) is a 3 dB coupler. The quadrature term comes from the 90 deg phase difference between the outputs at ports 2 and 3.

The coupling and insertion loss are both equal to 3 dB.

Ring hybrid (or rat-race) coupler



$$[S] = \frac{-j}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix}.$$

A microwave signal fed at port 1 will split evenly in both directions, giving identical signals out of ports 2 and 3. But the split signals are 180 deg out of phase at port 4, the isolated port, so they cancel and no power exits port 4.

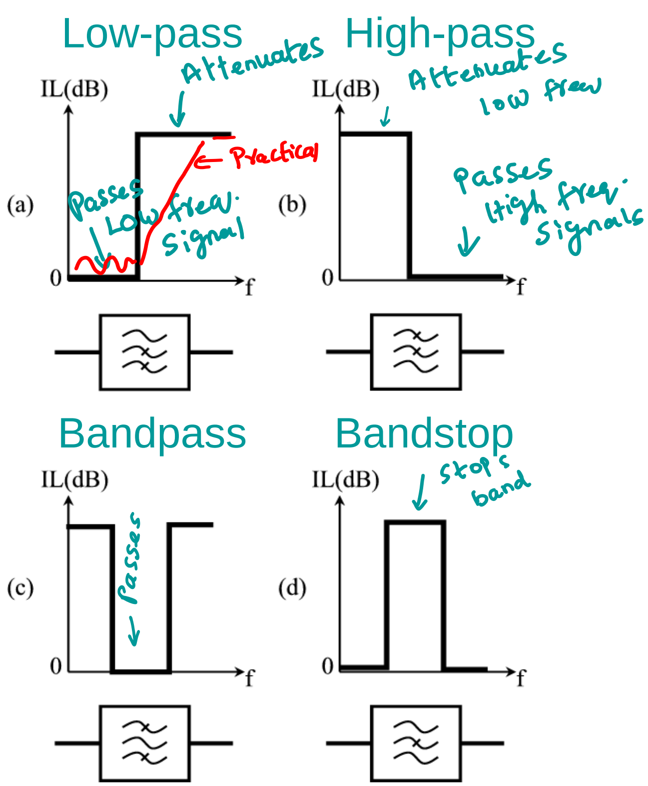
The insertion loss and coupling are both equal to 3 dB. Not only can the ring hybrid split power to two ports, but it can add and subtract a pair of signals.

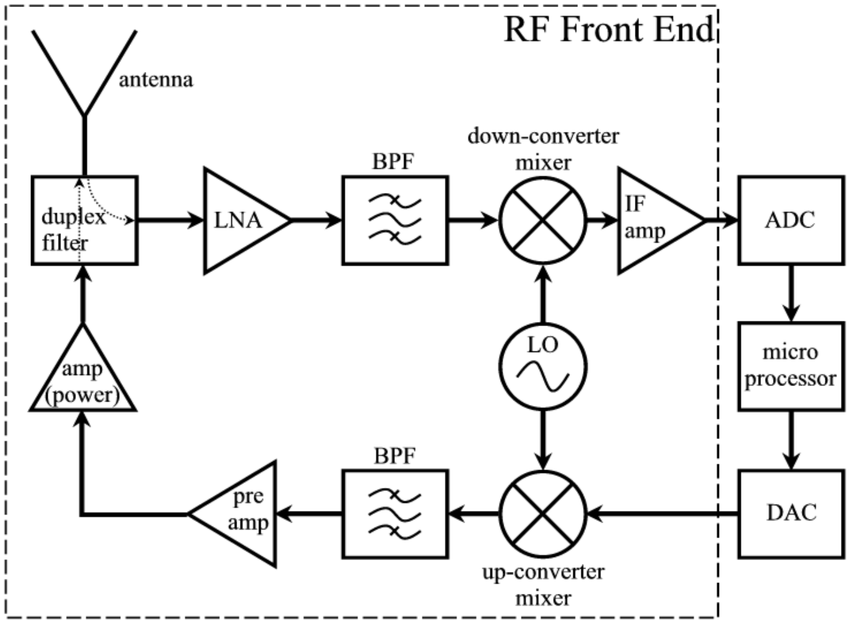
Filters

Filters are two-port networks used to attenuate undesirable frequencies.

