Chapter 3 Microwave Transistor Amplifier Design

3.1 Introduction

Design Considerations include

* stability
* power gain

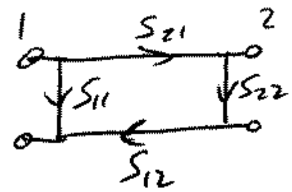
} chapter 3

* bandwidth
* noise
* dc

Stability — unconditionally stable
→ stable for all passive loads / terminations

— potentially unstable
→ care must be taken w/ passive terminations

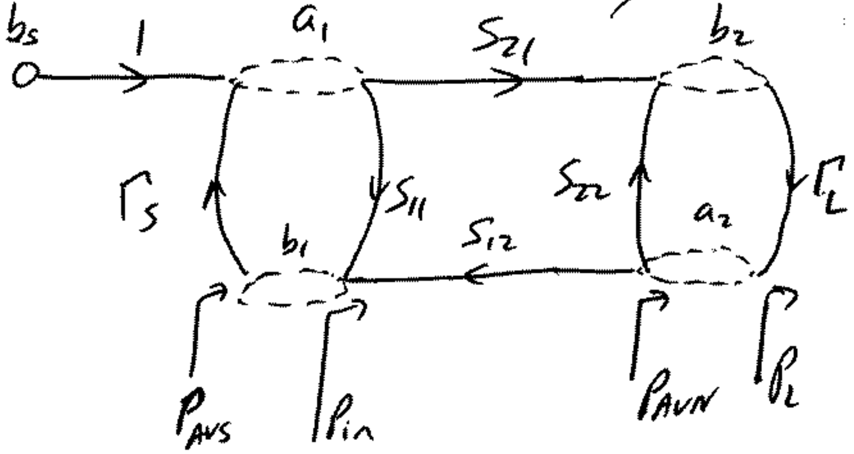
Unilateral Transistors – $S_{12} = 0$ (or is negligible)



↳ Else
Bilateral Transistor

3.2 Power Gain Equations

S parameters of the transistor



$P_L \equiv$ Power delivered to load $= \frac{1}{2}|b_2|^2 - \frac{1}{2}|a_2|^2$

$P_{AVN} \equiv$ Power available from network $= P_L \big|_{\Gamma_L = \Gamma_S^*}$

$P_{IN} \equiv$ Power input to network $= \frac{1}{2}|a_1|^2 - \frac{1}{2}|b_1|^2$

$P_{AVS} \equiv$ Power available from source $= P_{IN} \big|_{\Gamma_L = \Gamma_{OUT}^*}$

Transducer Power Gain $\equiv G_T = \dfrac{P_L}{P_{AVS}} = \dfrac{1-|\Gamma_S|^2}{|1-\Gamma_{IN}\Gamma_S|^2}\,|S_{21}|^2\,\dfrac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}$

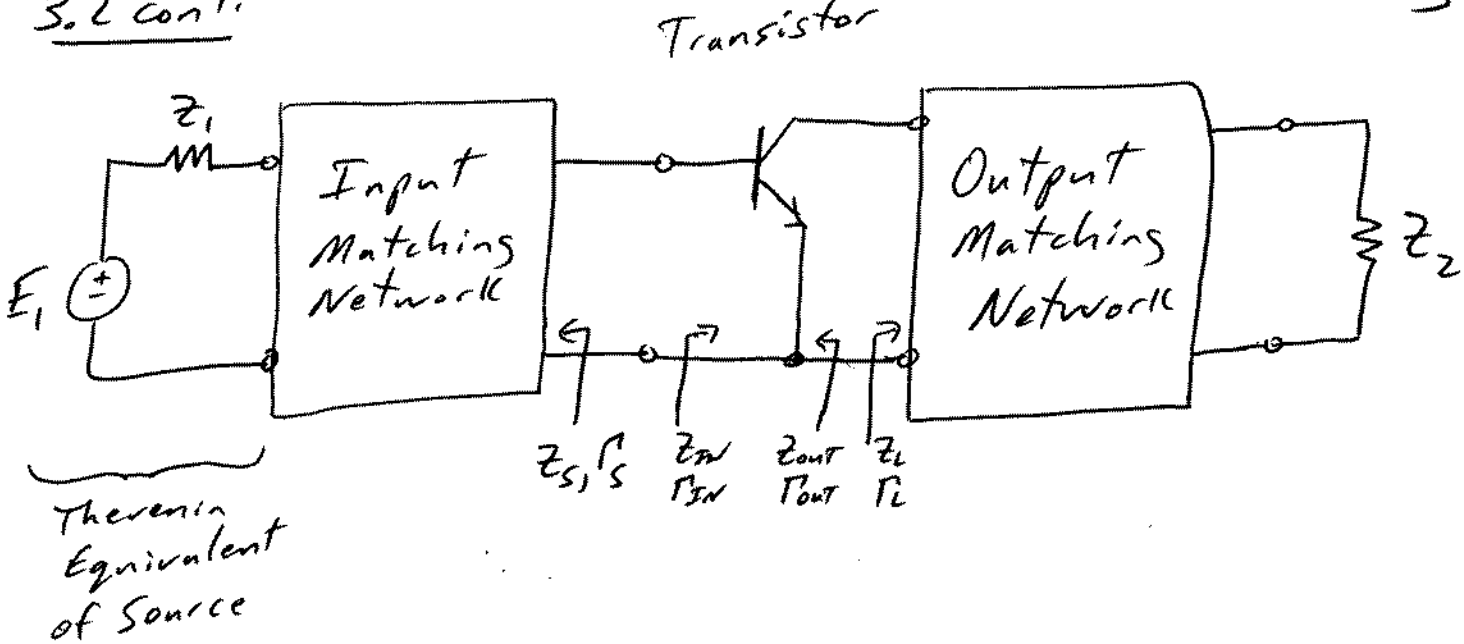
$$= \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2}\,|S_{21}|^2\,\frac{1-|\Gamma_L|^2}{|1-\Gamma_{OUT}\Gamma_L|^2}$$

