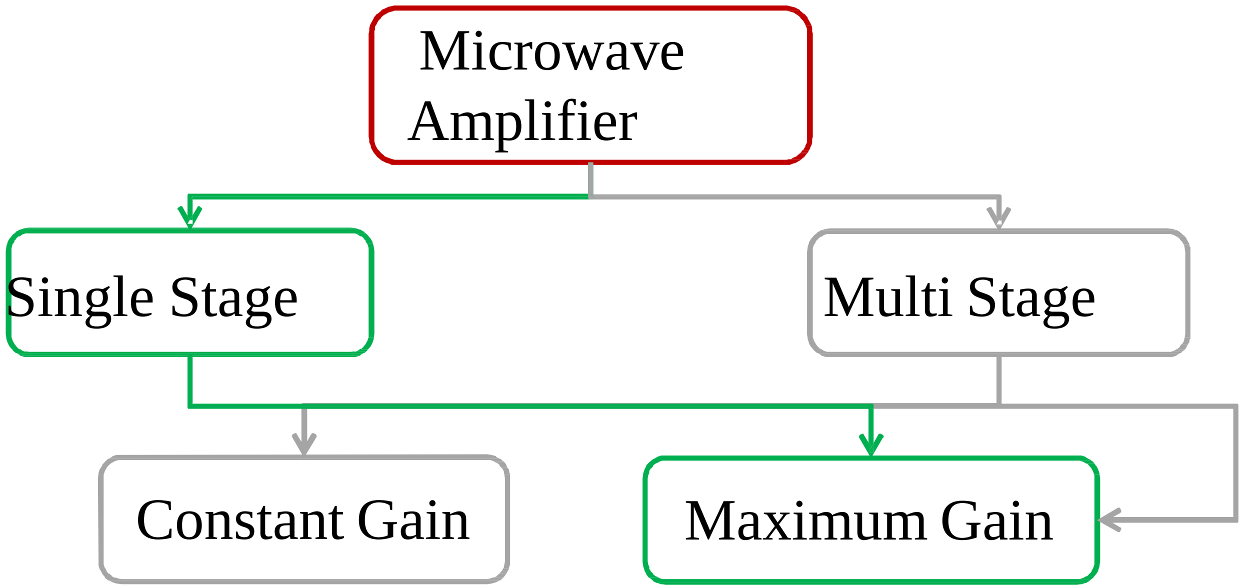
Module:7 Microwave Active Circuits

Microwave transistors, Microwave amplifiers: Two port power gains, stability of the amplifier, Microwave oscillator

Microwave Amplifier

- An amplifier is a device or a circuit that enhances the strength of a weak signal fed to its input terminals. This requires a transducer or an active element that draws energy from DC and utilizes it in enhancing the weak input *ac* signal
- Traditionally, microwave tubes (Klystron, TWT) were used as a single device to amplify weak signals, but with the advent of semiconductor transistors (BJT, FET), amplifier circuits consisting of both active and passive elements have taken lead in low to medium power applications