Microwave filters are commonly used in transceiver circuits.

The four basic filter types are low-pass, high-pass, bandpass and bandstop.





Filters

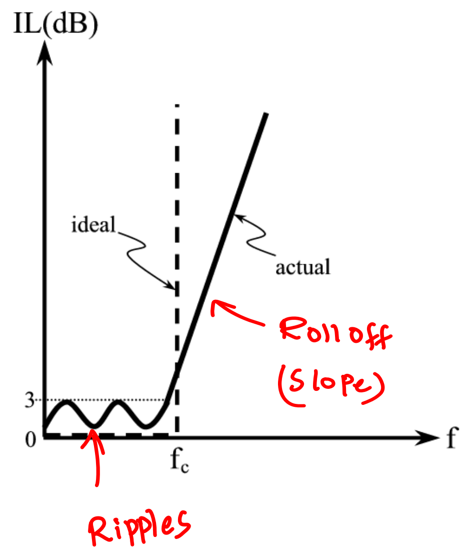
Low-pass Filters

A low-pass filter is characterized by the insertion loss versus frequency plot in Figure. Notice that there may be ripple in the passband (the frequency range desired to pass through the filter), and a roll off in transmission above the cutoff or corner frequency, fc.

Simple filters (like series inductors or shunt capacitors) feature 20 dB/decade roll off. Sharper roll off is available using active filters or multisection filters.

Active filters employ operational amplifiers that are limited by performance to the lower RF frequencies. Multisection filters use passive components (inductors and capacitors), to achieve filtering.

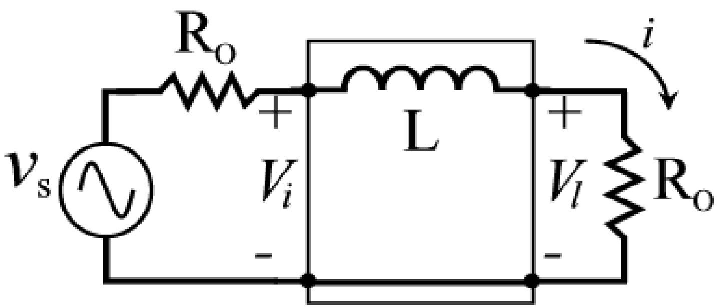
The two primary types are the Butterworth and the Chebyshev. A Butterworth filter has no ripple in the passband, while the Chebyshev filter features sharper roll off.



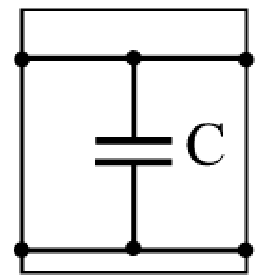
Lumped Element Filters

Some simple lumped element filter circuits are shown below.

Low-pass Filters

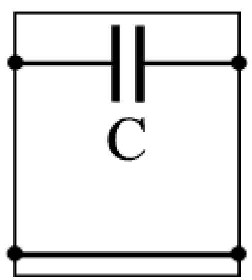


(a)

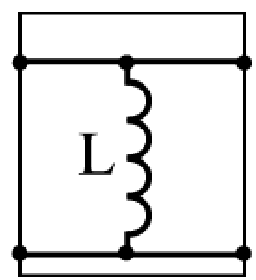


(b)

High-pass Filters

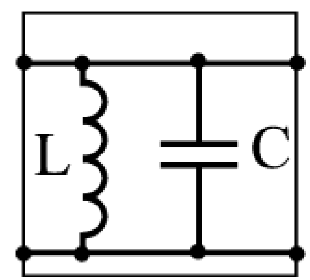


(c)



(d)

Band-pass Filters



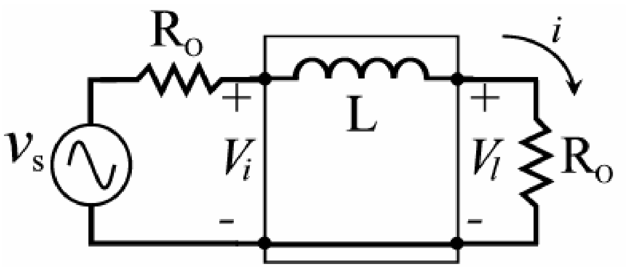
(e)