(Operating) Power Gain $\equiv G_P = \dfrac{P_L}{P_{IN}} = \dfrac{1}{1-|\Gamma_{IN}|^2}\,|S_{21}|^2\,\dfrac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}$

Available Power Gain $= G_A = \dfrac{P_{AVN}}{P_{AVS}} = \dfrac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2}\,|S_{21}|^2\,\dfrac{1}{1-|\Gamma_{OUT}|^2}$

$\Gamma_{IN} = S_{11} + \dfrac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}$ + $\Gamma_{OUT} = S_{22} + \dfrac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}$

3.2 cont.



* Typically, $Z_1 = Z_2 = 50\Omega$

* If the matching networks are passive,

  $|\Gamma_S| < 1$ and $|\Gamma_L| < 1$

  $\Rightarrow \text{Re}(Z_S) > 0$ and $\text{Re}(Z_L) > 0$

* It <u>is</u> possible for $|\Gamma_{IN}| > 1$ and/or $|\Gamma_{OUT}| > 1$ to result for certain S parameters, even when $|\Gamma_S|$ + $|\Gamma_L|$ are less than one.

  ↳ possible instability (oscillations)

Example- With an Advanced Semiconductor, Inc. MLN2037F NPN silicon RF power transistor (data sheets attached) in the microwave amplifier below, determine Γ_{IN}, Γ_{OUT}, G_T, G_P, and G_A at 1 GHz when $\Gamma_S = 0.8\angle -150°$ and $\Gamma_L = 0.3\angle 140°$.

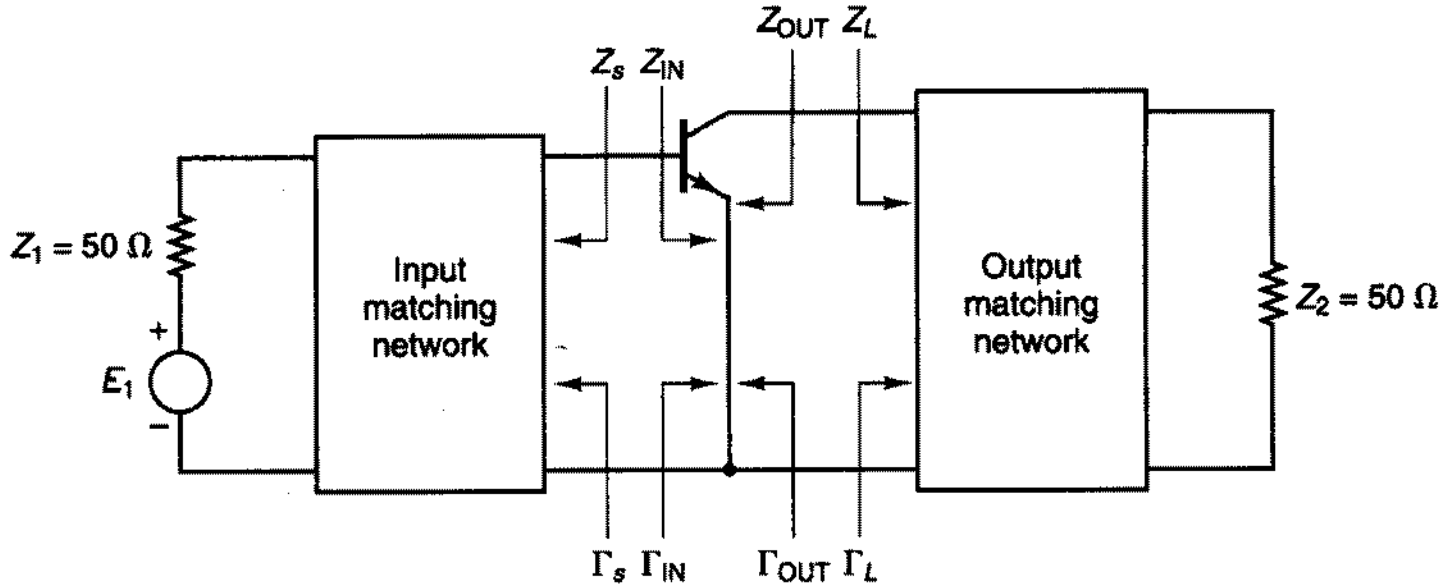


Figure 3.2.2 A microwave amplifier diagram.