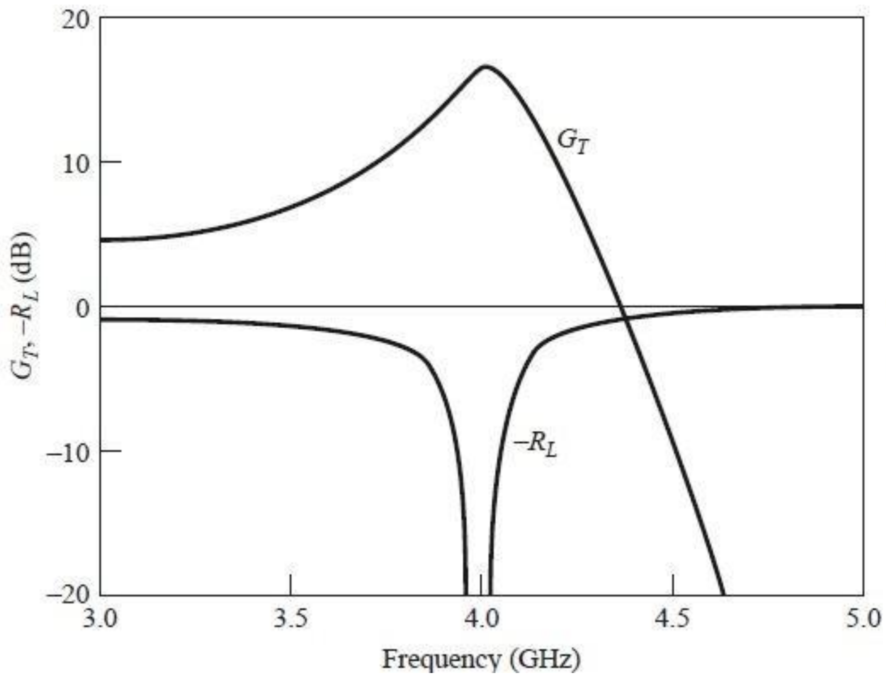


Microwave Amplifier

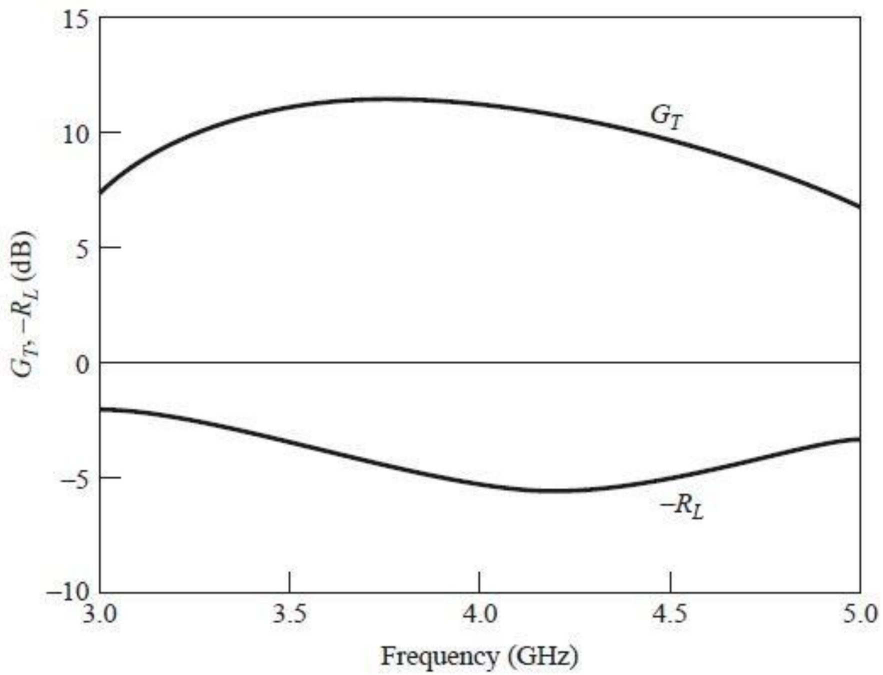
- A constant gain amplifier has uniform amplification factor over a wide frequency range, whereas a maximum gain amplifier has highest amplification at a particular frequency and the gain falls off rapidly away from the design frequency

- The type of gain response decides the bandwidth of the amplifier

Maximum Gain response



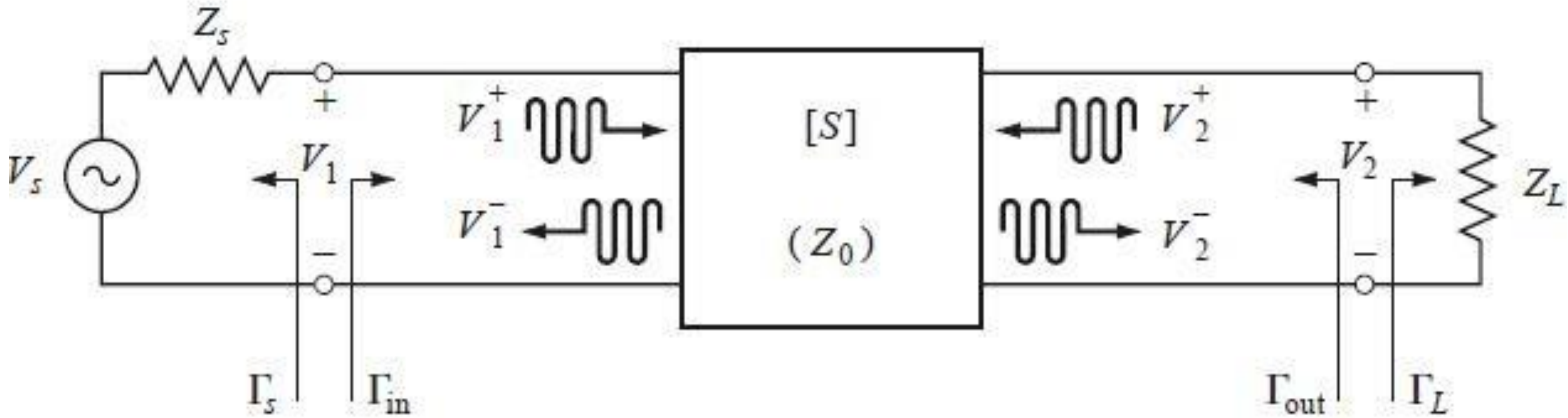
Constant Gain response



Two Port Amplifier Parameters

- The two major criteria in amplifier design are '*Gain*' and '*Stability*', although we have other important parameters such as '*Low Noise Figure*', '*Bandwidth*', '*Overall Size*' and '*Power Handling Capabilities*'

