Chapter 4

Microwave Amplifier

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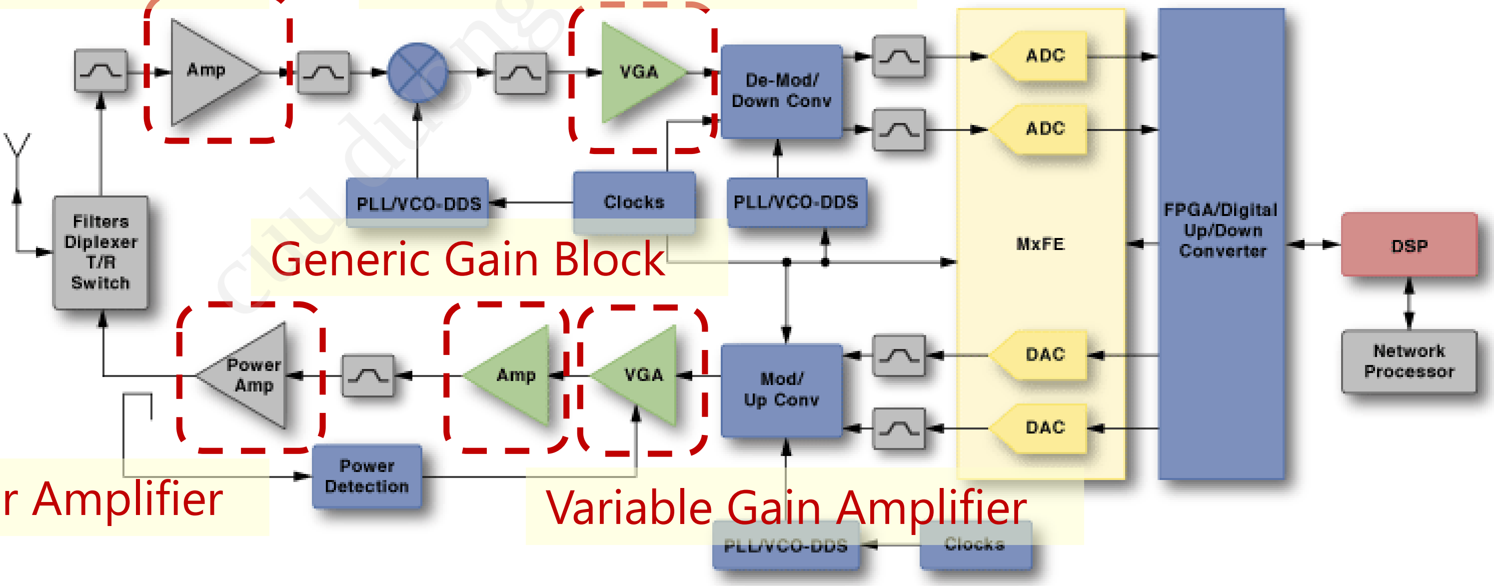
Contents

1. Introduction

❖ The function of an amplifier is simple: to amplify signals

- Recall from last lecture the typical strength of a GPS signal: -125 dBm; that is an extremely small power: -125 dBm ≈ 10-15 W!
- We want to make this signal stronger, actually a lot stronger, in order to be able to process it; all without distorting it in any way.
- Similar need is in the transmitter: signal generated by the oscillator is often quite weak; needs a lot of amplification before transmitting it in order to reach longer distances



Low Noise Amplifier

Variable Gain Amplifier

Generic Gain Block

Power Amplifier

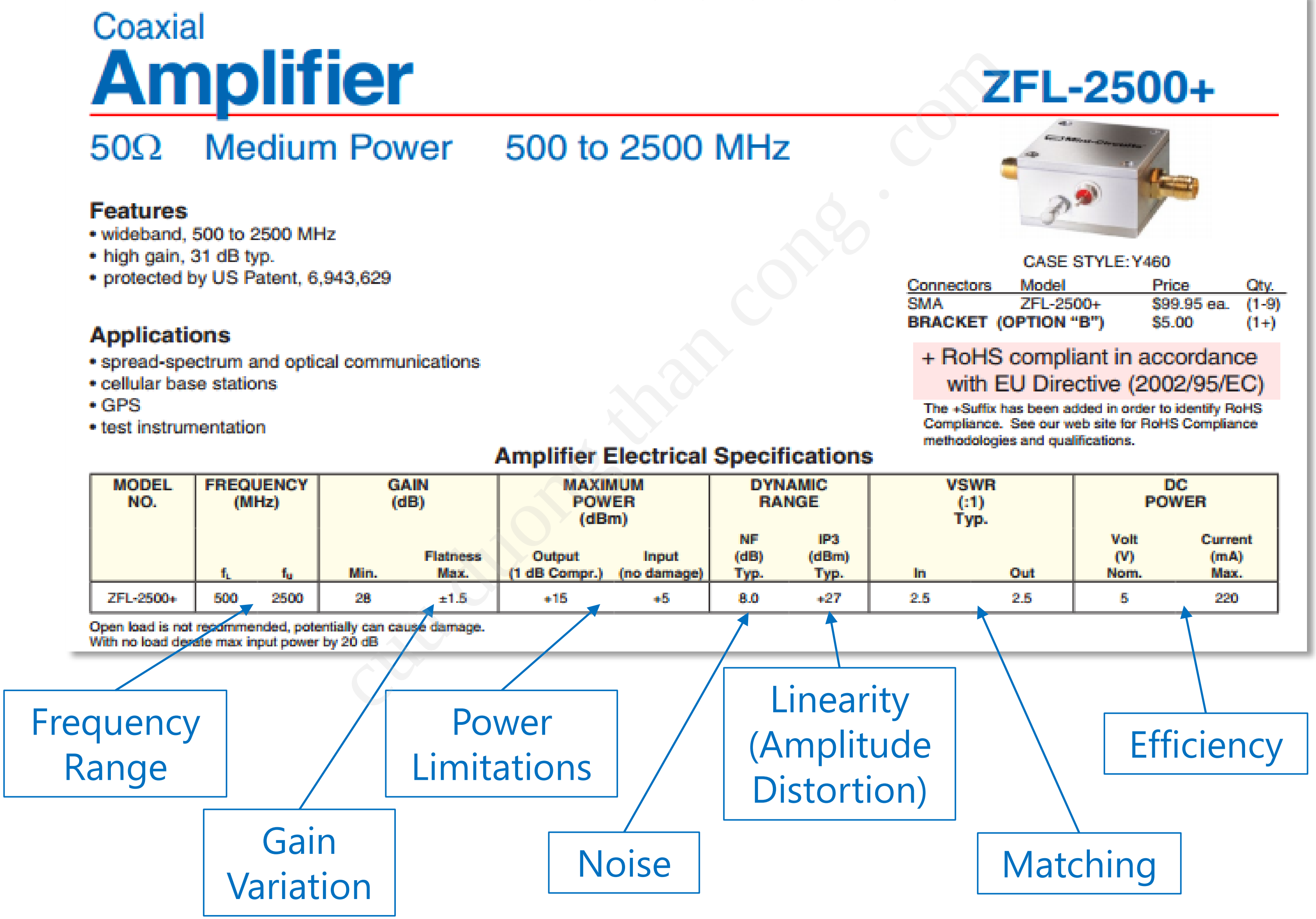
Variable Gain Amplifier

1. Introduction

- **Ideal RF/Microwave Amplifier:**
  - Infinite bandwidth
  - Constant gain
  - Signal travels only from input to output (unilateral)
  - Perfectly matched at the input and the output
  - No signal distortion
    - Doesn’t add noise to the signal
    - Doesn’t change the shape (either in amplitude or phase) of the signal
  - Amplifies any level of signal
  - 100% efficient

- **Real RF/Microwave Amplifier:**
  - Finite bandwidth
  - Gain variation, even within the bandwidth
  - Single feedback from output to input!
  - Finite (and sometimes intentional) mismatch at the input/output
  - Signal distortion
    - Noise
    - Amplitude
    - Phase (less of a concern)
  - Limited output power (of course!)
  - <100% efficiency (of course!)

1. Introduction



Coaxial

Amplifier

ZFL-2500+

50Ω Medium Power 500 to 2500 MHz

Features
- wideband, 500 to 2500 MHz
- high gain, 31 dB typ.
- protected by US Patent, 6,943,629

Applications
- spread-spectrum and optical communications
- cellular base stations
- GPS
- test instrumentation

CASE STYLE: Y460

Connectors	Model	Price	Qty.
SMA	ZFL-2500+	$99.95 ea.	(1-9)
BRACKET	**(OPTION "B")**	$5.00	(1+)

+ RoHS compliant in accordance with EU Directive (2002/95/EC)

The +Suffix has been added in order to identify RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications.

Amplifier Electrical Specifications

MODEL NO.	FREQUENCY (MHz)		GAIN (dB)		MAXIMUM POWER (dBm)		DYNAMIC RANGE		VSWR (:1) Typ.		DC POWER	
	f_L	f_U	Min.	Flatness Max.	Output (1 dB Compr.)	Input (no damage)	NF (dB) Typ.	IP3 (dBm) Typ.	In	Out	Volt (V) Nom.	Current (mA) Max.
ZFL-2500+	500	2500	28	±1.5	+15	+5	8.0	+27	2.5	2.5	5	220

Open load is not recommended, potentially can cause damage.
With no load derate max input power by 20 dB

Frequency Range

Gain Variation

Power Limitations

Noise

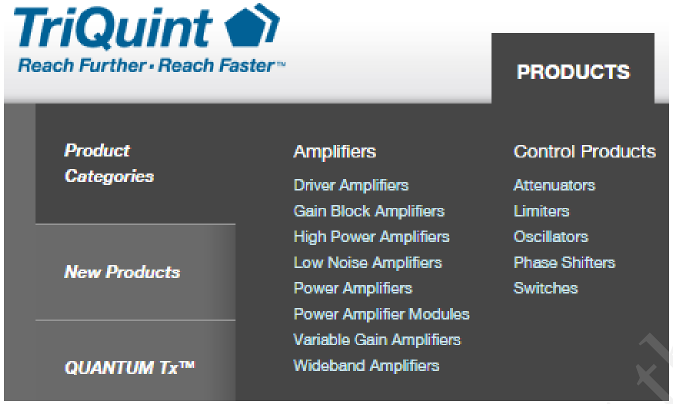
Linearity (Amplitude Distortion)

Matching

Efficiency

1. Introduction

❖ Types of RF amplifiers: Most vendors categorize RF amplifier by their intended use.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PRODUCTS

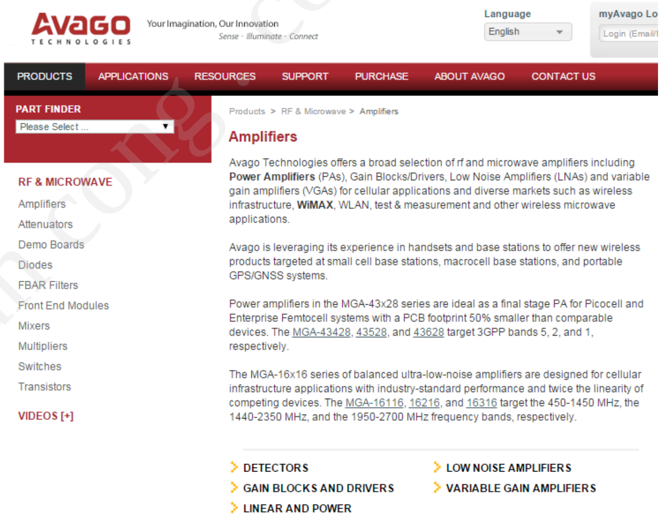
Product Categories

New Products

QUANTUM Tx™

Amplifiers
- Driver Amplifiers
- Gain Block Amplifiers
- High Power Amplifiers
- Low Noise Amplifiers
- Power Amplifiers
- Power Amplifier Modules
- Variable Gain Amplifiers
- Wideband Amplifiers

Control Products
- Attenuators
- Limiters
- Oscillators
- Phase Shifters
- Switches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PART FINDER
Please Select ...

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- Attenuators
- Demo Boards
- Diodes
- FBAR Filters
- Front End Modules
- Mixers
- Multipliers
- Switches
- Transistors

VIDEOS [+]

Products > RF & Microwave > Amplifiers

Amplifiers

Avago Technologies offers a broad selection of rf and microwave amplifiers including **Power Amplifiers** (PAs), Gain Blocks/Drivers, Low Noise Amplifiers (LNAs) and variable gain amplifiers (VGAs) for cellular applications and diverse markets such as wireless infrastructure, **WiMAX**, WLAN, test & measurement and other wireless microwave applications.

Avago is leveraging its experience in handsets and base stations to offer new wireless products targeted at small cell base stations, macrocell base stations, and portable GPS/GNSS systems.

Power amplifiers in the MGA-43x28 series are ideal as a final stage PA for Picocell and Enterprise Femtocell systems with a PCB footprint 50% smaller than comparable devices. The MGA-43428, 43528, and 43628 target 3GPP bands 5, 2, and 1, respectively.

The MGA-16x16 series of balanced ultra-low-noise amplifiers are designed for cellular infrastructure applications with industry-standard performance and twice the linearity of competing devices. The MGA-16116, 16216, and 16316 target the 450-1450 MHz, the 1440-2350 MHz, and the 1950-2700 MHz frequency bands, respectively.