From page 2/2 of the data sheet:

$$S_{11} = 0.8128\angle 156°, \quad S_{12} = 0.0944\angle 63°$$

$$S_{21} = 1.81\angle 55°, \quad S_{22} = 0.3801\angle -136°$$

$$(3.2.5) \quad \Gamma_{IN} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}$$

$$= (0.8128\angle 156°) + \frac{(0.0944\angle 63°)(1.81\angle 55°)(0.3\angle 140°)}{1-(0.3801\angle -136°)(0.3\angle 140°)}$$

$$= 0.8128\angle 156° + 0.05784\angle -101.486°$$

$$\underline{\underline{\Gamma_{IN} = 0.80226\angle 160.036°}}$$

$$(3.2.6)\quad \Gamma_{OUT} = S_{22} + \frac{S_{12} S_{21} \Gamma_S}{1 - S_{11} \Gamma_S}$$

$$= (0.3801\angle{-136°}) + \frac{(0.0944\angle 63°)(1.81\angle 55°)(0.8\angle{-150°})}{1 - (0.8128\angle 156°)(0.8\angle{-150°})}$$

$$= (0.3801\angle{-136°}) + (0.380\angle{-21.11°})$$

$$\underline{\underline{\Gamma_{OUT} = 0.40897\angle{-78.578°}}}$$

$$(3.2.1)\quad G_T = \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_{IN}\Gamma_S|^2} |S_{21}|^2 \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}$$

or Transducer Power Gain

$$= \frac{1 - 0.8^2}{|1 - (0.8023\angle 160°)(0.8\angle{-150°})|^2} (1.81^2) \frac{1 - 0.3^2}{|1 - (0.3801\angle{-136°})(0.3\angle 140°)|^2}$$

$$= (2.433)(3.2761)(1.159)$$

$$\underline{\underline{G_T = 9.2355 = 10\log_{10}(9.2355) = 9.6546\text{ dB}}}$$

Similarly

$$(3.2.2)\quad G_T = \frac{1 - |\Gamma_S|^2}{|1 - S_{11}\Gamma_S|^2} |S_{21}|^2 \frac{1 - |\Gamma_L|^2}{|1 - \Gamma_{OUT}\Gamma_L|^2}$$

$$= \frac{1 - 0.8^2}{|1 - (0.8128\angle 156°)(0.8\angle{-150°})|^2} (1.81)^2 \frac{1 - 0.3^2}{|1 - (0.409\angle{-78.6°})(0.3\angle 140°)|^2}$$

$$= (2.781)(3.2761)(1.014)$$

$$\underline{\underline{G_T = 9.2355 = 9.6546\text{ dB}}}$$

(3.2.3) $$G_P = \frac{1}{1-|\Gamma_{IN}|^2} |S_{21}|^2 \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}$$ ← Operating Power Gain

$$= \frac{1}{1-0.80226^2} (1.81)^2 \frac{1-0.3^2}{|1-(0.3801\angle -136°)(0.3\angle 140°)|^2}$$

$$= (2.806)(3.2761)(1.159)$$

$$\underline{\underline{G_P = 10.650 = 10.2734\,dB}}$$

(3.2.4) $$G_A = \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2} |S_{21}|^2 \frac{1}{1-|\Gamma_{OUT}|^2}$$ ← Available Power Gain

$$= \frac{1-0.8^2}{|1-(0.8128\angle 156°)(0.8\angle -150°)|^2} (1.81)^2 \frac{1}{1-0.409^2}$$

$$= (2.781)(3.2761)(1.201)$$

$$\underline{\underline{G_A = 10.9402 = 10.3903\,dB}}$$

Note: * G_P is $10.2734 - 9.6546 = 0.6188\,dB$ larger than G_T. This implies that $P_{IN} < P_{AVS}$ (common sense).

* Also, note that all three gains are w/in a 1dB range ⇒ fairly good matching.

ASI

MLN2037F

NPN SILICON RF POWER TRANSISTOR

DESCRIPTION:

The **ASI MLN2037F** is Designed for Class A Linear Applications up to 2.0 GHz.

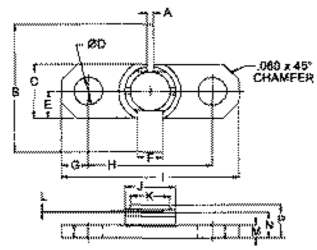
FEATURES:

- Class A Operation
- **P_G** = 5.0 dB at 5.0 W/2.0 GHz
- ***Omnigold***™ Metalization System
- Common Emitter

MAXIMUM RATINGS

I_C	10 A
V_{CB}	60 V
V_{CE}	35 V
P_{DISS}	140 W @ T_C = 25 °C
T_J	-65 °C to +200 °C
T_{STG}	-65 °C to +150 °C
θ_{JC}	5.5 °C/W

PACKAGE STYLE .250 2L FLG



DIM	MINIMUM inches / mm	MAXIMUM inches / mm
A	.028 / 0.71	.032 / 0.81
B	.740 / 18.80	
C	.245 / 6.22	.255 / 6.48
D	.128 / 3.25	.132 / 3.35
E	.125 / 3.18	
F	.110 / 2.79	.117 / 2.97
G	.117 / 2.97	
H	.560 / 14.22	.570 / 14.48
I	.790 / 20.07	.810 / 20.57
J	.225 / 5.72	.235 / 5.97
K	.165 / 4.19	.185 / 4.70
L	.003 / 0.08	.007 / 0.18
M	.058 / 1.47	.068 / 1.73
N	.119 / 3.02	.135 / 3.43
P	.149 / 3.78	.187 / 4.75