- Let us consider a two-port amplifier as shown in the figure



- The two port network is characterized by the [*S*] parameters and has a source and load impedance of Z_s & Z_L respectively. Due to mismatch of impedance of network with source, we have source reflection Γ_s and due to load mismatch, we have Γ_L

Two Port Amplifier Gain

- Now we have to define various '*Gains*' of the two port amplifier in terms of the reflection coefficients and *S*-parameters of the circuit

- Based on how the impedances are matched at the source and load end, we can define '*three types of Gain*'

1. Power Gain : It is the ratio of power delivered to the load (P_L) to the power at the input terminals of the two-port network (P_i). The gain is independent of source impedance Z_S

$$\boxed{G = \frac{P_L}{P_i}}$$

2. Available Power Gain : It is the ratio of power available at the output of two port network (P_{avn}) to the power available from source (P_{avs}). The gain is independent of Z_L but depends on Z_S

$$\boxed{G_A = \frac{P_{avn}}{P_{avs}}}$$

Two Port Amplifier Gain

3. <u>Transducer Power Gain</u> : It is the ratio of power delivered to the load (P_L) to the power available from source (P_{avs}). The gain is dependent on both Z_L and Z_s.

$$\boxed{G_T = \frac{P_L}{P_{avs}}}$$

- When the source and load are conjugate matched with the input and output impedances of the network, then we have, $G = G_A = G_T$
- To find the respective powers mentioned in above definitions, we need to find the reflection coefficients in the circuit. The reflection coefficient looking into the load (from network end) is

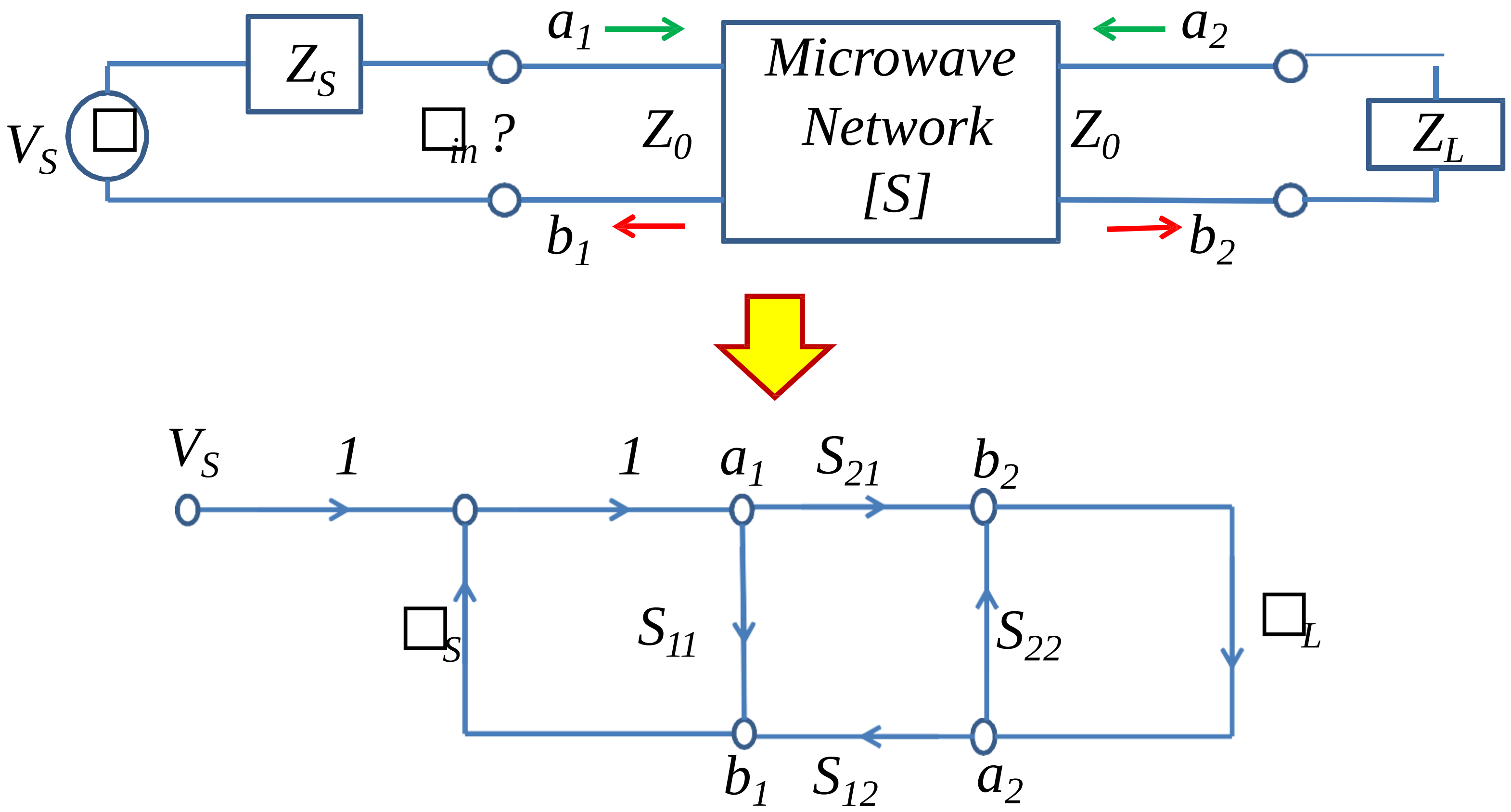
$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$