- DETECTORS
- GAIN BLOCKS AND DRIVERS
- LINEAR AND POWER
- LOW NOISE AMPLIFIERS
- VARIABLE GAIN AMPLIFIERS


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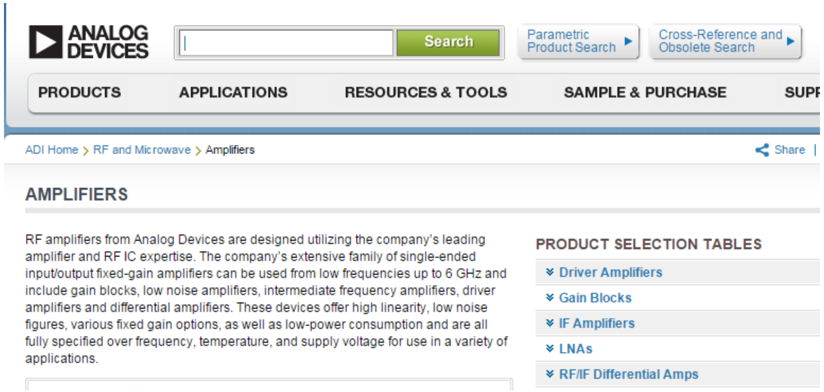
  - Smart Energy-Connected Home and Automation
  - BDS/GPS/GNSS
  - Broad Market LNAs and Low Noise Transistors
  - Driver Amplifiers / Linear Amplifiers
  - Gain Block
  - Variable Gain Amplifiers


ANALOG DEVICES
Search | Parametric Product Search | Cross-Reference and Obsolete Search

PRODUCTS | APPLICATIONS | RESOURCES & TOOLS | SAMPLE & PURCHASE | SUPP

ADI Home > RF and Microwave > Amplifiers | Share

AMPLIFIERS

RF amplifiers from Analog Devices are designed utilizing the company's leading amplifier and RF IC expertise. The company's extensive family of single-ended input/output fixed-gain amplifiers can be used from low frequencies up to 6 GHz and include gain blocks, low noise amplifiers, intermediate frequency amplifiers, driver amplifiers and differential amplifiers. These devices offer high linearity, low noise figures, various fixed gain options, as well as low-power consumption and are all fully specified over frequency, temperature, and supply voltage for use in a variety of applications.

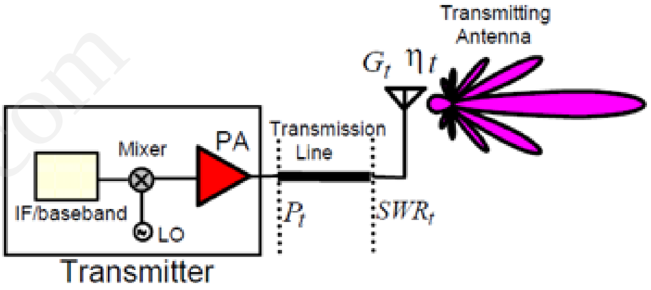
PRODUCT SELECTION TABLES
- Driver Amplifiers
- Gain Blocks
- IF Amplifiers
- LNAs
- RF/IF Differential Amps

1. Introduction

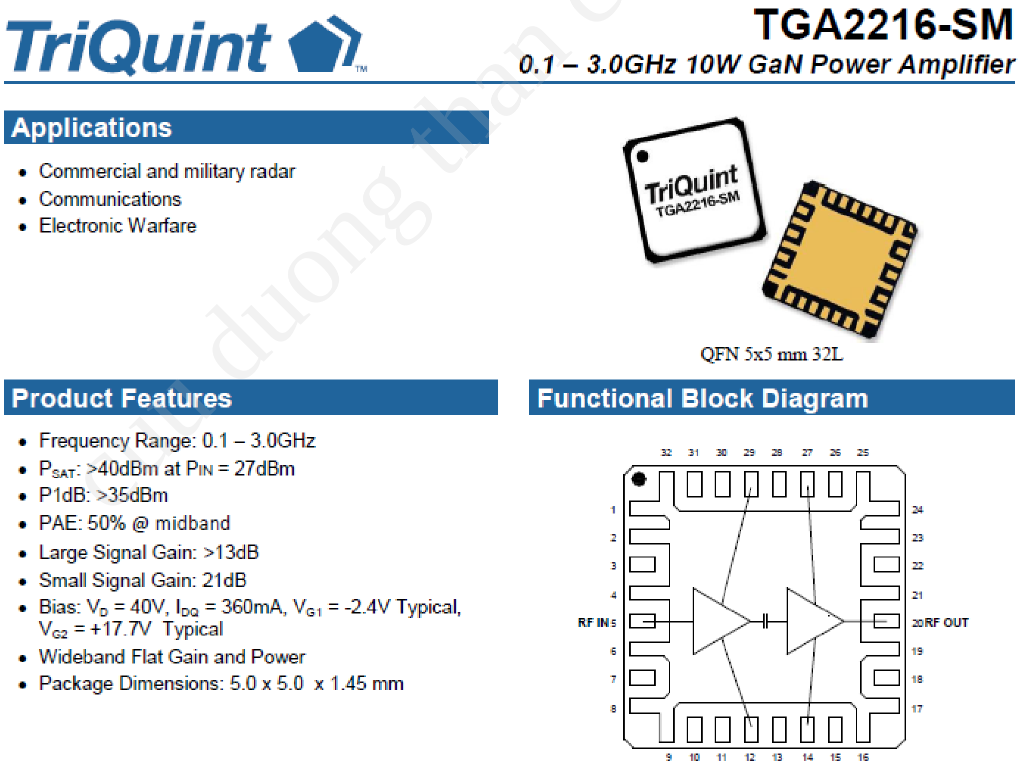
- Common types of RF amplifiers
    - Low noise amplifiers: Optimized for low noise and high gain
    - Power amplifiers:
        - Optimized for high output power and efficiency
        - Gain can be moderate if there is no driver included
    - Variable gain amplifiers
        - Gain can be changed analogly or digitally
    - Linear amplifier
        - Optimized for linearity
    - Gain block/Driver amplifiers
        - General purpose amplifier with well balanced specs
    - Wideband amplifiers
        - Optimized for wide bandwidth; it's not uncommon to see decade (10:1) bandwidth amplifiers in this category.
- Bottom line is: look at the quantitative metrics (noise, linearity, power handling, efficiency, size, cost) when choosing your amplifier

1. Introduction

- Power Amplifier: for Transmitter (Tx)
  - Considerations: Output power, Gain Efficiency, non-linear intermodulation effects.



- Example: TGA2216-SM



TriQuint

TGA2216-SM

0.1 – 3.0GHz 10W GaN Power Amplifier

Applications

- Commercial and military radar
- Communications
- Electronic Warfare

QFN 5x5 mm 32L

Product Features

- Frequency Range: 0.1 – 3.0GHz
- P_{SAT}: >40dBm at P_{IN} = 27dBm
- P1dB: >35dBm
- PAE: 50% @ midband
- Large Signal Gain: >13dB
- Small Signal Gain: 21dB
- Bias: V_D = 40V, I_{DQ} = 360mA, V_{G1} = -2.4V Typical, V_{G2} = +17.7V Typical
- Wideband Flat Gain and Power
- Package Dimensions: 5.0 x 5.0 x 1.45 mm

Functional Block Diagram

1. Introduction

Absolute Maximum Ratings

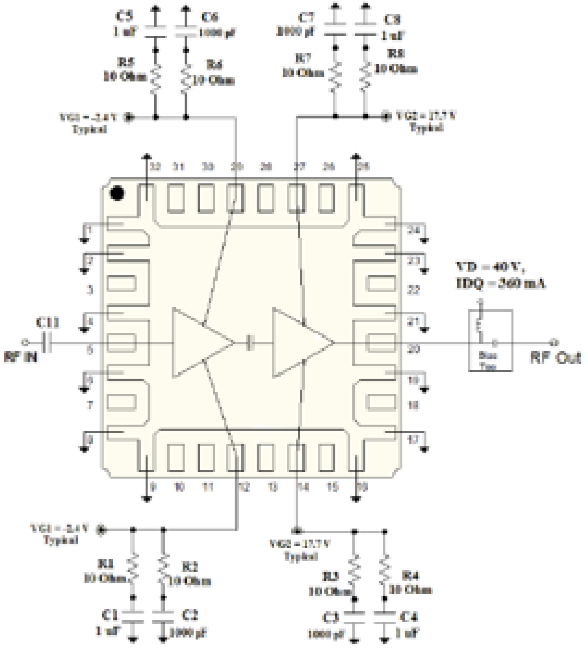
Parameter	Value
Drain Voltage (V_D)	80V
Gate Voltage Range (V_{G1})	-8 to 0V
Gate Voltage Range (V_{G2})	0 to 40V
Drain Current (I_D)	760mA
Gate Current (I_{G1})	-5 to 5.6mA
Gate Current (I_{G2})	-5 to 5.6mA
Power Dissipation (P_{DISS}), 85°C	28W
Input Power (P_{IN}), CW, 50 Ω, 85°C,	33dBm
Input Power (P_{IN}), CW, VSWR 10:1, V_D = 40V, 85°C	27dBm
Channel Temperature (T_{CH})	275°C
Mounting Temperature (30 Seconds)	320°C
Storage Temperature	-55 to 150°C

Recommended Operating Conditions

Parameter	Value
Drain Voltage (V_D)	40V
Drain Current (I_{DQ})	360mA
Gate Voltage (V_{G1})	-2.4V (Typ.)
Gate Voltage (V_{G2})	+17.7V (Typ.)

Electrical specifications are measured at specified test conditions. Specifications are not guaranteed over all recommended operating conditions.

Application Circuit



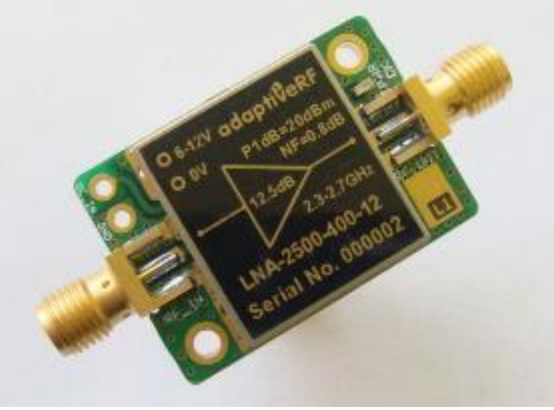
Electrical Specifications

Test conditions unless otherwise noted: 25^{0}C, V_D = 40V, I_{DQ} = 360mA, V_{G1} = -2.4V Typical, V_{G2} = +17.7V Typical

Parameter	Min	Typical	Max	Units
Operational Frequency Range	0.1		3.0	GHz
Small Signal Gain		21		dB
Input Return Loss		> 8		dB
Output Return Loss		> 11		dB
Output Power (Pin = 27dBm)		> 40		dBm
Power Added Efficiency (Pin = 27dBm)		50 (mid band)		%
Power @ 1dB Compression (P1dB)		> 35		dBm
IM3 @ 120mA, POUT/tone = 30dBm		-25		dBc
IM5 @ 120mA, POUT/tone = 30dBm		-33		dBc
Small Signal Gain Temperature Coefficient		-0.03		dB/°C
Output Power Temperature Coefficient		-0.007		dBm/°C
Recommended Operating Voltage:		40	48	V

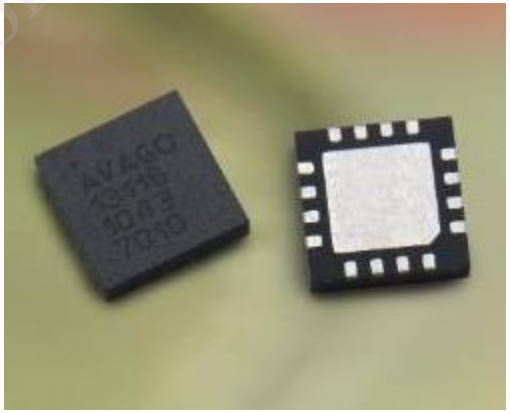
1. Introduction

❖ Low Noise Amplifiers: Optimized for low noise and high gain

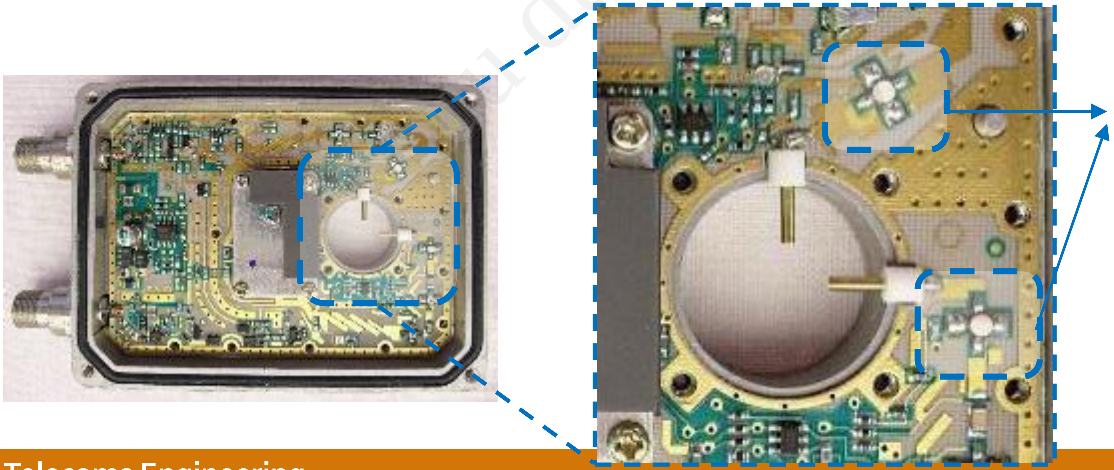


Connectorized 2.3 – 2.7-GHz LNA module with 0.8-dB NF (AdaptiveRF, UK)