Lumped Element Filters

Low-pass Filter Example

Power delivered to the load

$$P_L = \frac{v_l^2}{R_o}, \qquad v_l = \frac{R_o}{2R_o + j\omega L} v_s.$$



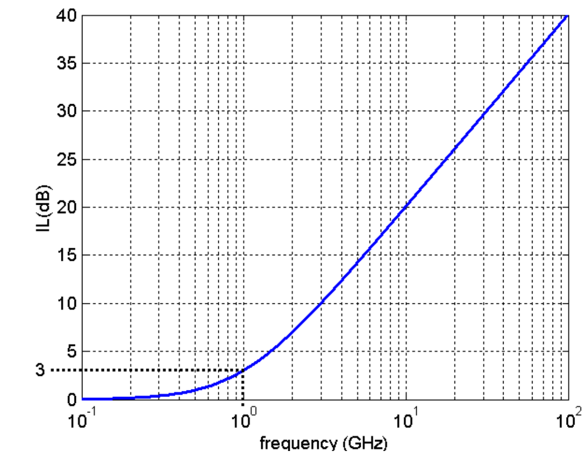
Maximum available Power:

$$P_A = \frac{v_l^2}{R_o} = \frac{\left(v_s/2\right)^2}{R_o} = \frac{v_s^2}{4R_o}.$$

Insertion Loss

$$IL = 10\log\left(\frac{P_L}{P_A}\right)$$

$$IL = 20\log\left(\left|1 + \frac{j\omega L}{2R_o}\right|\right).$$



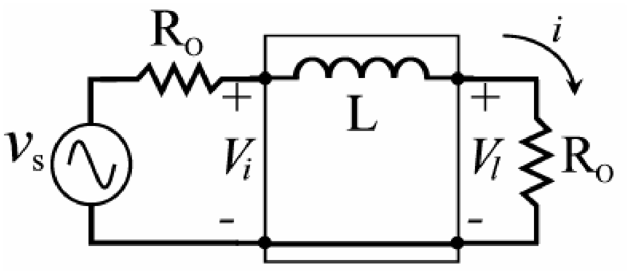
The 3 dB cutoff frequency, also termed the corner frequency, occurs where insertion loss reaches 3 dB.

$$20\log\left(\left|1 + \frac{j\omega L}{2R_o}\right|\right) = 3 \Rightarrow \left|1 + \frac{j\omega L}{2R_o}\right| = 10^{\frac{3}{20}} = \sqrt{2} \Rightarrow \frac{\omega L}{2R_o} = 1, \Rightarrow f_c = \frac{R_o}{\pi L}.$$

Lumped Element Filters

Low-pass Filter Example

Example 10.12: Let us design a low-pass filter for a 50.0 Ω system using a series inductor. The 3 dB cutoff frequency is specified as 1.00 GHz.



The 3 dB cutoff frequency is given by

$$f_c = \frac{R_o}{\pi L}.$$

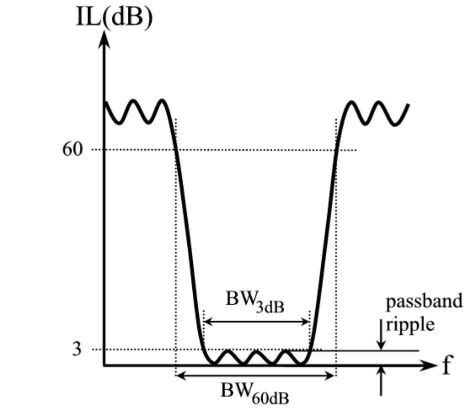
Therefore, the required inductance value is

$$L = \frac{R_o}{\pi f} = \frac{50\Omega}{\pi\left(1x10^9\, 1/s\right)}\left(\frac{H}{\Omega s}\right) = 15.9\ nH.$$