- Similarly reflection coefficient looking into source (from network end)

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0}$$

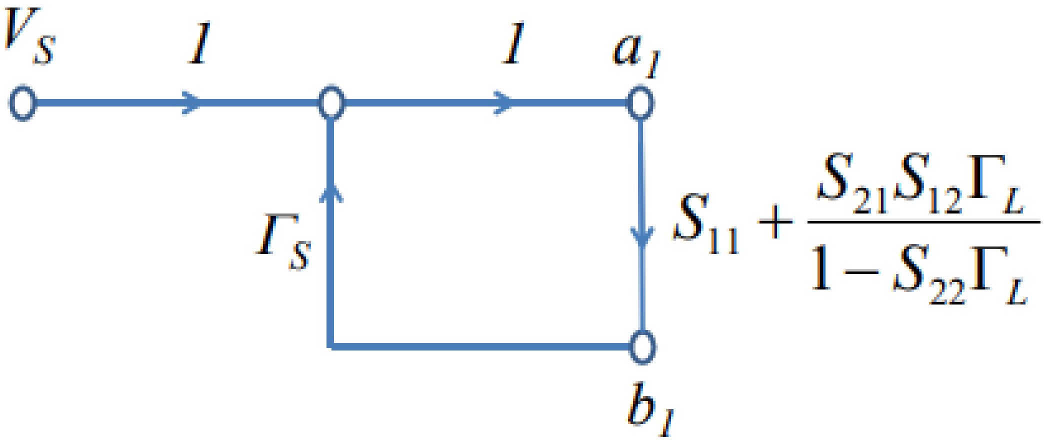
Two Port Amplifier Gain

- Likewise, we have to find the other two reflection coefficients $\square_{in}$ & $\square_{at}$
- Recall how we found the input reflection coefficient of a two-port network using signal flow graph



Two Port Amplifier Gain

- We use the series and parallel rules to reduce the graph between a_1 and b_1 which is nothing but the reflection coefficient Γ_{in}



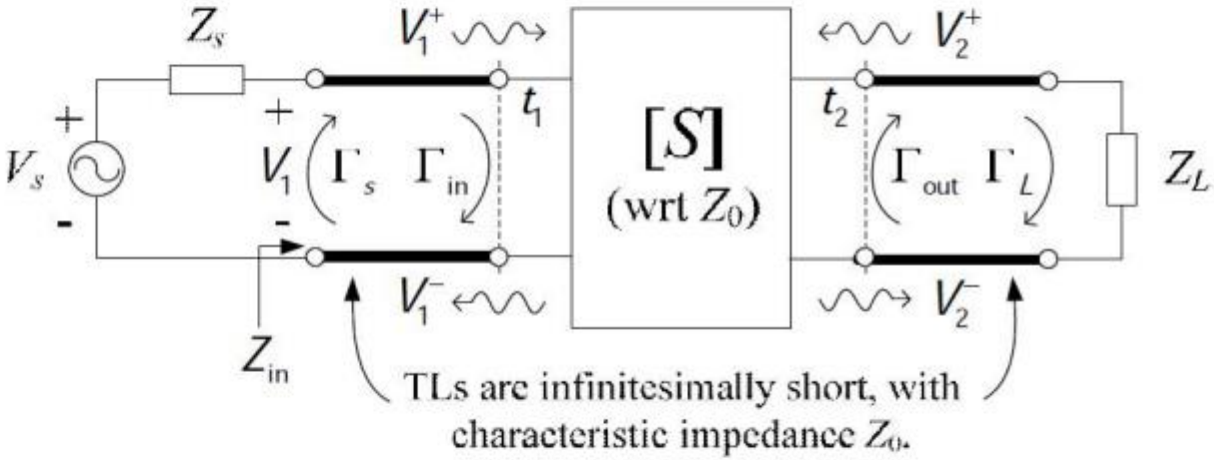
- Therefore the input reflection coefficient can be written as

$$\Gamma_{in} = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1 - S_{22}\Gamma_L} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