ORDER CODE: ASI10635

CHARACTERISTICS T_C = 25 °C

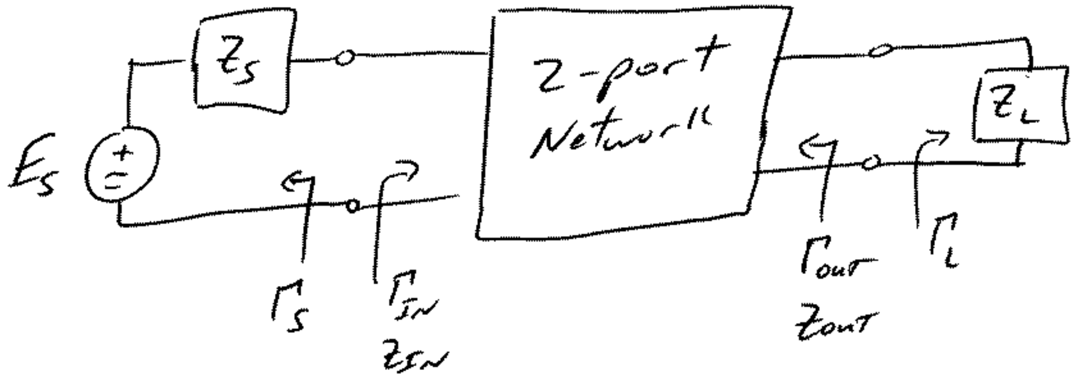
SYMBOL	TEST CONDITIONS	MINIMUM	TYPICAL	MAXIMUM	UNITS
BV_{CEO}	I_C = 50 mA	35			V
BV_{CER}	I_C = 50 mA R_{BE} = 10 Ω	60			V
BV_{EBO}	I_E = 10 mA	4.0			V
I_{CES}	V_E = 28 V			5	mA
h_{FE}	V_{CE} = 5.0 V I_C = 1.0 A	10		100	---
C_{ob}	V_{CB} = 28 V f = 1.0 MHz			15	pF
P_G	V_{CE} = 20 V I_{CQ} = 800 mA f = 2.0 GHz P_{OUT} = 5.0 W	5.0			dB

TYPICAL S PARAMETERS:

Z_O = 50 Ω V_{CE} = 15 V, I_C = 160 mA, T_A = 25°C

FREQ.	S21			S12		S11		S22	
GHz	dB	Mag	Ang	Mag	Ang	Mag	Ang	Mag	Ang
0.20	16.40	6.60	90	0.0281	42	0.8709	-173	0.2511	-138
0.50	9.00	2.81	71	0.0467	52	0.8709	170	0.4027	-144
1.00	5.20	1.81	55	0.0944	63	0.8128	156	0.3801	-136
1.50	1.40	1.17	42	0.1548	62	0.7673	141	0.5888	-139
2.00	-0.60	0.93	24	0.2344	52	0.7762	112	0.6998	-171

3.3 Stability Considerations



Unconditionally stable when

$$|\Gamma_S| < 1$$

$$|\Gamma_L| < 1$$

$\Rightarrow$ passive source + load

$$|\Gamma_{IN}| = \left| S_{11} + \frac{S_{12} S_{21} \Gamma_L}{1 - S_{22}\Gamma_L} \right| < 1$$

and

$$|\Gamma_{OUT}| = \left| S_{22} + \frac{S_{12} S_{21} \Gamma_S}{1 - S_{11}\Gamma_S} \right| < 1$$

$\Rightarrow$ $Re\{Z_{IN}\} > 0$, $Re\{Z_{OUT}\} > 0$

$\rightarrow$ all Γ are with respect to characteristic impedance Z_0

$\rightarrow$ for a unilateral two-port network ($S_{12} = 0$),

$$|\Gamma_{IN}| = |S_{11}| < 1$$

$$|\Gamma_{OUT}| = |S_{22}| < 1$$

3.3 cont.

What if the two-port network (e.g. transistor) is potentially unstable?

⇒ Be very helpful to know which values of Γ_S and Γ_L would result in a stable amplifier and which would not.

Start by finding Γ_S & Γ_L values which result in $|\Gamma_{IN}|=1$ and $|\Gamma_{OUT}|=1$, the boundary between the stable regions and unstable regions. Setting the $|\Gamma_{IN}|$ and $|\Gamma_{OUT}|$ equation equal to one, results in (see Appendix A)

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

and

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

stability circles

where $\Delta = S_{11}S_{22} - S_{12}S_{21}$.

The first stability circle is the output stability circle where $|\Gamma_{IN}|=1$ which yields Γ_L values. The second circle is the input stability circle where $|\Gamma_{OUT}|=1$ which yields Γ_S values.

3.3 cont.