Waveguide LNA modules up to 100 GHz (NRAO, US)



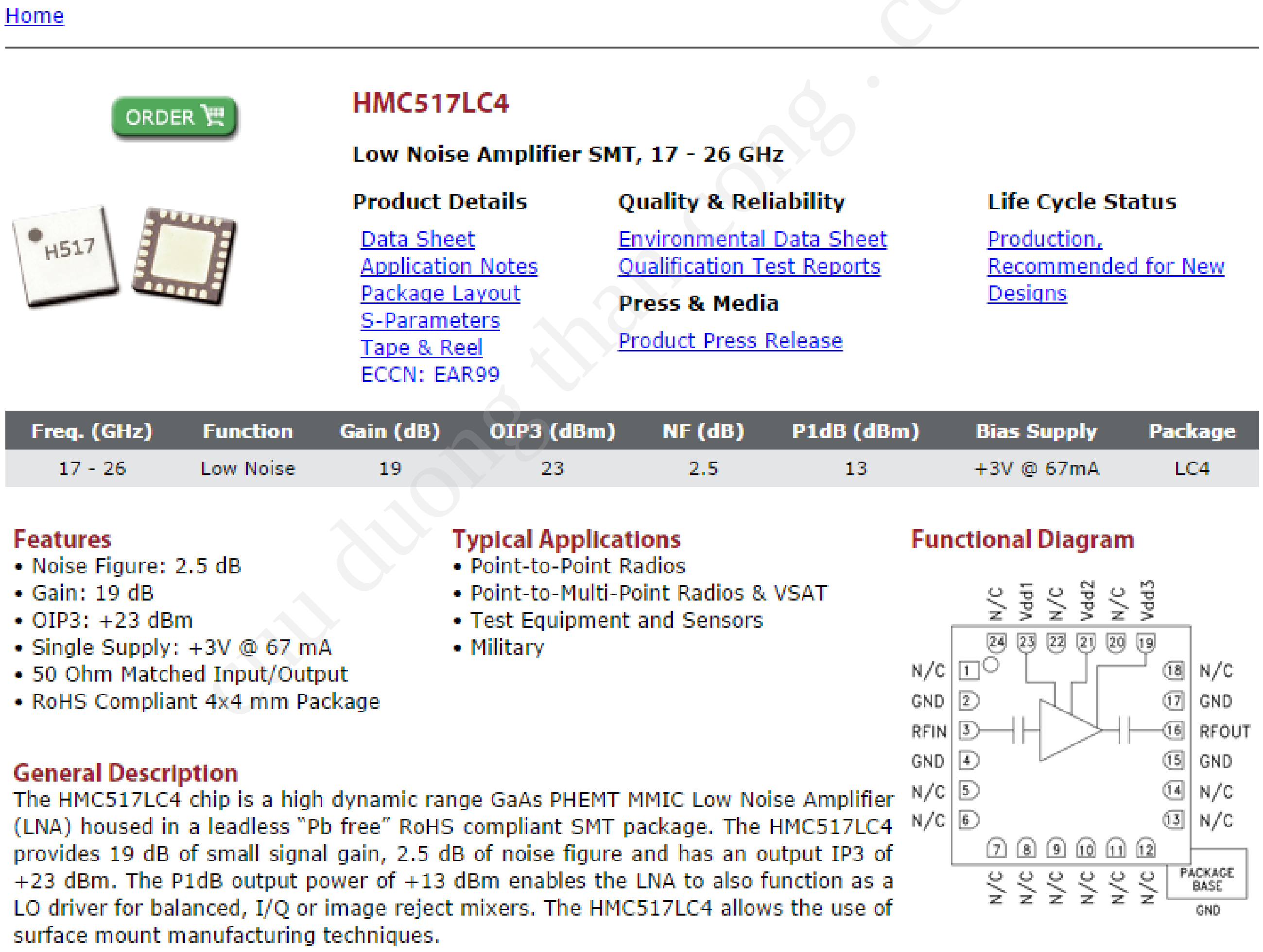
Packaged LNA IC with 0.27-dB NF (Avago, US)



LNA circuits of a microwave receiver implemented on PCB; They are easily recognizable as the first block after the antenna feeds (this is a dual-polarization system so there are two feeds)

1. Introduction

- An example of Low Noise Amplifier: Hittite HMC517LC4.



Home

ORDER

HMC517LC4

Low Noise Amplifier SMT, 17 - 26 GHz

Product Details

Data Sheet
Application Notes
Package Layout
S-Parameters
Tape & Reel
ECCN: EAR99

Quality & Reliability

Environmental Data Sheet
Qualification Test Reports

Press & Media

Product Press Release

Life Cycle Status

Production, Recommended for New Designs

Freq. (GHz)	Function	Gain (dB)	OIP3 (dBm)	NF (dB)	P1dB (dBm)	Bias Supply	Package
17 - 26	Low Noise	19	23	2.5	13	+3V @ 67mA	LC4

Features

- Noise Figure: 2.5 dB
- Gain: 19 dB
- OIP3: +23 dBm
- Single Supply: +3V @ 67 mA
- 50 Ohm Matched Input/Output
- RoHS Compliant 4x4 mm Package

Typical Applications

- Point-to-Point Radios
- Point-to-Multi-Point Radios & VSAT
- Test Equipment and Sensors
- Military

General Description

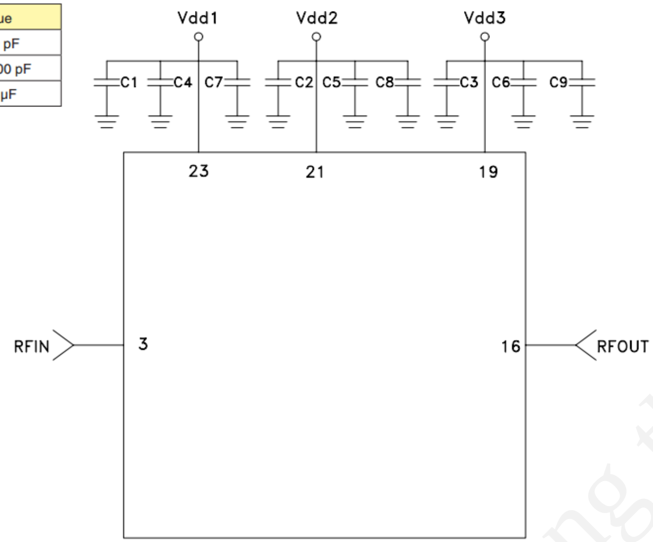
The HMC517LC4 chip is a high dynamic range GaAs PHEMT MMIC Low Noise Amplifier (LNA) housed in a leadless "Pb free" RoHS compliant SMT package. The HMC517LC4 provides 19 dB of small signal gain, 2.5 dB of noise figure and has an output IP3 of +23 dBm. The P1dB output power of +13 dBm enables the LNA to also function as a LO driver for balanced, I/Q or image reject mixers. The HMC517LC4 allows the use of surface mount manufacturing techniques.

Functional Diagram

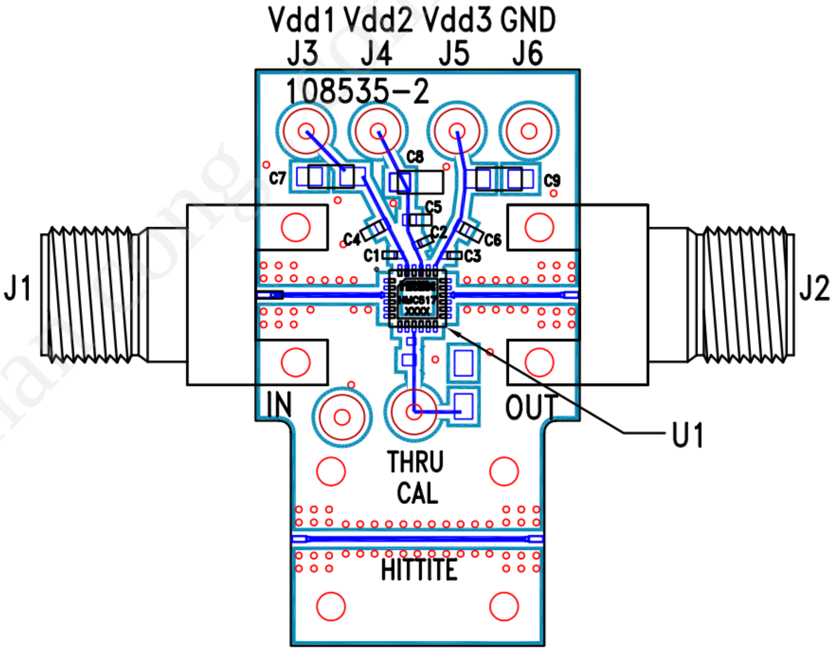
1. Introduction

Application Circuit

Component	Value
C1, C2, C3	100 pF
C4, C5, C6	1,000 pF
C7, C8, C9	2.2 µF



Evaluation PCB



List of Materials for Evaluation PCB 108537 [1]

Item	Description
J1 - J2	PCB Mount K Connector
J3 - J6	DC Pin
C1 - C3	100 pF Capacitor, 0402 Pkg.
C4 - C6	1,000 pF Capacitor, 0603 Pkg.
C7 - C9	2.2 µF Capacitor, Tantalum
U1	HMC517LC4 Amplifier
PCB [2]	108535 Evaluation PCB

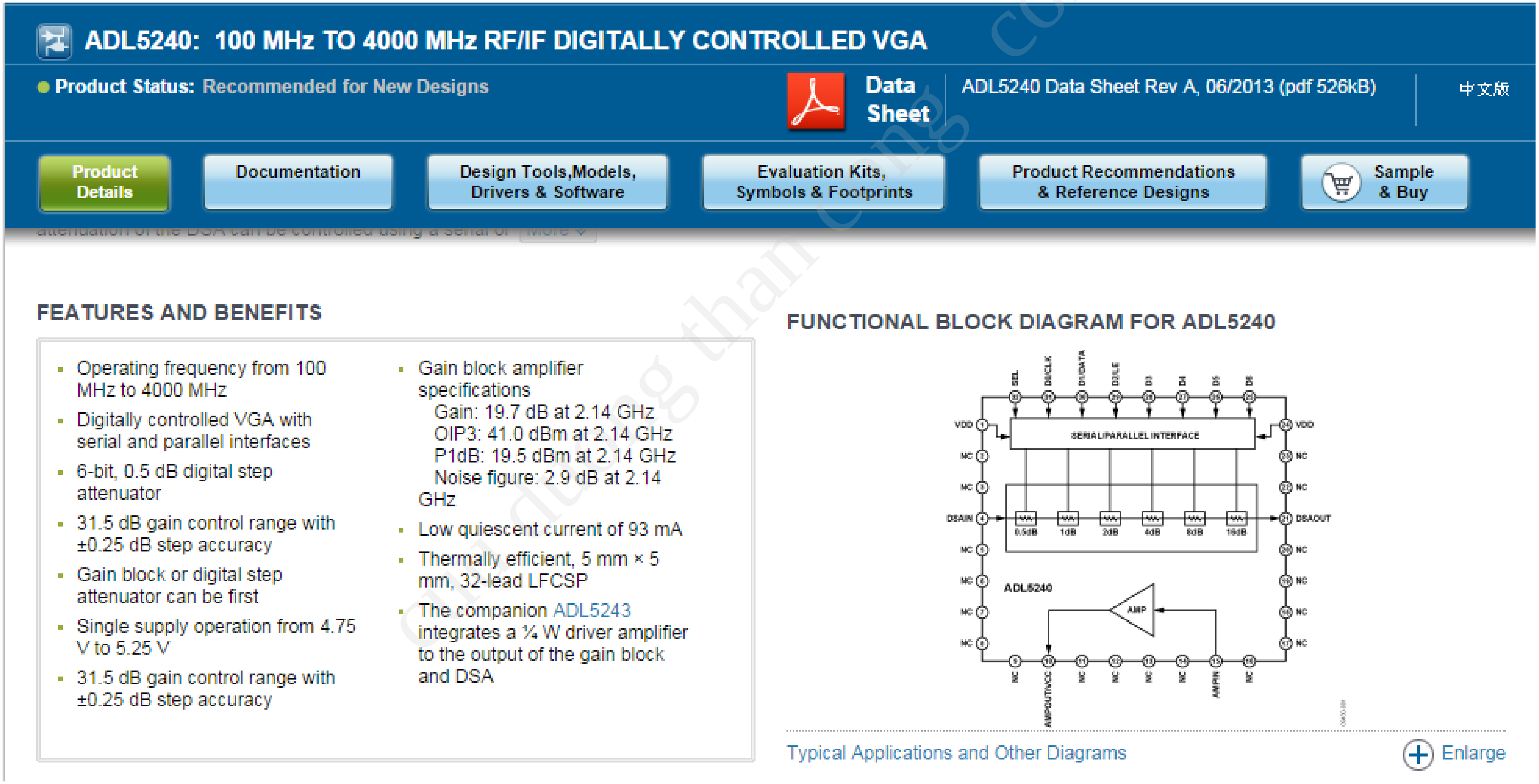
[1] Reference this number when ordering complete evaluation PCB

[2] Circuit Board Material: Rogers 4350

The circuit board used in the application should use RF circuit design techniques. Signal lines should have 50 Ohm impedance while the package ground leads and exposed paddle should be connected directly to the ground plane similar to that shown. A sufficient number of via holes should be used to connect the top and bottom ground planes. The evaluation board should be mounted to an appropriate heat sink. The evaluation circuit board shown is available from Hittite upon request.