- Similarly the output reflection coefficient can be written as

$$\Gamma_{out} = S_{22} + \frac{S_{21}S_{12}\Gamma_S}{1 - S_{11}\Gamma_S}$$

Two Port Amplifier Gain



- Finally the power gain can be written as

$$\boxed{G = \frac{P_L}{P_{in}} = \frac{|S_{21}|^2 (1 - |\Gamma_L|^2)}{(1 - |\Gamma_{in}|^2)\, |1 - S_{22}\Gamma_L|^2}}$$

- The above gain is calculated assuming that there is a mismatch between the input impedance of the network and the source impedance

Two Port Amplifier Gain

the available power gain can be written as

$$\boxed{G_A = \frac{P_{avn}}{P_{avs}} = \frac{|S_{21}|^2(1-|\Gamma_S|^2)}{|1-S_{11}\Gamma_S|^2(1-|\Gamma_{out}|^2)}}$$

- And the transducer gain can be written as

$$\boxed{G_T = \frac{P_L}{P_{avs}} = \frac{|S_{21}|^2(1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|1-\Gamma_S\Gamma_{in}|^2|1-S_{22}\Gamma_L|^2}}$$

- A special case when input and outputs are matched i,e, $\Gamma_S = \Gamma_L = 0$, then

$$\boxed{G_T = |S_{21}|^2}$$

- Another special case is *unilateral* transducer power gain i,e, $S_{12} = 0$, which means that there is only unidirectional power flow. Also $\Gamma_{in} = S_{11}$ & $\Gamma_{out} = S_{22}$

$$\boxed{G_{TU} = \frac{|S_{21}|^2(1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|1-S_{11}\Gamma_S|^2|1-S_{22}\Gamma_L|^2}}$$

Problems

1.A silicon bipolar junction transistor has the following scattering parameters at 1.0 GHz, with a 50Ω reference impedance:

$S_{11} = 0.38\angle -158^\circ$

$S_{12} = 0.11\angle 54^\circ$

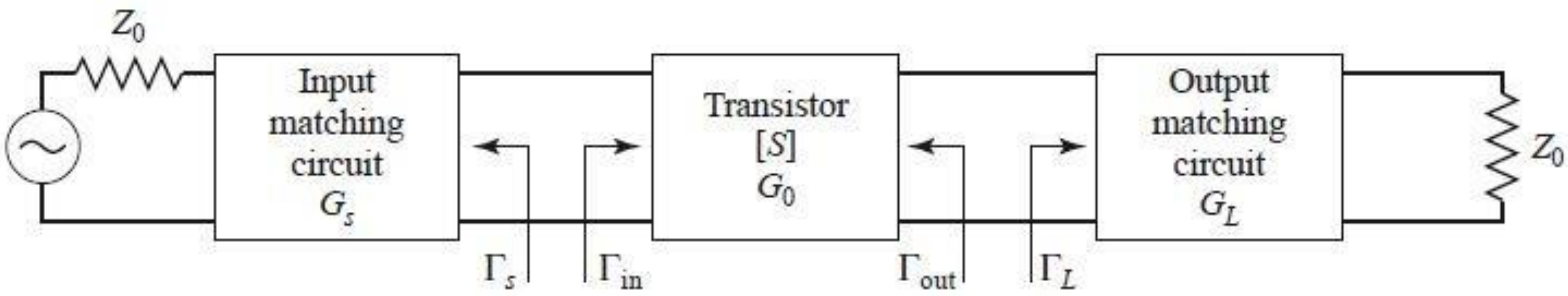
$S_{21} = 3.50\angle 80^\circ$

$S_{22} = 0.40\angle -43^\circ$

The source impedance is $Z_S = 25\ \Omega$ and the load impedance is $Z_L = 40\ \Omega$. Compute the power gain, the available power gain, and the transducer power gain

Single Stage Amplifier Gain

- A single stage amplifier consists of an active element such as a transistor and two matching networks at the input and output sections to match the source and load impedances



- In the above case we can define three different gains for the input & output matching networks and the transistor i,e, $G_T = G_S\, G_0\, G_L$

$$G_S = \frac{1-|\Gamma_S|^2}{|1-\Gamma_{in}\Gamma_S|^2}$$

$$G_0 = |S_{21}|^2 \quad \& \quad G_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}$$

Single Stage Amplifier Gain

- If the amplifier is unilateral, then $G_{TU} = G_{0U}\, G_{SU}\, G_{LU}$

$$\boxed{\begin{aligned} G_{SU} &= \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2} \\ G_0 &= |S_{21}|^2 \quad \& \quad G_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \end{aligned}}$$

Microwave Amplifier Stability

- Another important criteria in the amplifier design is '*Stability*'. An amplifier is said to be stable when it does not generate oscillations of its own, but only enhances the signal fed to its input terminals
- The amplifier is stable when the condition $|\Gamma_{in}| < 1$ & $|\Gamma_{out}| < 1$, is met
- The input and output reflection coefficients are in turn dependent on the source and load mismatch, therefore, for the above condition to apply we additionally require $|\Gamma_S| < 1$ & $|\Gamma_L| < 1$