Using the stability circle equations, we can find the radii and centers of the circles:

Output Stability Circle; Γ_L where $|\Gamma_{IN}=1|$

radius $r_L = \left| \dfrac{S_{12}S_{21}}{|S_{22}|^2 - |\Delta|^2} \right|$ ← real positive #

center $C_L = |C_L| \measuredangle C_L = \dfrac{(S_{22} - \Delta S_{11}^*)^*}{|S_{22}|^2 - |\Delta|^2}$ ← complex #

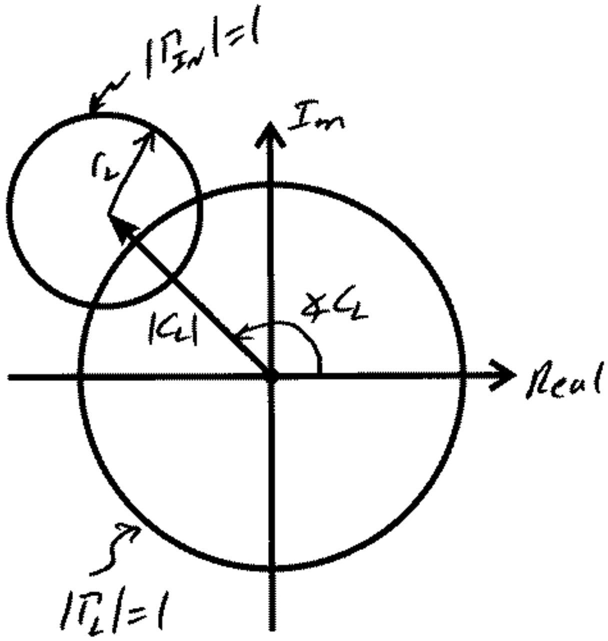
Input Stability Circle; Γ_S where $|\Gamma_{OUT}=1|$

$$r_S = \left| \frac{S_{12}S_{21}}{|S_{11}|^2 - |\Delta|^2} \right| \quad \text{← real positive \#}$$

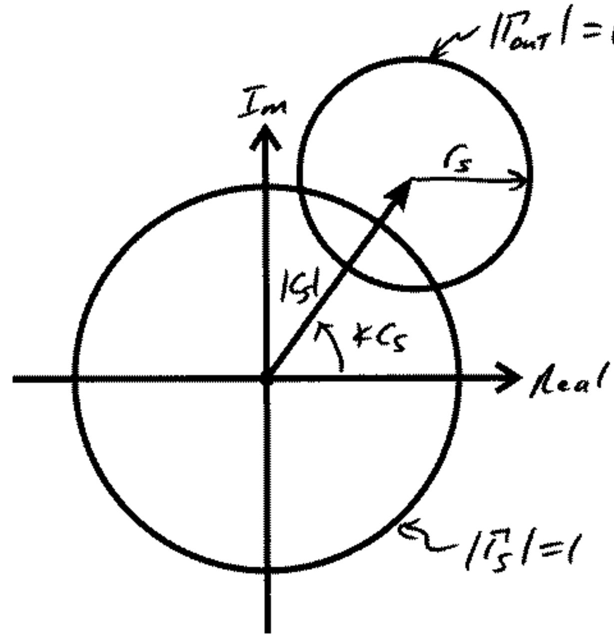
$$C_S = \frac{(S_{11} - \Delta S_{22}^*)^*}{|S_{11}|^2 - |\Delta|^2} \quad \text{← complex \#}$$

We'll plot these circles on Γ_L &/or Γ_S complex planes (e.g. Smith Charts), taking particular note of the regions where $|\Gamma_L| \le 1$ and $|\Gamma_S| \le 1$ (passive), where we are inside the standard Smith Chart circle.

3.3 cont.



Γ_L complex plane



Γ_S complex plane

How can we determine stable regions (i.e., $|\Gamma_{IN}|<1$ and $|\Gamma_{OUT}|<1$?

Method to determine stable regions

1) Choose a point for Γ_L inside/outside the $|\Gamma_{IN}|=1$ circle.

2) Calculate $|\Gamma_{IN}| = \left| S_{11} + \dfrac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L} \right|$

3) If $|\Gamma_{IN}|<1$, then the region inside/outside the $|\Gamma_{IN}|=1$ circle is stable. If not, the region inside/outside the $|\Gamma_{IN}|=1$ circle (where Γ_L point is located) is unstable.

4) Repeat for Γ_S and $|\Gamma_{OUT}|=1$ circle.

3.3 cont.

A particularly easy set of points to test are $\Gamma_L = 0$ (matched load, $Z_L = Z_0$) where $|\Gamma_{IN}| = |S_{11}|$. Is $|S_{11}| < 1$? Yes → $\Gamma_L = 0$ point in stable region

No → $\Gamma_L = 0$ point in unstable region

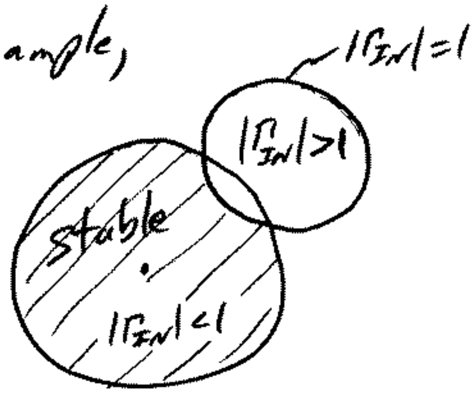
and

$\Gamma_S = 0$ (matched source, $Z_S = Z_0$) where

$|\Gamma_{OUT}| = |S_{22}|$. Is $|S_{22}| < 1$? Yes → $\Gamma_S = 0$ point in stable region