1. Introduction

❖ Variable Gain Amplifier: Analog Devices ADL5240.



ADL5240: 100 MHz TO 4000 MHz RF/IF DIGITALLY CONTROLLED VGA

● **Product Status:** Recommended for New Designs

Data Sheet ADL5240 Data Sheet Rev A, 06/2013 (pdf 526kB) 中文版

attenuation of the DSA can be controlled using a serial or

FEATURES AND BENEFITS

- Operating frequency from 100 MHz to 4000 MHz
- Digitally controlled VGA with serial and parallel interfaces
- 6-bit, 0.5 dB digital step attenuator
- 31.5 dB gain control range with ±0.25 dB step accuracy
- Gain block or digital step attenuator can be first
- Single supply operation from 4.75 V to 5.25 V
- 31.5 dB gain control range with ±0.25 dB step accuracy
- Gain block amplifier specifications
  Gain: 19.7 dB at 2.14 GHz
  OIP3: 41.0 dBm at 2.14 GHz
  P1dB: 19.5 dBm at 2.14 GHz
  Noise figure: 2.9 dB at 2.14 GHz
- Low quiescent current of 93 mA
- Thermally efficient, 5 mm × 5 mm, 32-lead LFCSP
- The companion ADL5243 integrates a ¼ W driver amplifier to the output of the gain block and DSA

FUNCTIONAL BLOCK DIAGRAM FOR ADL5240

Typical Applications and Other Diagrams

1. Introduction

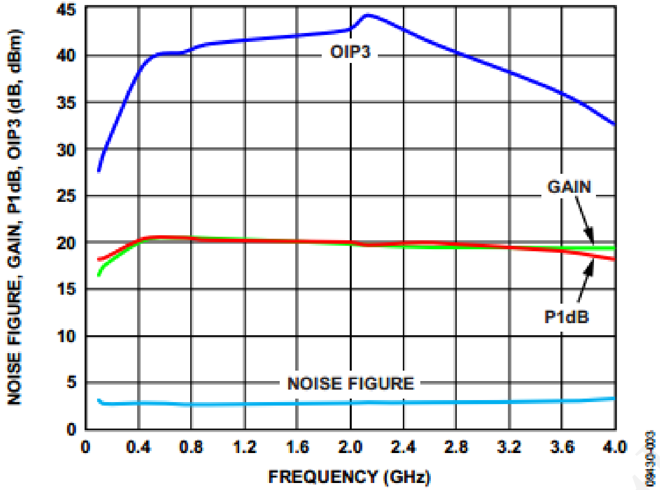


Figure 3. AMP: Gain, P1dB, OIP3 at P_{OUT} = 4 dBm/Tone and Noise Figure vs. Frequency

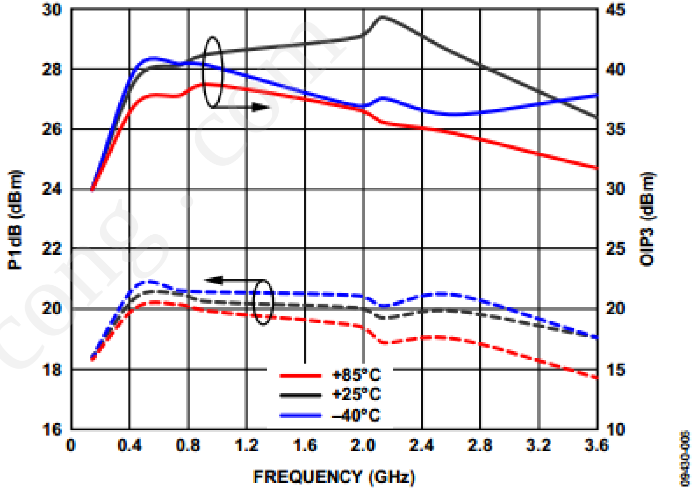


Figure 6. AMP: OIP3 at P_{OUT} = 4 dBm/Tone and P1dB vs. Frequency and Temperature

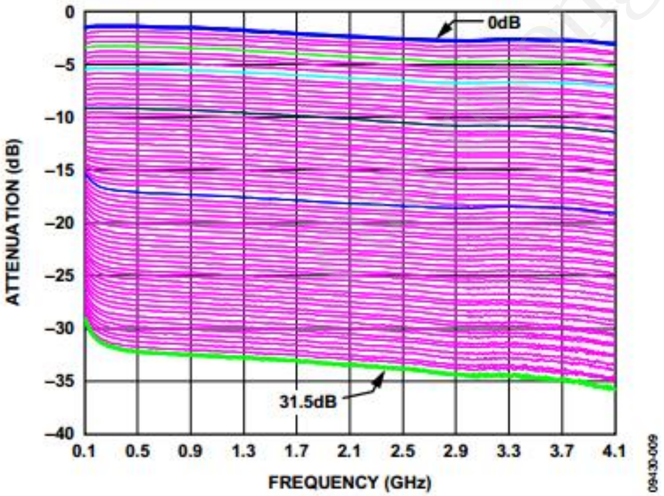


Figure 9. DSA: Attenuation vs. Frequency

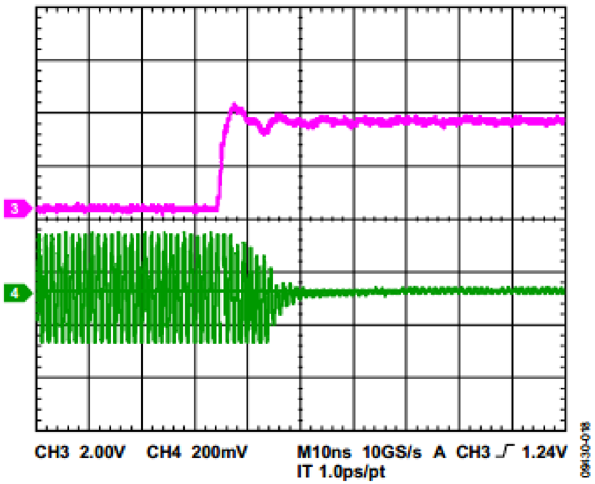


Figure 18. DSA: Gain Settling Time, 0 dB to 31.5 dB

2. Transducer Power Gain

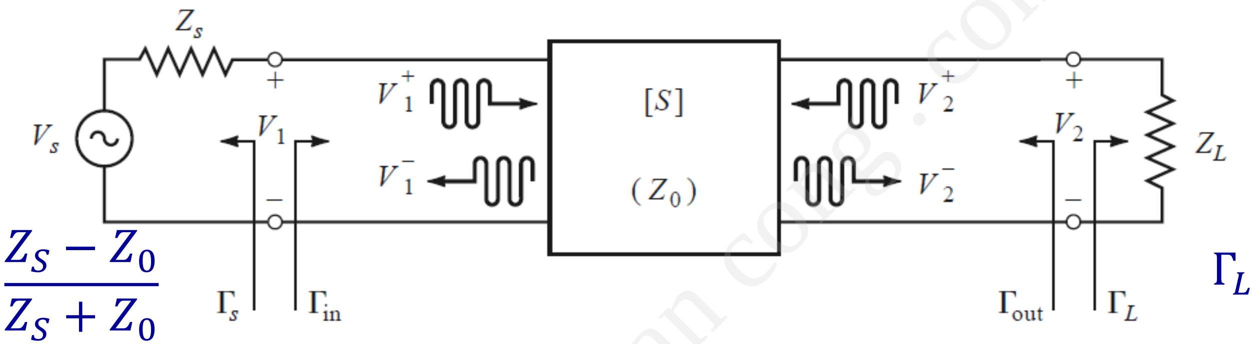
Typical Common Source S-Parameters and noise data

$V_{DS} = 3$ V $I_D = 180$ mA $Z_o = 50\ \Omega$

Freq. [GHz]	|S11|	<S11	|S21|	<S21	|S12|	<S12	|S22|	<S22
100	0.992	-13.3	10.120	170.7	0.008	101.1	0.115	-34.6
200	0.974	-26.4	9.778	162.6	0.014	74.1	0.140	-57.5
300	0.950	-38.6	9.278	154.7	0.021	74.0	0.171	-72.3
400	0.922	-49.5	8.683	147.8	0.025	68.0	0.200	-82.0
500	0.896	-59.1	8.042	141.8	0.031	64.8	0.226	-89.1
600	0.871	-67.1	7.444	137.0	0.033	63.0	0.248	-93.8
700	0.849	-74.0	6.880	132.5	0.036	60.6	0.267	-96.9
800	0.828	-79.9	6.373	129.1	0.038	60.2	0.284	-98.8
900	0.813	-85.0	5.900	125.9	0.039	59.1	0.299	-100.1
1,000	0.800	-89.2	5.485	123.4	0.041	59.5	0.312	-100.4
1,100	0.790	-92.6	5.110	121.3	0.041	59.4	0.323	-100.5
1,200	0.780	-95.5	4.780	119.3	0.043	60.2	0.335	-100.0
1,300	0.773	-97.7	4.498	117.7	0.043	61.6	0.345	-99.3
1,400	0.766	-99.6	4.225	116.2	0.044	62.3	0.354	-98.2
1,500	0.760	-100.9	3.987	115.3	0.045	64.1	0.364	-97.1
1,600	0.754	-102.0	3.769	114.4	0.045	65.9	0.372	-95.7
1,700	0.751	-102.7	3.588	113.6	0.045	67.7	0.380	-94.3
1,800	0.748	-103.3	3.426	112.9	0.046	70.0	0.388	-92.6
1,900	0.743	-103.5	3.268	112.3	0.046	71.8	0.397	-90.9
2,000	0.741	-103.8	3.119	111.7	0.047	74.525	0.404	-89.2

2. Transducer Power Gain

- Definition of Two-port power gains:



$$\Gamma_S = \frac{V_1^+}{V_1^-} = \frac{Z_S - Z_0}{Z_S + Z_0}$$

$$\Gamma_L = \frac{V_2^+}{V_2^-} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

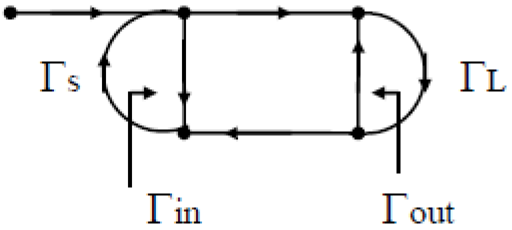
A two-port network with arbitrary source and load impedances.

- Transducer power gain: $G_T = {}^{P_L}/_{P_{avs}}$ is the ratio of the power delivered to the load to the power available from the source. This depends on both Z_S and Z_L where:

$$P_{avs} = P_{in}\Big|_{\Gamma_{in}=\Gamma_S^*}$$

$$\Gamma_{in} = \frac{V_1^-}{V_1^+} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}$$

$$\Gamma_{out} = \frac{V_2^-}{V_2^+} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S}$$



2. Transducer Power Gain

- The voltage at input port is given by

$$V_1 = V_S \frac{Z_{in}}{Z_{in} + Z_S} = V_1^+ + V_1^- = V_1^+(1 + \Gamma_{in}) \quad \rightarrow V_1^+ = \frac{V_S}{(1 + \Gamma_{in})} \frac{Z_{in}}{Z_{in} + Z_S} = \frac{V_S}{2} \frac{1 - \Gamma_S}{1 - \Gamma_S \Gamma_{in}}$$

- The average power deliver to the network is

$$P_{in} = \frac{1}{2Z_o} |V_1^+|^2 (1 - |\Gamma_{in}|^2) = \frac{|V_S|^2}{8Z_o} \frac{|1 - \Gamma_S|^2}{|1 - \Gamma_S \Gamma_{in}|^2} (1 - |\Gamma_{in}|^2)$$

- The average power deliver to the load is

$$P_L = \frac{1}{2Z_o} |V_2^-|^2 (1 - |\Gamma_L|^2) = \frac{|V_1^+|^2}{2Z_o} \frac{|S_{21}|^2}{|1 - S_{22}\Gamma_L|^2} (1 - |\Gamma_L|^2)$$

$$= \frac{|V_S|^2}{8Z_o} \frac{|S_{21}|^2 (1 - |\Gamma_L|^2) |1 - \Gamma_S|^2}{|1 - S_{22}\Gamma_L|^2 |1 - \Gamma_S \Gamma_{in}|^2}$$

2. Transducer Power Gain

- The power gain can be expressed as: $G = \dfrac{P_L}{P_{in}} = \dfrac{|S_{21}|^2(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2|1-\Gamma_{in}|^2}$

- The power available from the source, P_{avs}, is the maximum power that can be delivered to the network. This occurs when the input impedance of the terminated network is conjugately matched to the source impedance:

$$P_{avs} = P_{in}\Big|_{\Gamma_{in}=\Gamma_S^*} = \frac{|V_S|^2}{8Z_o}\frac{|1-\Gamma_S|^2}{(1-|\Gamma_S|^2)}$$

$$P_{avn} = P_L\Big|_{\Gamma_L=\Gamma_{out}^*} = \frac{|V_S|^2}{8Z_o}\frac{|S_{21}|^2|1-\Gamma_S|^2(1-|\Gamma_{out}|^2)}{|1-S_{22}\Gamma_{out}^*|^2|1-\Gamma_S\Gamma_{in}|^2}$$

where: $\Gamma_{in} = S_{11} + \dfrac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}$ $\rightarrow |1-\Gamma_S\Gamma_{in}|^2\Big|_{\Gamma_L=\Gamma_{out}^*} = \dfrac{|1-S_{11}\Gamma_S|^2(1-|\Gamma_{out}|^2)^2}{|1-S_{22}\Gamma_{out}^*|^2}$