Amplifier Stability

Potentially unstable

<u>Unconditionally Stable</u>
$|\Gamma_{in}| < 1$ & $|\Gamma_{out}| < 1$, for all passive source and load impedances

<u>Conditionally Stable</u>
$|\Gamma_{in}| < 1$ & $|\Gamma_{out}| < 1$, for '*certain*' passive source and load impedances

Microwave Amplifier Stability

- Another important criteria in the amplifier design is '*Stability*'. An amplifier is said to be stable when it does not generate oscillations of its own, but only enhances the signal fed to its input terminals
- The amplifier is stable when the condition $|\Gamma_{in}| < 1$ & $|\Gamma_{out}| < 1$, is met
- The input and output reflection coefficients are in turn dependent on the source and load mismatch, therefore, for the above condition to apply we additionally require $|\Gamma_S| < 1$ & $|\Gamma_L| < 1$

Amplifier Stability

- Unconditionally Stable: $|\Gamma_{in}| < 1$ & $|\Gamma_{out}| < 1$, for all passive source and load impedances
- Conditionally Stable: $|\Gamma_{in}| < 1$ & $|\Gamma_{out}| < 1$, for '*certain*' passive source and load impedances

Microwave Amplifier Stability

- Applying the condition of *unconditional stability* to the input and output reflection coefficients gives

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} < 1 \qquad \Gamma_{out} = S_{22} + \frac{S_{21}S_{12}\Gamma_S}{1 - S_{11}\Gamma_S} < 1$$

- If the amplifier is *unilateral* i,e, $S_{12} = 0$, the above unconditional stability simply becomes $|S_{11}| < 1$ & $|S_{22}| < 1$
- The inequalities above define a range of values for Γ_S & Γ_L over which, the amplifier is stable
- The range of Γ_S & Γ_L can be defined by stability circles on the Smith chart. A stability circle is defined as the loci of Γ_S & Γ_L for which $|\Gamma_{in}| = 1$ & $|\Gamma_{out}| = 1$
- To derive equation for output stability circle let us take $|\Gamma_{in}| = 1$

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} = 1$$

Microwave Amplifier Stability

- On simplification, we get

$$\left| \Gamma_L - \frac{\left(S_{22} - \Delta S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2} \right| = \left| \frac{S_{12} S_{21}}{\left|S_{22}\right|^2 - \left|\Delta\right|^2} \right|$$

- The above equation resembles a circle (Γ - C = R) on the complex Γ - plane. This is the equation of output stability circle

- The center and the radius of the output stbility circle are given as

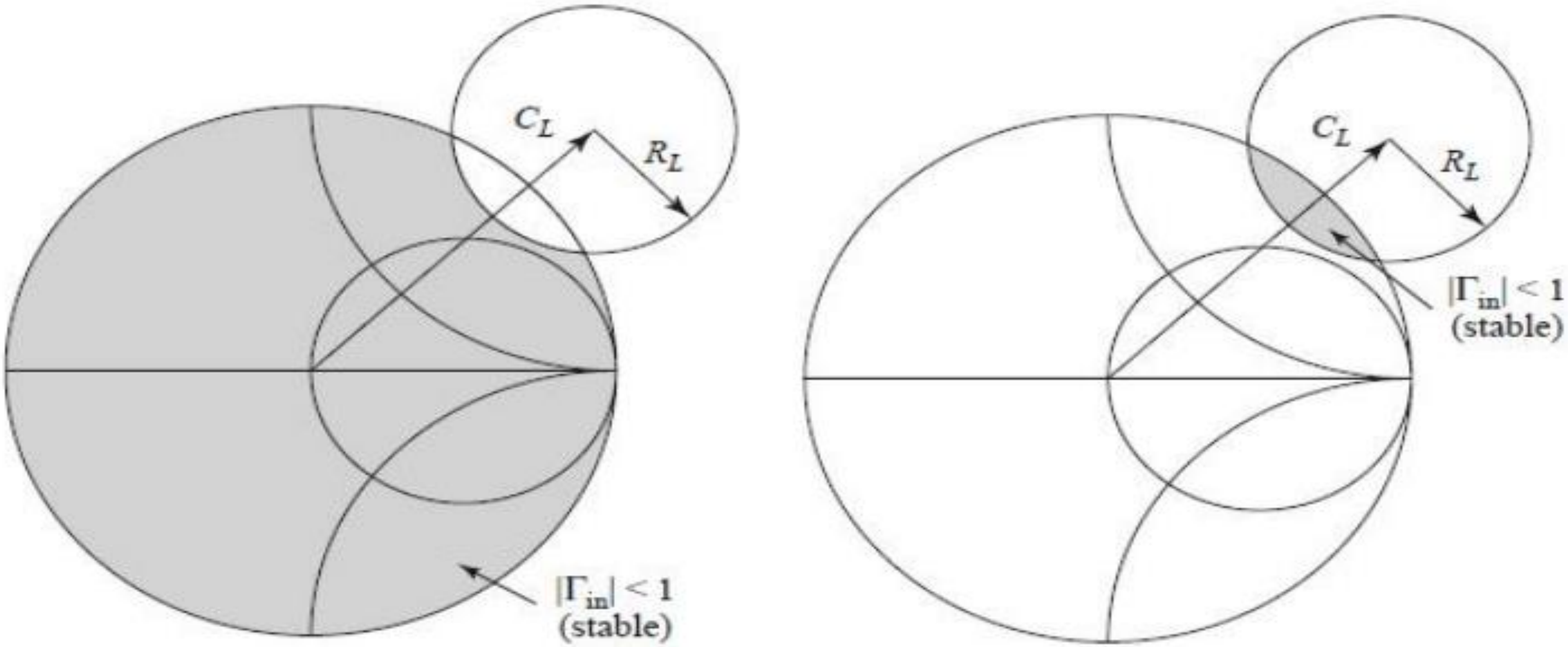
$$\boxed{C_L = \frac{\left(S_{22} - \Delta S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}} \qquad \boxed{R_L = \left| \frac{S_{12} S_{21}}{\left|S_{22}\right|^2 - \left|\Delta\right|^2} \right|}$$