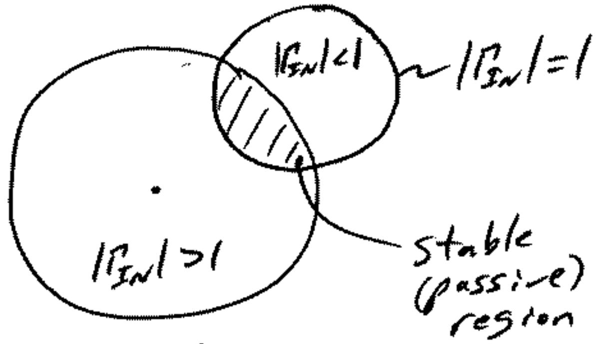
No → $\Gamma_S = 0$ point in unstable region

for example,



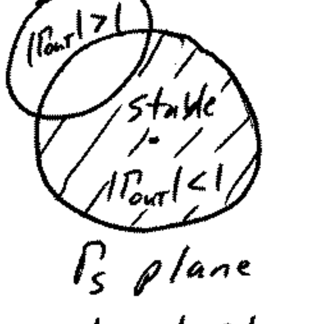
Γ_L plane

$|S_{11}| < 1$



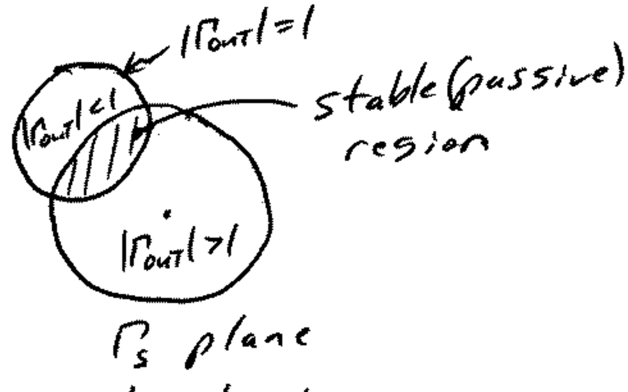
Γ_L plane

$|S_{11}| > 1$



Γ_S plane

$|S_{22}| < 1$



Γ_S plane

$|S_{22}| > 1$

3.3 cont.

Note, if $|S_{11}| > 1$ or $|S_{22}| > 1$, the network can NOT be unconditionally stable since $|\Gamma_{IN}|$ or $|\Gamma_{OUT}| > 1$ will be greater than 1, even when Γ_L or Γ_S are zero (matched!).

Necessary & sufficient conditions for a two-port to be unconditionally stable.

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

② $$1-|S_{11}|^2 > |S_{12}S_{21}|$$

③ $$1-|S_{22}|^2 > |S_{12}S_{21}|$$

where $\Delta = S_{11}S_{22} - S_{12}S_{21}$

OR

$$\left.\begin{array}{l} \text{① } K > 1 \\ \text{② } |\Delta| < 1 \end{array}\right\} \text{Easier!}$$

If these conditions are NOT met, the two-port is potentially unstable.

Example- Let's revisit our earlier example with an Advanced Semiconductor, Inc. MLN2037F NPN silicon RF power transistor operating at 1 GHz with $\Gamma_S = 0.8\angle -150°$ and $\Gamma_L = 0.3\angle 140°$.

Using the datasheet, the S parameters at 1 GHz are:

$$S_{11} = 0.8128\angle 156°, \quad S_{12} = 0.0944\angle 63°$$

$$S_{21} = 1.81\angle 55°, \quad S_{22} = 0.3801\angle -136°$$

We calculated:

$$\underline{\Gamma_{IN} = 0.80226\angle 160.036°} \text{ and } \underline{\Gamma_{OUT} = 0.40897\angle -78.578°}.$$

<u>Output Stability Circle</u> (Γ_L values for $|\Gamma_{IN}| = 1$)

First, calculate $\Delta = S_{11} S_{22} - S_{12} S_{21}$

$$= (0.8128\angle 156°)(0.3801\angle -136°) - (0.0944\angle 63°)(1.81\angle 55°)$$

$$\underline{\Delta = 0.37328\angle -6.9548°}$$

$$(3.3.7) \quad r_L = \left| \frac{S_{12} S_{21}}{|S_{22}|^2 - |\Delta|^2} \right| = \left| \frac{(0.0944\angle 63°)(1.81\angle 55°)}{0.3801^2 - 0.37328^2} \right|$$

$$= \left| \frac{0.170864\angle 118°}{0.005138} \right| = \left| 33.235\angle 118° \right|$$

$$\underline{\underline{r_L = 33.235}}$$

complex conjugate operator

$$(3.3.8) \quad C_L = \frac{(S_{22} - \Delta S_{11}^*)^*}{|S_{22}|^2 - |\Delta|^2} = \frac{[(0.3801\angle -136°) - (0.3733\angle -7°)(0.8128\angle -156°)]^*}{0.3801^2 - 0.37328^2}$$

$$\underline{\underline{C_L = (34.21368\angle +84.5682°)}}$$

<u>Input Stability Circle</u> (Γ_S values where $|\Gamma_{OUT}|=1$)

(3.3.9) $$r_S = \left|\frac{S_{12}S_{21}}{|S_{11}|^2-|\Delta|^2}\right| = \left|\frac{(0.0944\angle 63^\circ)(1.81\angle 55^\circ)}{0.8128^2-0.373^2}\right|$$

$$= |0.32776\angle 118^\circ|$$

$$\underline{\underline{r_S = 0.32776}}$$

(3.3.10) $$C_S = \frac{[S_{11}-\Delta S_{22}^*]^*}{|S_{11}|^2-|\Delta|^2}$$

$$= \frac{[(0.8128\angle 156^\circ)-(0.373\angle -7^\circ)(0.3801\angle +136^\circ)]^*}{0.8128^2-0.373^2}$$

$$= \frac{0.68934\angle -161.353^\circ}{0.8128^2-0.373^2}$$

$$\underline{\underline{C_S = 1.32232\angle -161.3533^\circ}}$$

Circle plots on next pages. Note that both $|S_{11}|<1$ and $|S_{22}|<1$. So, Γ_L + $\Gamma_L = 0$ are stable.