- Then: $P_{avn} = \dfrac{|V_S|^2}{8Z_o}\dfrac{|S_{21}|^2|1-\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2(1-|\Gamma_{out}|^2)}$

2. Transducer Power Gain

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

- Transducer power gain: $$G_T = \frac{P_L}{P_{avs}} = \frac{(1-|\Gamma_S|^2)}{|1-\Gamma_S\Gamma_{in}|^2}|S_{21}|^2\frac{(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2} = G_S G_0 G_L$$

- Both input and output are matched for zero reflection: $\Gamma_L = \Gamma_S = 0$: $G_T = |S_{21}|^2$

- If $\Gamma_{in} = \Gamma_S^*$ and $\Gamma_{out} = \Gamma_L^*$: $$G_{Tmax} = \frac{1}{(1-|\Gamma_S|^2)}|S_{21}|^2\frac{(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2}$$

- If $S_{12} = 0$: unilateral transducer power gain: $$G_{TU} = \frac{(1-|\Gamma_S|^2)}{|1-S_{11}\Gamma_S|^2}|S_{21}|^2\frac{(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2}$$
  - If $\Gamma_S = S_{11}^*$ and $\Gamma_L = S_{22}^*$: $$G_{TUmax} = \frac{1}{1-|S_{11}|^2}|S_{21}|^2\frac{1}{1-|S_{22}|^2}$$

2. Transducer Power Gain

Example 1: A silicon BJT has the following scattering parameters at 1.0GHz with a 50Ω reference impedance:

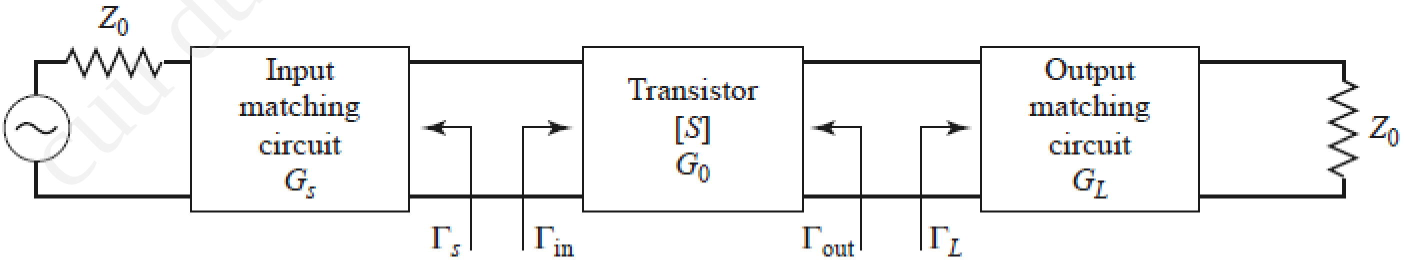
$$[S] = \begin{bmatrix} 0.38\angle -150^0 & 0.11\angle 54^0 \\ 3.5\angle 80^0 & 0.4\angle -43^0 \end{bmatrix}$$

The source impedance is 50Ω and the load impedance is 40Ω. Compute the power gain $G = {}^{P_L}/_{P_{in}}$, the available power gain $G_A = {}^{P_{avn}}/_{P_{avs}}$ and the transducer power gain $G_T = {}^{P_L}/_{P_{avs}}$.

$G = 13.1$

$G_A = 19.8$

$G_T = 12.6$



3. Stability

- Oscillation is possible if either the input or output port impedance has a negative real part. This would then imply $|\Gamma_{in}| < 1$ and $|\Gamma_{out}| < 1$

- Unconditional Stability: $|\Gamma_{in}| < 1$ and $|\Gamma_{out}| < 1$ for ALL passive source impedance and load impedance.
- Conditional Stability: $|\Gamma_{in}| < 1$ and $|\Gamma_{out}| < 1$ for a certain range of passive source impedance and load impedance.

- Stability condition is frequency dependent. Hence an amplifier may be stable in the design frequency but unstable at other frequencies.

- Unconditional Stability:

$$|\Gamma_{in}| = \left| S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \right| < 1 \quad \xrightarrow{if\, S_{12}=0} \quad |S_{11}| < 1$$

$$|\Gamma_{out}| = \left| S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} \right| < 1 \quad \xrightarrow{if\, S_{12}=0} \quad |S_{22}| < 1$$

3. Stability

- **Output Stability: $|\Gamma_{in}| < 1$**
- $|\Gamma_{in}| = 1$ is the border between stable and unstable region.

$$|\Gamma_{in}| = \left| S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \right| = 1 \longrightarrow |S_{11}(1 - S_{22}\Gamma_L) + S_{12}S_{21}\Gamma_L| = |1 - S_{22}\Gamma_L|$$

$$\longrightarrow \quad |S_{11} - \Delta\Gamma_L|^2 = |1 - S_{22}\Gamma_L|^2 \qquad \text{where: } \Delta = S_{11}S_{22} - S_{12}S_{21}$$

$$\longrightarrow \quad (S_{11} - \Delta\Gamma_L)(S_{11} - \Delta\Gamma_L)^* = (1 - S_{22}\Gamma_L)(1 - S_{22}\Gamma_L)^*$$

$$\longrightarrow \quad |S_{11}|^2 - |\Delta|^2|\Gamma_L|^2 - (\Delta\Gamma_L S_{11}^* + \Delta^*\Gamma_L^* S_{11}) = 1 + |S_{22}|^2|\Gamma_L|^2 - (S_{22}\Gamma_L + S_{22}^*\Gamma_L^*)$$

$$\longrightarrow \quad (|S_{22}|^2 - |\Delta|^2)\Gamma_L\Gamma_L^* - (S_{22} - \Delta S_{11}^*)\Gamma_L - (S_{22}^* - \Delta^* S_{11})\Gamma_L^* = |S_{11}|^2 - 1$$

$$\longrightarrow \quad \Gamma_L\Gamma_L^* - \frac{(S_{22} - \Delta S_{11}^*)\Gamma_L + (S_{22}^* - \Delta^* S_{11})\Gamma_L^*}{(|S_{22}|^2 - |\Delta|^2)} = \frac{|S_{11}|^2 - 1}{(|S_{22}|^2 - |\Delta|^2)}$$

3. Stability

- Adding $|S_{22}-\Delta S_{11}^*|^2/(|S_{22}|^2-|\Delta|^2)^2$ to both side, we get:

$$\left|\Gamma_L-\frac{(S_{22}-\Delta S_{11}^*)^*}{|S_{22}|^2-|\Delta|^2}\right|^2=\frac{|S_{11}|^2-1}{(|S_{22}|^2-|\Delta|^2)^2}+\frac{|S_{22}-\Delta S_{11}^*|^2}{(|S_{22}|^2-|\Delta|^2)^2}$$

- In the complex Γ plane, this defines the output stability circle with a center C_L and radius R_L:

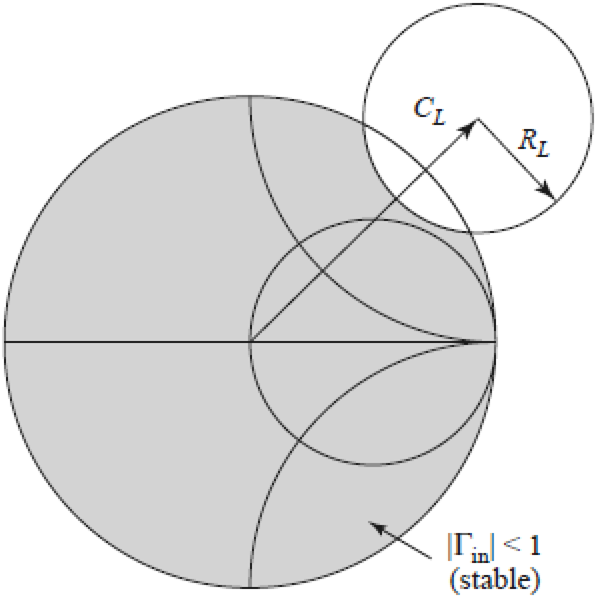
$$C_L=\frac{(S_{22}-\Delta S_{11}^*)^*}{|S_{22}|^2-|\Delta|^2} \qquad R_L=\left|\frac{S_{12}S_{21}}{(|S_{22}|^2-|\Delta|^2)}\right|$$

- Similar results can be obtained for the input stability circle:

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

3. Stability

- Given S parameters of the device, we can plot output and input stability circles to define where $|\Gamma_{in}| = 1$ and $|\Gamma_{out}| = 1$.
- If we set $Z_L = Z_0$: $\Gamma_L = 0$ and $|\Gamma_{in}| = |S_{11}|$
- $\Gamma_L = 0$ is the center of the Smith Chart. It will be used as the reference point to determine the stable region.
- **Case A:** If the output stability circle does not include the center of the Smith Chart
- **Case A1:** $S_{11} < 1 \longrightarrow |\Gamma_{in}| < 1$
  - The center of the Smith Chart must be in the stable region.
  - All of the Smith Chart defines the stable range for Γ_L

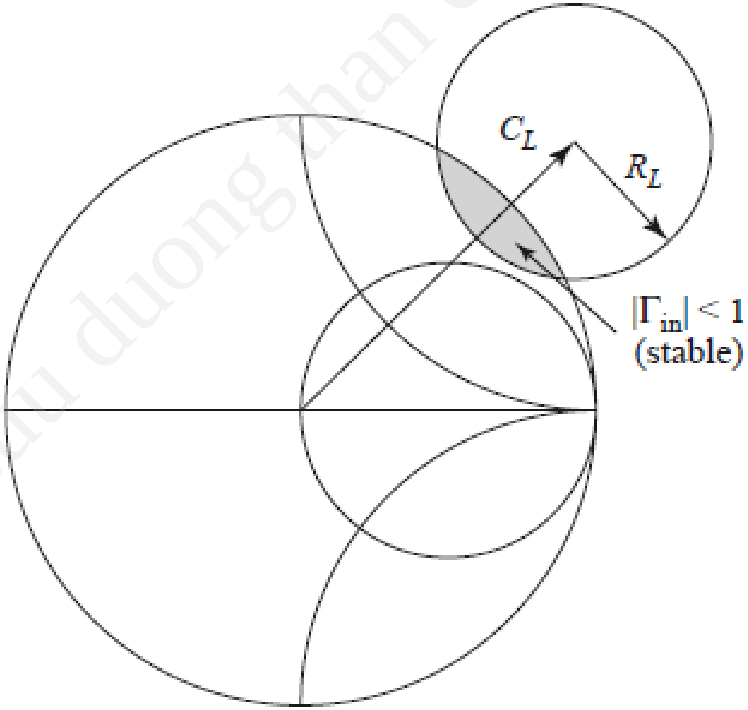


(a)

3. Stability

❖ **Case A2:** $S_{11} > 1 \longrightarrow |\Gamma_{in}| > 1$

- ○ The center of the Smith Chart must be in the unstable region.
- ○ The stable region is the inside region of the stability circle that intersects the Smith Chart.



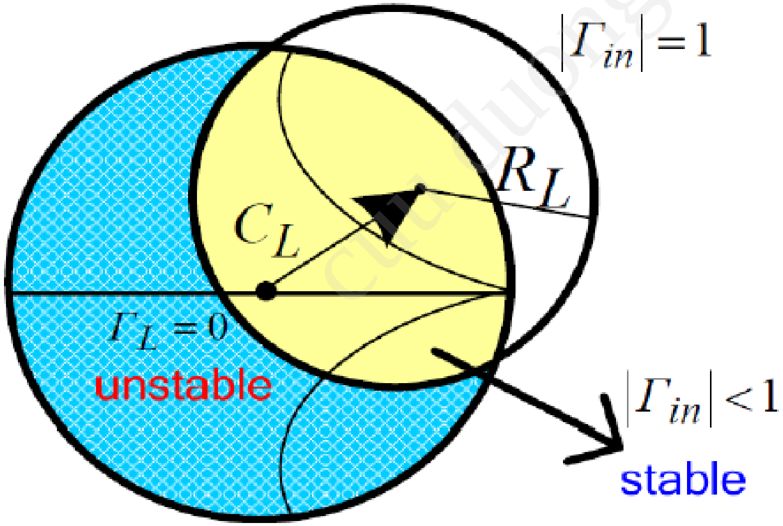
(b)

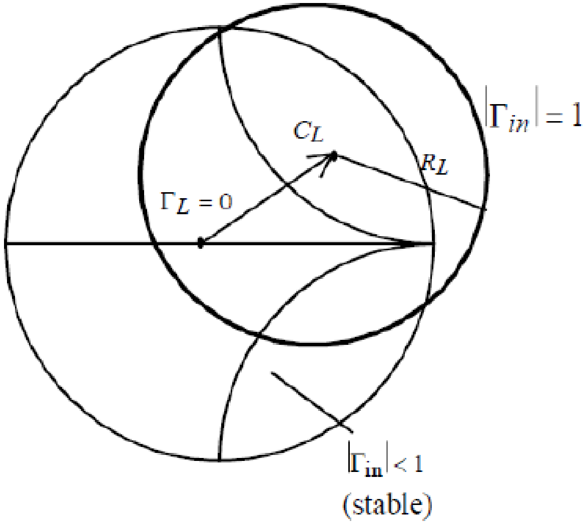
3. Stability

- **Case B:** If the output stability circle include the center of the Smith Chart

- **Case B1:** $S_{11} < 1 \longrightarrow |\Gamma_{in}| < 1$
  - The center of the Smith Chart must be in the stable region.
  - All of the Smith Chart that is inside region of the stability circles define the stable range for Γ_L

- **Case B2:** $S_{11} > 1 \longrightarrow |\Gamma_{in}| > 1$
  - The center of the Smith Chart must be in the unstable region.
  - The stable region is exterior to the stability circle that intersects the Smith Chart.