- Similarly the center and radius of the input stability circles are

$$\boxed{C_S = \frac{\left(S_{11} - \Delta S_{22}^*\right)^*}{\left|S_{11}\right|^2 - \left|\Delta\right|^2}} \qquad \boxed{R_S = \left| \frac{S_{12} S_{21}}{\left|S_{11}\right|^2 - \left|\Delta\right|^2} \right|}$$

Microwave Amplifier Stability

- The output stability circles corresponding to two cases of $|S_{11}|$ are plotted. Similar input stability circles can be plotted for two cases of $|S_{22}|$



$|S_{11}| < 1 \Rightarrow |\Gamma_{in}| < 1, \ \forall \ \Gamma_L = 0$ $\quad$ $|S_{11}| > 1 \Rightarrow |\Gamma_{in}| > 1, \ \forall \ \Gamma_L = 0$

Output stability circle for conditionally stable devices

Microwave Amplifier Stability

- If the amplifier is *unconditionally stable* then the stability circles fall completely outside the Smith chart

$$||C_L| - R_L| > 1 \;\forall\; |S_{11}| < 1$$

$$||C_S| - R_S| > 1 \;\forall\; |S_{22}| < 1$$

- If the amplifier is *conditionally stable* then the Γ_S & Γ_L values must be chosen in the stable regions of the Smith chart

➢ Test for Unconditional Stability :

- Before we plot the stability circles on Smith chart it is important to find if the amplifier is *unconditionally stable* using two simple tests

❖ The K - Δ test : An amplifier is unconditionally stable if it satisfies the *Rollet's* (K) as well as an auxiliary condition (Δ) simultaneously

$$\boxed{K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} > 1} \qquad \boxed{|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1}$$

Microwave Amplifier Stability

- The K - Δ test cannot be used to compare relative stability of two or more devices, the μ test mitigates this problem

- The μ test : If $\mu > 1$ the device is unconditionally stable, and greater the value of μ, greater is the stability