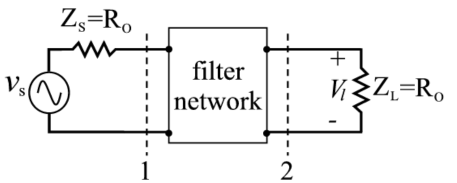
Filters

Band-pass Filters

The insertion loss for a bandpass filter is shown in Figure. Here the passband ripple is desired small. The sharpness of the filter response is given by the shape factor, SF, related to the filter bandwidth at 3dB and 60dB by



$$SF = \frac{BW_{60dB}}{BW_{3dB}}.$$



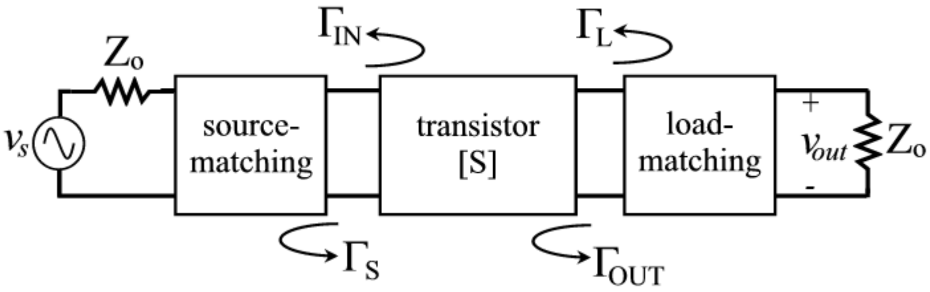
A filter's insertion loss relates the power delivered to the load without the filter in place (PL) to the power delivered with the filter in place (PLf):