3. Stability

- Tests for Unconditional Stability:
  - $K-\Delta$ test: the device will be unconditional stability if Rollet's conditions are satified

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

$$|\Delta|=|S_{11}S_{22}-S_{12}S_{21}|<1$$

  - μ test: new criterion that can be used to compare the stability between two devices

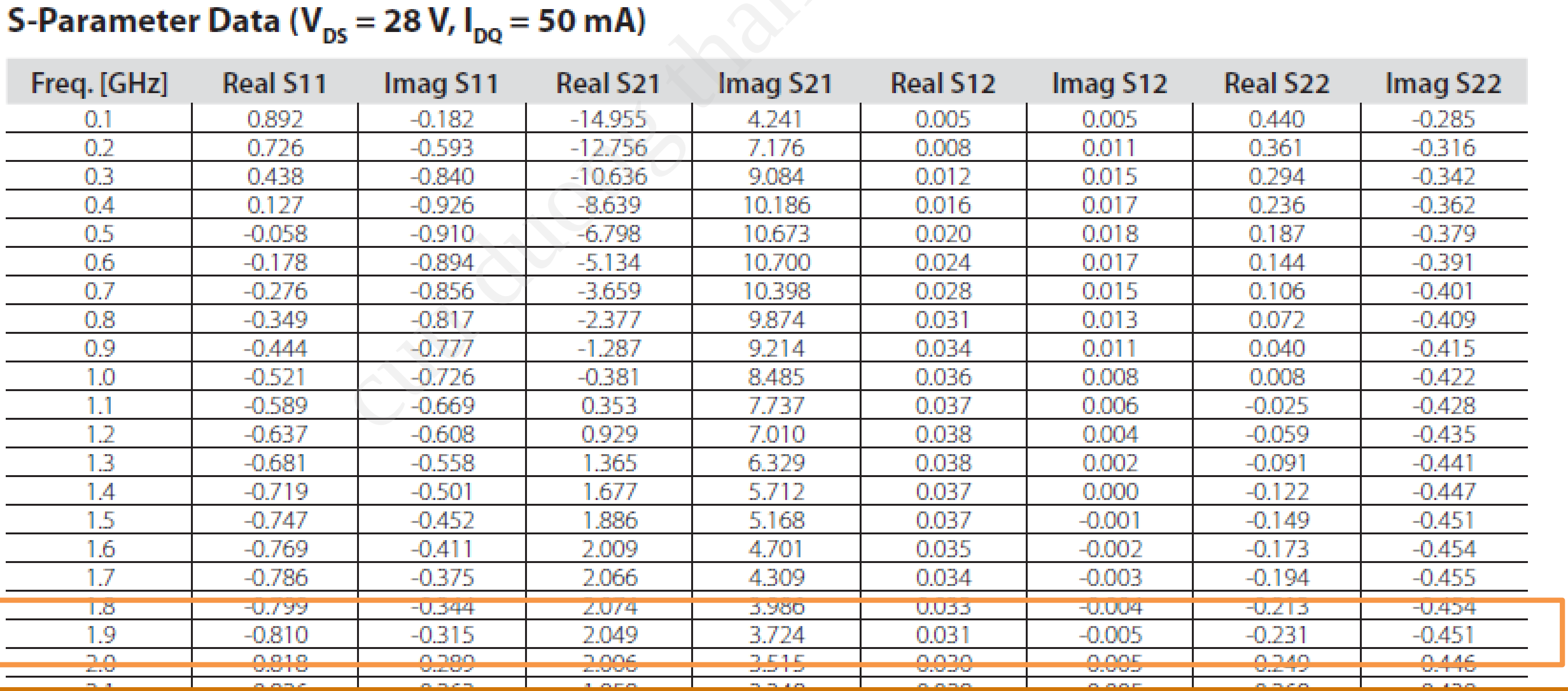
$$\mu=\frac{1-|S_{11}|^2}{|S_{22}-\Delta S_{11}^*|+|S_{12}S_{21}|}>1$$

3. Stability

Example 2: The Triquint T1G6000528 GaN HEMT has the following scattering parameters at 1.9 GHz ($Z_0 = 50\Omega$):

$$[S] = \begin{bmatrix} 0.869\angle -159^0 & 0.031\angle -9^0 \\ 4.25\angle 61^0 & 0.507\angle -117^0 \end{bmatrix}$$

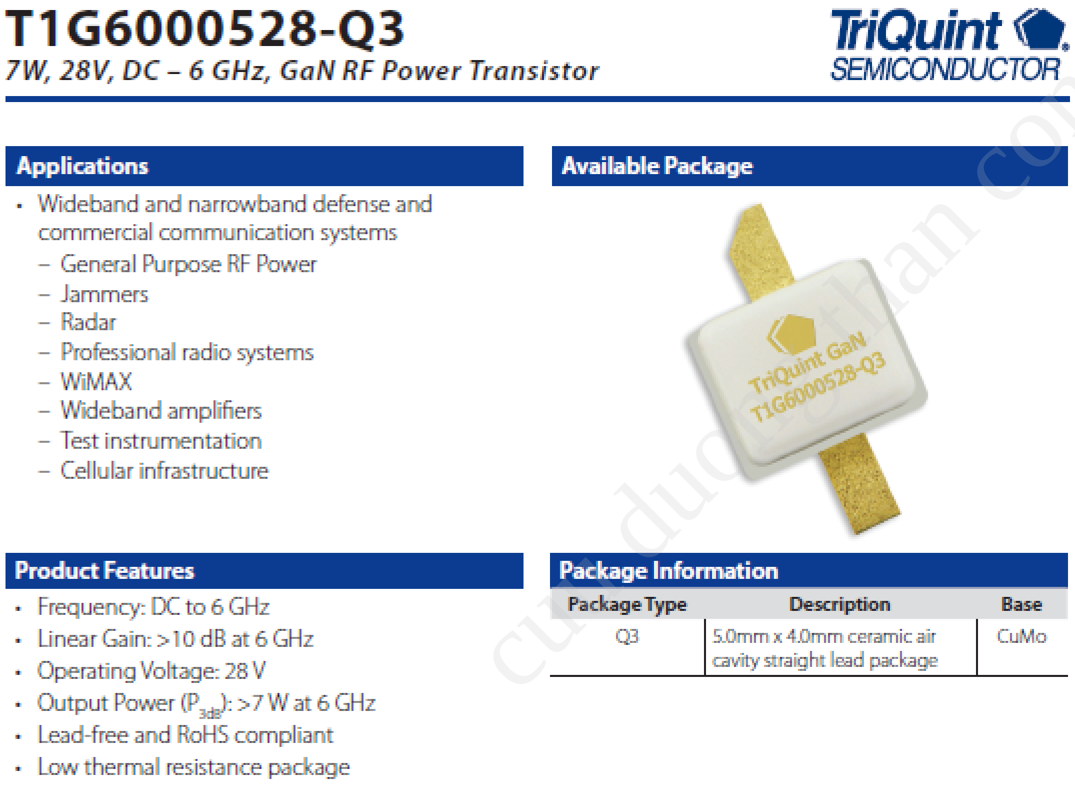
Determine the stability of this transistor by using the $K-\Delta$ test and μ test. Plot the stability circles on a Smith chart.



S-Parameter Data (V_{DS} = 28 V, I_{DQ} = 50 mA)

Freq. [GHz]	Real S11	Imag S11	Real S21	Imag S21	Real S12	Imag S12	Real S22	Imag S22
0.1	0.892	-0.182	-14.955	4.241	0.005	0.005	0.440	-0.285
0.2	0.726	-0.593	-12.756	7.176	0.008	0.011	0.361	-0.316
0.3	0.438	-0.840	-10.636	9.084	0.012	0.015	0.294	-0.342
0.4	0.127	-0.926	-8.639	10.186	0.016	0.017	0.236	-0.362
0.5	-0.058	-0.910	-6.798	10.673	0.020	0.018	0.187	-0.379
0.6	-0.178	-0.894	-5.134	10.700	0.024	0.017	0.144	-0.391
0.7	-0.276	-0.856	-3.659	10.398	0.028	0.015	0.106	-0.401
0.8	-0.349	-0.817	-2.377	9.874	0.031	0.013	0.072	-0.409
0.9	-0.444	-0.777	-1.287	9.214	0.034	0.011	0.040	-0.415
1.0	-0.521	-0.726	-0.381	8.485	0.036	0.008	0.008	-0.422
1.1	-0.589	-0.669	0.353	7.737	0.037	0.006	-0.025	-0.428
1.2	-0.637	-0.608	0.929	7.010	0.038	0.004	-0.059	-0.435
1.3	-0.681	-0.558	1.365	6.329	0.038	0.002	-0.091	-0.441
1.4	-0.719	-0.501	1.677	5.712	0.037	0.000	-0.122	-0.447
1.5	-0.747	-0.452	1.886	5.168	0.037	-0.001	-0.149	-0.451
1.6	-0.769	-0.411	2.009	4.701	0.035	-0.002	-0.173	-0.454
1.7	-0.786	-0.375	2.066	4.309	0.034	-0.003	-0.194	-0.455
1.8	-0.799	-0.344	2.074	3.986	0.033	-0.004	-0.213	-0.454
1.9	-0.810	-0.315	2.049	3.724	0.031	-0.005	-0.231	-0.451
2.0	0.818	0.289	2.006	3.515	0.030	0.005	0.249	0.446

3. Stability



T1G6000528-Q3

7W, 28V, DC – 6 GHz, GaN RF Power Transistor

TriQuint SEMICONDUCTOR

Applications

- Wideband and narrowband defense and commercial communication systems
  - General Purpose RF Power
  - Jammers
  - Radar
  - Professional radio systems
  - WiMAX
  - Wideband amplifiers
  - Test instrumentation
  - Cellular infrastructure

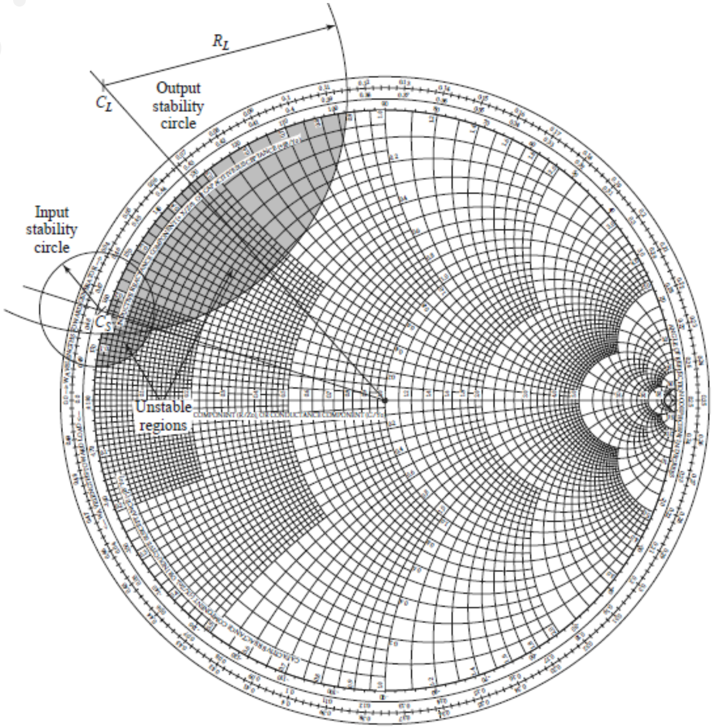
Available Package

Product Features

- Frequency: DC to 6 GHz
- Linear Gain: >10 dB at 6 GHz
- Operating Voltage: 28 V
- Output Power (P_{3dB}): >7 W at 6 GHz
- Lead-free and RoHS compliant
- Low thermal resistance package

Package Information

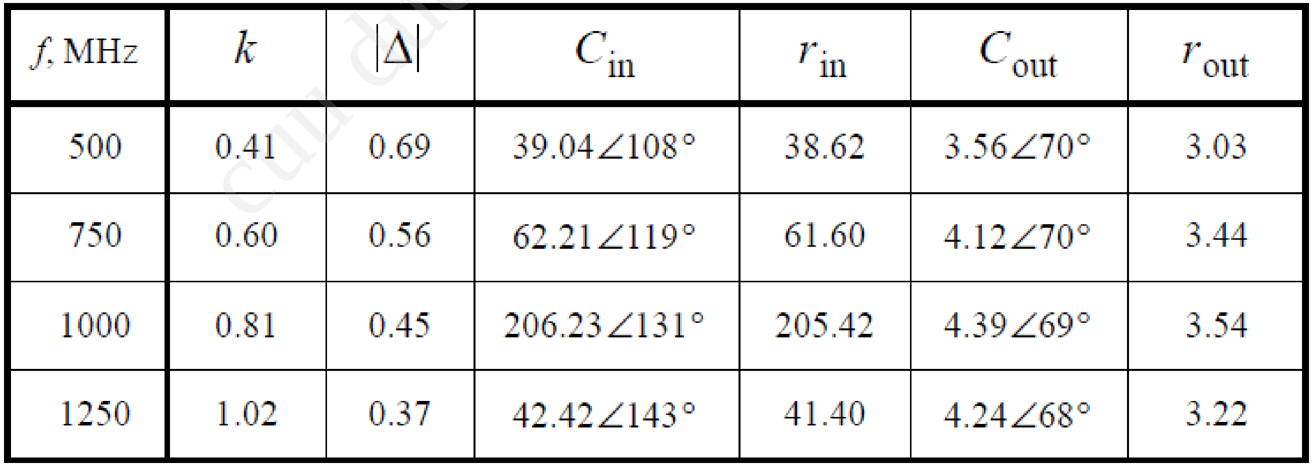
Package Type	Description	Base
Q3	5.0mm x 4.0mm ceramic air cavity straight lead package	CuMo