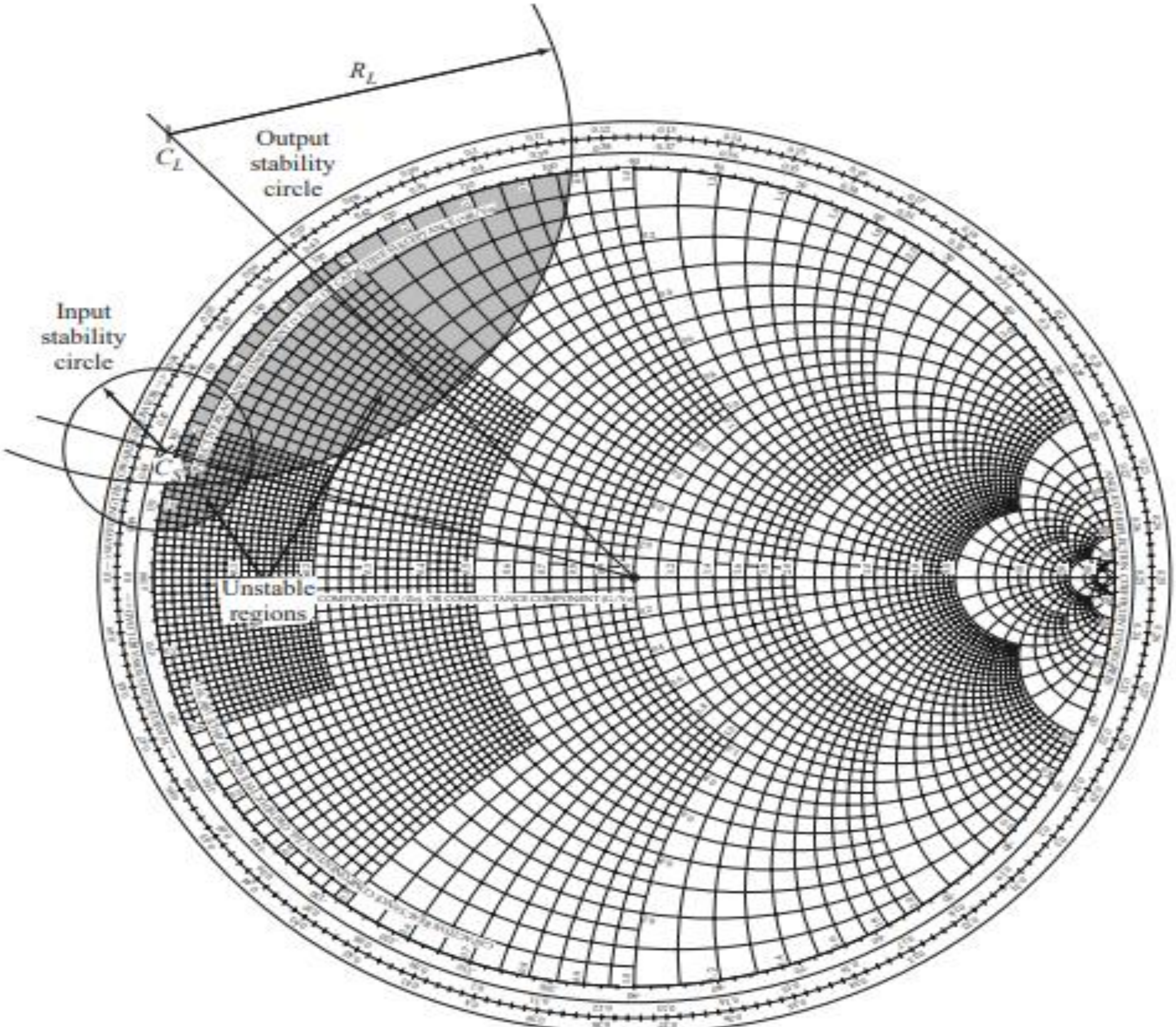
$$\boxed{\mu = \frac{1 - |S_{11}|^2}{|S_{22} - \Delta S_{11}^*| + |S_{12}S_{21}|} > 1}$$

- Apart from the above tests one can recall that $|S_{11}| < 1$ & $|S_{22}| < 1$ for the amplifier to be unconditionally stable

Problems

2. The Triquint T1G6000528 GaN HEMT has the following scattering parameters at 1.9 GHz ($Z0 = 50\Omega$):
$S_{11} = 0.869\angle{-159}\circ$, $S_{12} = 0.031\angle{-9}\circ$, $S_{21} = 4.250\angle 61\circ$, $S_{22} = 0.507\angle{-117}\circ$. Determine the stability of this transistor by using the $K - \Delta$ test and the μ-test

3. A microwave transistor has the following S parameters: $S_{11} = 0.34\angle{-170}\circ$, $S_{12} = 0.06\angle 70\circ$, $S_{21} = 4.3\angle 80\circ$, $S_{22} = 0.45\angle{-25}$. Determine the stability of this transistor by using the $K - \Delta$ test and the μ-test


R_L
C_L
Output
stability
circle
Input
stability
circle
C_S
Unstable
regions

Problems

4. A microwave transistor has the following scattering parameters at 10 GHz, with a 50Ω reference impedance:

$S_{11} = 0.45\angle 150^\circ$
$S_{12} = 0.01\angle -10^\circ$
$S_{21} = 2.05\angle 10^\circ$
$S_{22} = 0.40\angle -150^\circ$

The source impedance is $Z_S = 20\ \Omega$ and the load impedance is $Z_L = 30\ \Omega$. Compute the power gain, the available power gain, and the transducer power gain

5. the S- parameter for the HP HFET-102 GaAs FET at 2 GHz ($Z_0 = 50\Omega$) is given as follows:

$S_{11} = 0.894\angle -60.6^\circ$, $S_{12} = 0.02\angle 62.4^\circ$, $S_{21} = 3.122\angle 123.6^\circ$, $S_{22} = 0.781\angle -27.6^\circ$. Determine the stability of this transistor by using the $K - \Delta$ test and the μ-test