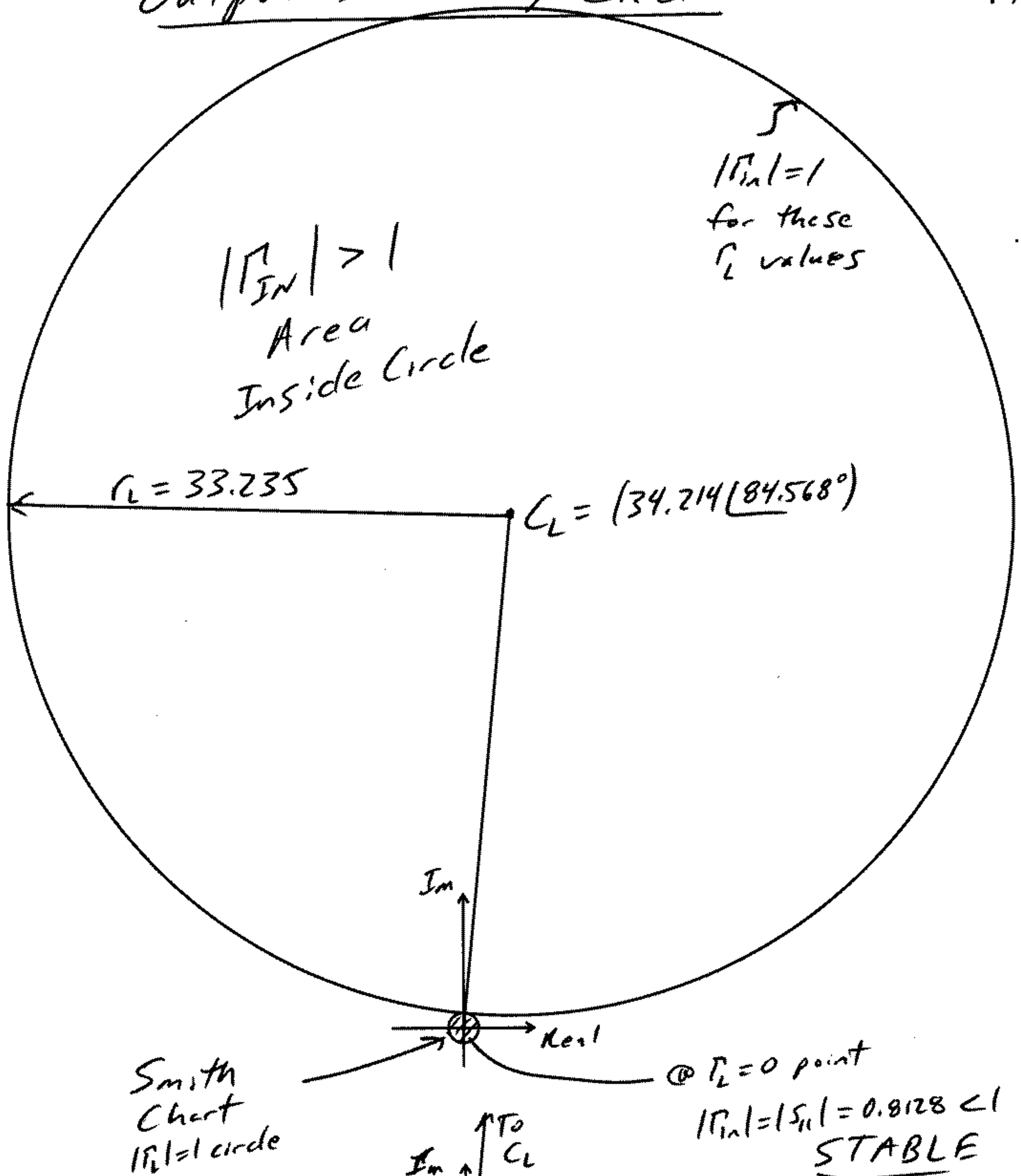
Unconditionally stable?