3. Stability

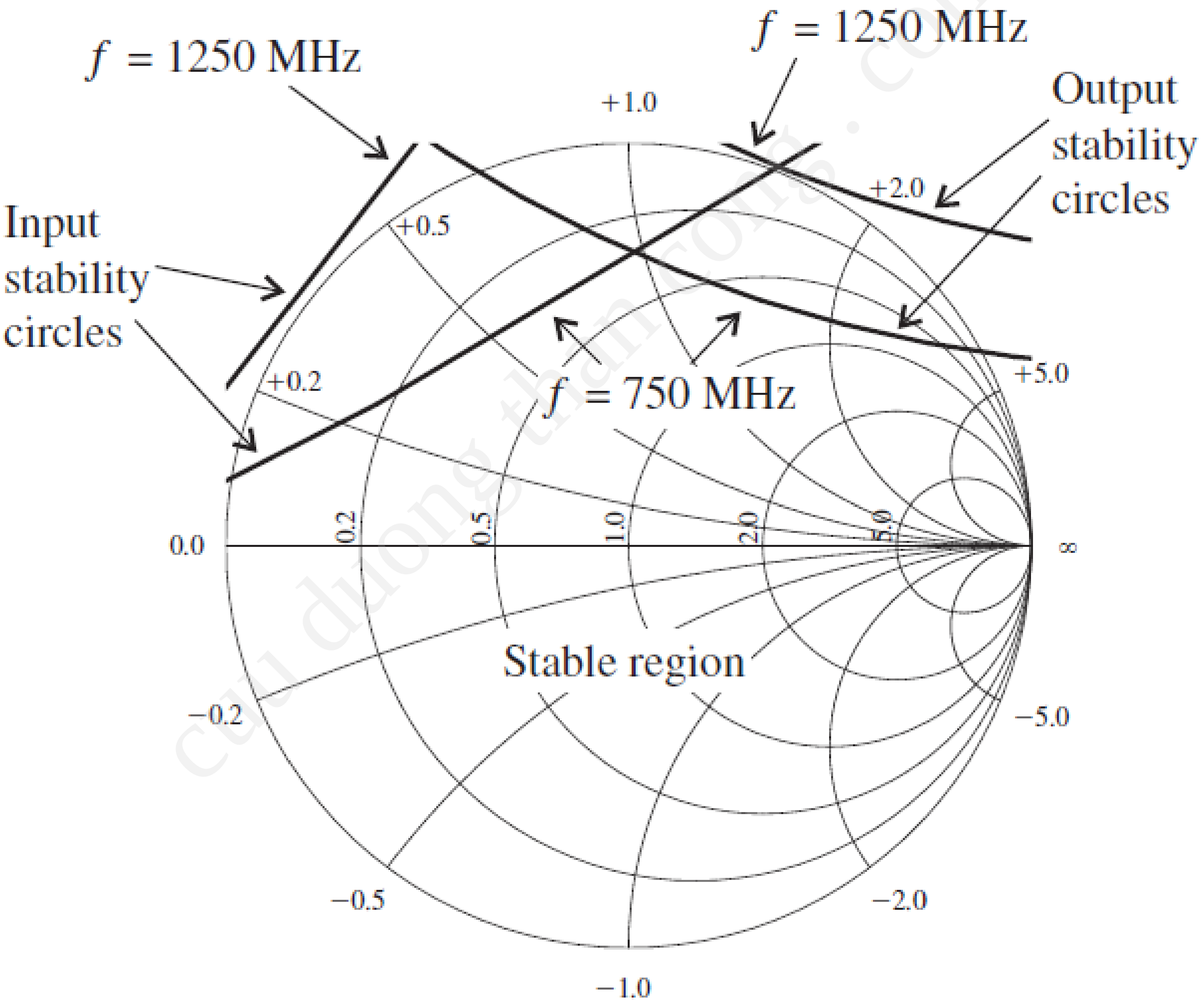
Example 3: Determine the stability regions of the BJT BFG505W (NXP) biased at $V_{CE} = 6V$ and $I_C = 4mA$. The corresponding S-parameters as functions of frequency are given in the following table:

Frequency	S_{11}	S_{12}	S_{21}	S_{22}
$500\ MHz$	$0.70\angle -57^0$	$0.04\angle 47^0$	$10.5\angle 136^0$	$0.79\angle -33^0$
$750\ MHz$	$0.56\angle -78^0$	$0.05\angle 33^0$	$8.6\angle 122^0$	$0.66\angle -42^0$
$1000\ MHz$	$0.46\angle -97^0$	$0.06\angle 22^0$	$7.1\angle 112^0$	$0.57\angle -48^0$
$1250\ MHz$	$0.38\angle -115^0$	$0.06\angle 14^0$	$6.0\angle 104^0$	$0.50\angle -52^0$



f, MHz	k	$\lvert\Delta\rvert$	C_{in}	r_{in}	C_{out}	r_{out}
500	0.41	0.69	$39.04\angle 108°$	38.62	$3.56\angle 70°$	3.03
750	0.60	0.56	$62.21\angle 119°$	61.60	$4.12\angle 70°$	3.44
1000	0.81	0.45	$206.23\angle 131°$	205.42	$4.39\angle 69°$	3.54
1250	1.02	0.37	$42.42\angle 143°$	41.40	$4.24\angle 68°$	3.22

3. Stability

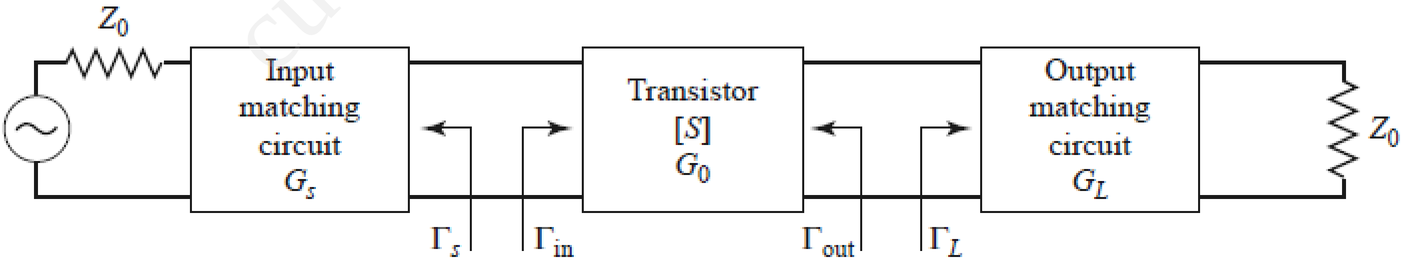

f = 1250 MHz
f = 1250 MHz
Output stability circles
Input stability circles
f = 750 MHz
Stable region
+1.0
+2.0
+0.5
+0.2
+5.0
0.0
0.2
0.5
1.0
2.0
5.0
∞
−0.2
−5.0
−0.5
−2.0
−1.0

4. Maximum Transducer Power Gain Design

- Design Process:
  - ***Step 1:*** Determine the stability of the transistor and the stable regions for Γ_S and Γ_L on the Smith chart.
  - ***Step 2:*** Design the input and output matching sections.
  - ***Step 3:*** Compute maximum gain.

- G_0 is fixed for a given transistor. The overall transducer gain G_T will be controlled by the gain $\boldsymbol{G_S}$ and $\boldsymbol{G_L}$ of the matching sections.

$$G_T = \frac{P_L}{P_{avs}} = \frac{(1-|\Gamma_S|^2)}{|1-\Gamma_S\Gamma_{in}|^2}|S_{21}|^2\frac{(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2} = G_S G_0 G_L$$



4. Maximum Transducer Power Gain Design

- Maximum gain will be realized by conjugate match between the source, load and the transistor.

$$\Gamma_S = \Gamma_{in}^* = \left(S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}\right)^* \qquad \Gamma_L = \Gamma_{out}^* = \left(S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S}\right)^*$$

- Maximum gain will be: $\boldsymbol{G_{Tmax} = \frac{1}{(1 - |\Gamma_S|^2)}|S_{21}|^2 \frac{(1 - |\Gamma_L|^2)}{|1 - S_{22}\Gamma_L|^2}}$

- Γ_S and Γ_L can be solved as:

$$\Gamma_S = \frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2C_1}$$

$$\Gamma_L = \frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2C_2}$$

where

$$B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2$$

$$B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2$$

$$C_1 = S_{11} - \Delta S_{22}^*$$

$$C_2 = S_{22} - \Delta S_{11}^*$$

4. Maximum Transducer Power Gain Design

Example 4: Design an amplifier for maximum gain at 4 GHz using single-stub matching sections. Calculate and plot the input return loss and the gain from 3 to 5 GHz. The transistor is a GaAs MESFET with the following scattering parameters ($Z_0 = 50\Omega$):

f (GHz)	S_{11}	S_{12}	S_{21}	S_{22}
3.0	$0.80\angle{-89°}$	$0.03\angle{56°}$	$2.86\angle{99°}$	$0.76\angle{-41°}$
4.0	$0.72\angle{-116°}$	$0.03\angle{57°}$	$2.60\angle{76°}$	$0.73\angle{-54°}$
5.0	$0.66\angle{-142°}$	$0.03\angle{62°}$	$2.39\angle{54°}$	$0.72\angle{-68°}$

- Design Process:
  - ○ ***Step 1:*** Check stability of the transistor by calculating K and Δ.

f (GHz)	K	Δ
3.0	0.77	0.592
4.0	1.19	0.487
5.0	1.53	0.418

4. Maximum Transducer Power Gain Design

- Design Process:
  - ○ ***Step 2:*** Design matching sections to maximize gain.

$$\Gamma_S = \frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2C_1} = 0.872\angle 123^\circ,$$

$$\Gamma_L = \frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2C_2} = 0.876\angle 61^\circ.$$

  - ○ ***Step 3:*** Compute maximum gain

$$\boldsymbol{G_{Tmax} = \frac{1}{(1-|\Gamma_S|^2)}|S_{21}|^2 \frac{(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2} = G_S G_0 G_L}$$

$$G_S = \frac{1}{(1-|\Gamma_S|^2)} = 4.17 = 6.2dB$$

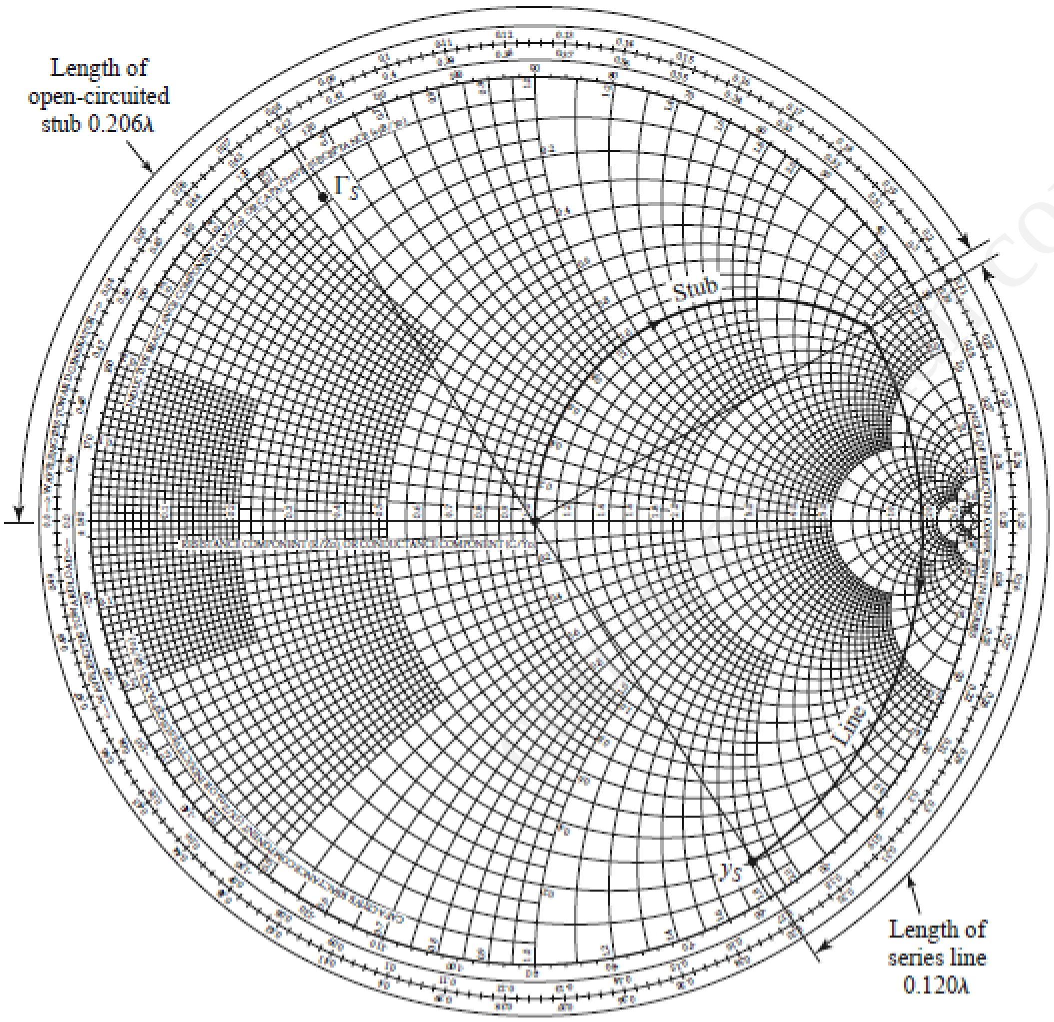
$$G_0 = |S_{21}|^2 = 6.76 = 8.3dB$$

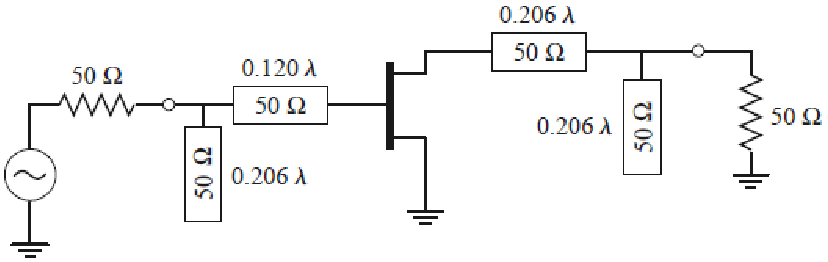
$$G_L = \frac{(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2} = 1.67 = 2.22dB$$