$$IL = 10\log\left(\frac{P_L}{P_{Lf}}\right).$$

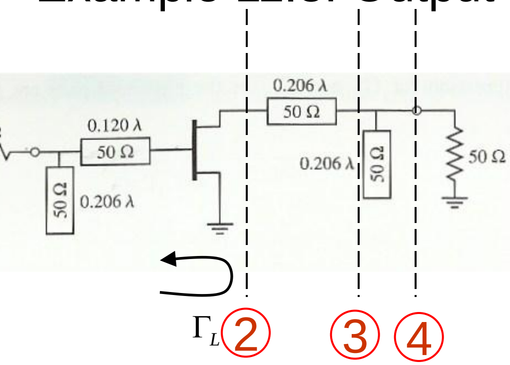
Amplifier Design

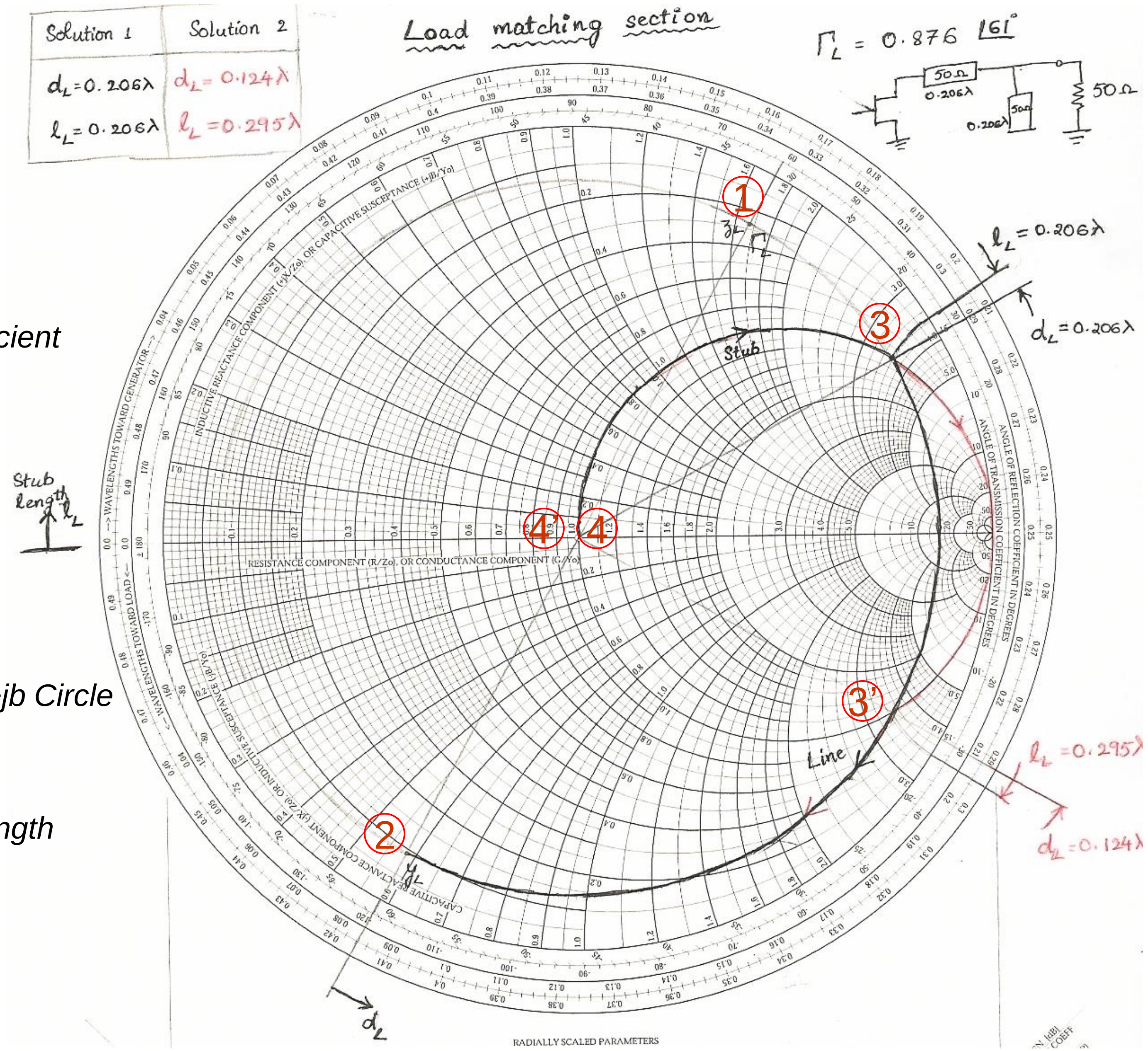
Microwave amplifiers are a common and crucial component of wireless transceivers. They are constructed around a microwave transistor from the field effect transistor (FET) or bipolar junction transistor (BJT) families.

A general microwave amplifier can be represented by the 2-port S-matrix network between a pair of impedance-matching networks as shown in the Figure below. The matching networks are necessary to minimize reflections seen by the source and to maximize power to the output.



Example 11.3: Output Matching Network





Step 1: Plot the reflection coefficient

$$\Gamma_L = 0.876\angle 61^\circ$$

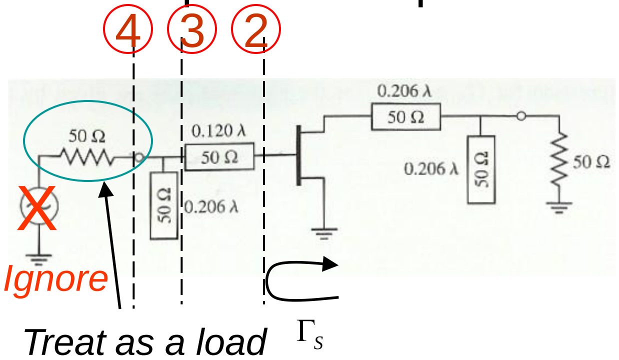
Shunt Stub Problem: Admittance Calculation

Step 2: Find the Admittance y_L

Step 3:Intersection points on 1+jb Circle

Step 4:Open-Circuited Stub Length

Example 11.3: Input Matching Network



Step 1: Plot the reflection coefficient

$$\Gamma_s = 0.872\angle 123°$$

Shunt Stub Problem:
Admittance Calculation

Step 2: Find the Admittance y_s

Step 3:Intersection points on 1+jb Circle

$$y_1 = 1 + j3.5$$

$$d_1 = 0.120\lambda$$

Step 4:Open-Circuited Stub Length

$$\ell_1 = 0.206\lambda$$