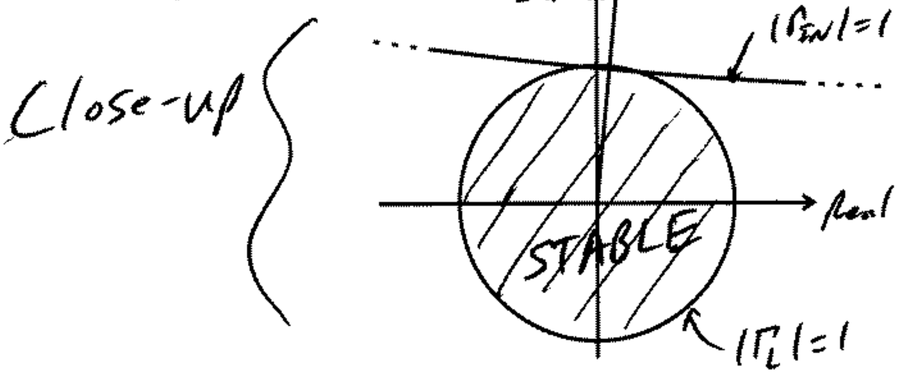
① $$K = \frac{1-|S_{11}|^2-|S_{22}|^2+|\Delta|^2}{2|S_{12}S_{21}|} = \frac{1-0.8128^2-0.3801^2+0.373^2}{2|(0.0944\angle 63^\circ)(1.81\angle 55^\circ)|}$$

$$= 0.978 \not> 1$$ <u>NOT unconditionally stable</u>

② $|\Delta| = 0.373 < 1$ ← This condition is met

Output Stability Circle

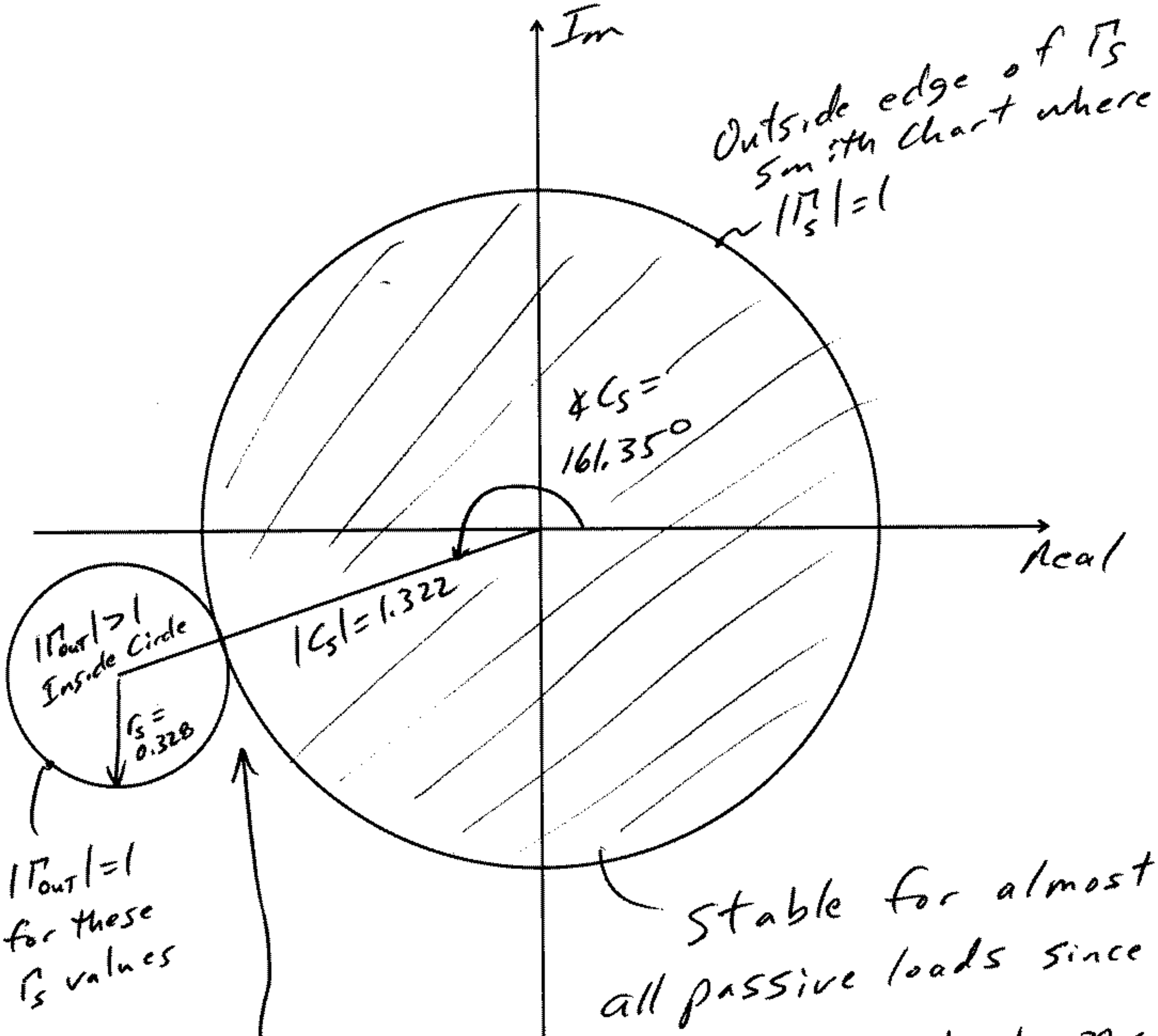




← Note that Output stability circle & Γ_L Smith Chart intersect!

Input Stability Circle

→ On Γ_S complex plane



Stable for almost all passive loads since @ $\Gamma_S = 0$, $|\Gamma_{OUT}| = |S_{22}| = 0.38 < 1$

Note that input stability circle & Γ_S Smith Chart <u>intersect</u> (barely)!