$$\boldsymbol{G_T = 16.7dB}$$

4. Maximum Transducer Power Gain Design

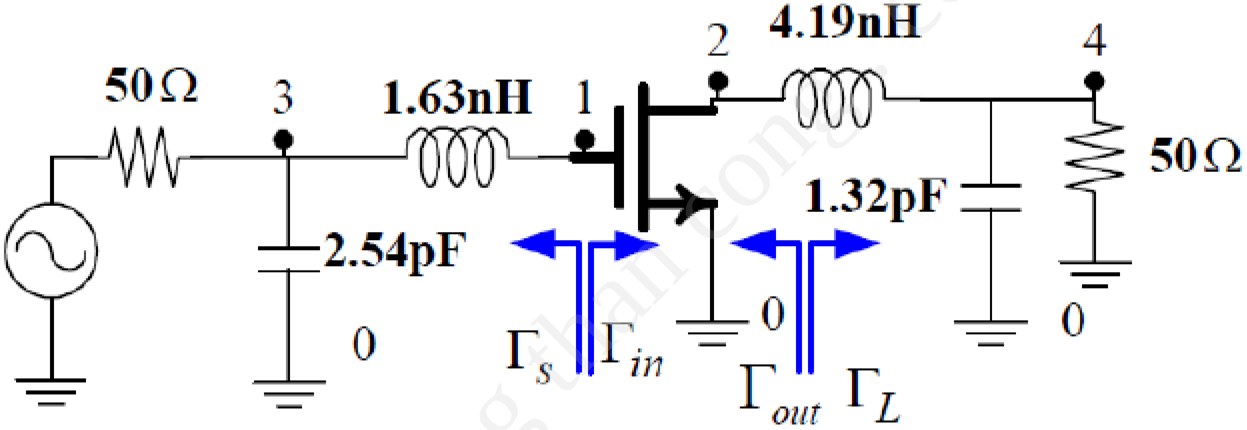
- Matching Network using stubs:





4. Maximum Transducer Power Gain Design

- Matching Network using lumped elements (L-section network)



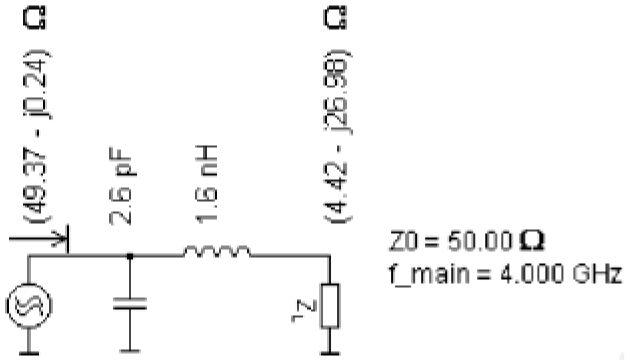
$$\begin{cases}\Gamma_S = 0.872\angle 123^\circ \\ \Gamma_L = 0.876\angle 61^\circ\end{cases}$$

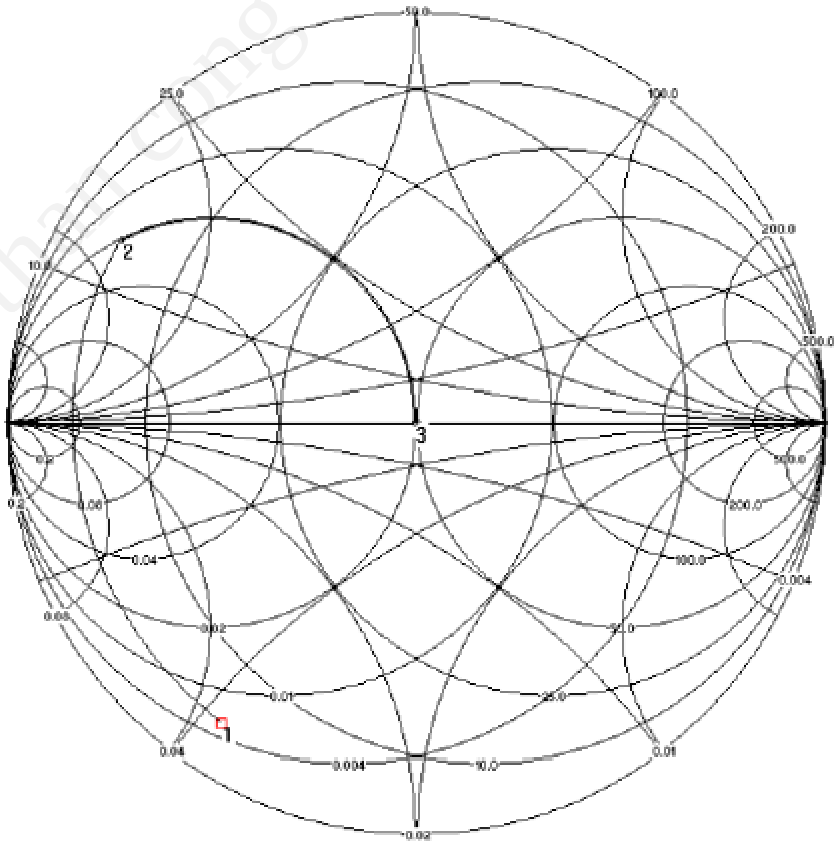
$$\Gamma_{in} = \Gamma_S^* = 0.87\angle -123^o = 4.43 - j26.97$$

$$\Gamma_{out} = \Gamma_L^* = 0.87\angle -61^o = 12.68 - j83.50$$

4. Maximum Transducer Power Gain Design

- Matching Network using lumped elements (L-section network)

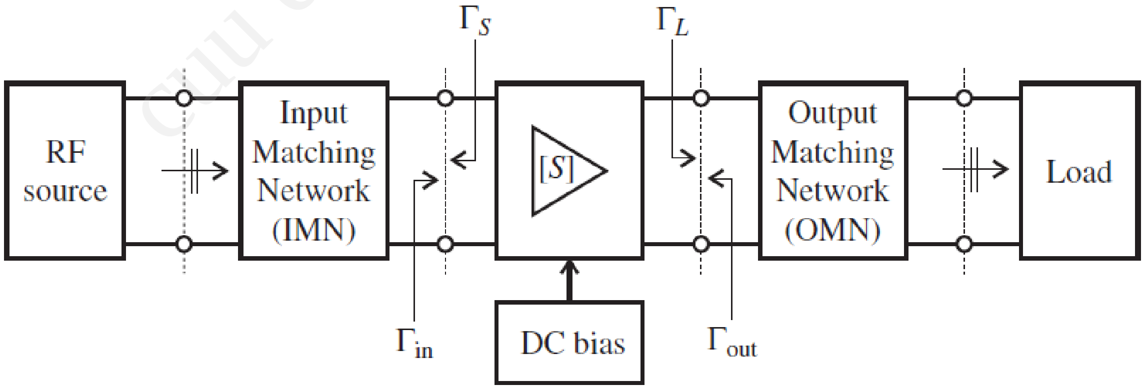




Exercise: Pozar 12.1, 12.2, 12.3, 12.4

5. Constant Gain Circles and Specified Gain Amplifier

- In many cases it is preferable to design for less than the maximum obtainable gain, to improve bandwidth or to obtain a specific value of amplifier gain.
- For these cases, mismatches are purposely introduced.
- Design process:
  - Step 1: Plot constant gain circles on the Smith Chart (loci of Γ_S and Γ_L that give fixed G_S and G_L).
- Two scenarios:
  - Case 1: Unilateral amplifier ($S_{12} = 0$): Pozar P.576, Lugwig P.483.
  - Case 2: Bilateral amplifier ($S_{12} \neq 0$) : Lugwig P.492.



5. Constant Gain Circles and Specified Gain Amplifier

- In many cases, S_{12} is small enough to be ignored and the device can then be assumed to be unilateral to simplify the design process.

$$G_T = \frac{1-|\Gamma_S|^2}{|1-\Gamma_{in}\Gamma_S|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} = G_S G_0 G_L$$

- For unilateral case: $S_{12} = 0$, matching equations is equivalent:

$$\Gamma_S = \Gamma_{in}^* = \left(S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}\right)^* = S_{11}^* \qquad \Gamma_L = \Gamma_{out}^* = \left(S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}\right)^* = S_{22}^*$$

- Then:

$$G_S = \frac{1-|\Gamma_S|^2}{|1-\Gamma_{in}\Gamma_S|^2} \rightarrow G_{Smax} = \frac{1}{1-|S_{11}|^2}$$

$$G_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \rightarrow G_{Lmax} = \frac{1}{1-|S_{22}|^2}$$

5. Constant Gain Circles and Specified Gain Amplifier

- The normalized gain factors g_S and g_L are defined as

$$g_s = \frac{G_S}{G_{Smax}} = \frac{1-|\Gamma_S|^2}{|1-\Gamma_{in}\Gamma_S|^2}\left(1-|S_{11}|^2\right) \qquad g_L = \frac{G_L}{G_{Lmax}} = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}\left(1-|S_{22}|^2\right)$$

- For fixed values of g_S and g_L, the above equations can be shown to represent circles in the Γ_S and Γ_L planes.

$$|\Gamma_S - C_S| = R_S \qquad |\Gamma_L - C_L| = R_L$$

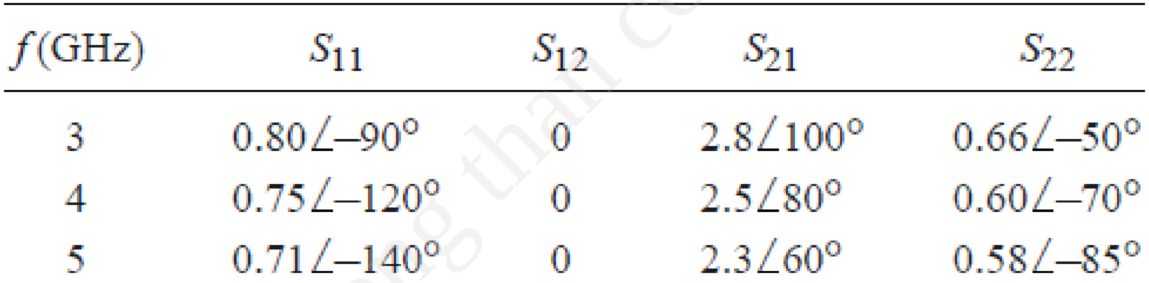
where:

$$C_S = \frac{g_s S_{11}^*}{1-(1-g_s|S_{11}|^2)} \qquad C_L = \frac{g_s S_{22}^*}{1-(1-g_L|S_{22}|^2)}$$

$$R_S = \frac{\sqrt{1-g_s}\left(1-|S_{11}|^2\right)}{1-(1-g_s|S_{11}|^2)} \qquad R_L = \frac{\sqrt{1-g_L}\left(1-|S_{22}|^2\right)}{1-(1-g_L|S_{22}|^2)}$$

5. Constant Gain Circles and Specified Gain Amplifier

Example 5: Design an amplifier to have a gain of 11 dB at 4.0 GHz. Plot constant-gain circles for $G_S = 2$ and $3dB$, and $G_L = 0$ and $1dB$. Calculate and plot the input return loss and overall amplifier gain from 3 to 5 GHz. The transistor has the following scattering parameters ($Z_0 = 50\Omega$):



f(GHz)	S_{11}	S_{12}	S_{21}	S_{22}
3	$0.80\angle{-90°}$	0	$2.8\angle{100°}$	$0.66\angle{-50°}$
4	$0.75\angle{-120°}$	0	$2.5\angle{80°}$	$0.60\angle{-70°}$
5	$0.71\angle{-140°}$	0	$2.3\angle{60°}$	$0.58\angle{-85°}$

- Since $S_{12} = 0$ and $|S_{11}| < 1$, $|S_{22}| < 1$, the transistor is unilateral and unconditionally stable. The maximum matching section gains:

$$G_{Smax} = \frac{1}{1 - |S_{11}|^2} = 2.29 = 3.6dB \qquad G_{Lmax} = \frac{1}{1 - |S_{22}|^2} = 1.56 = 1.9dB$$

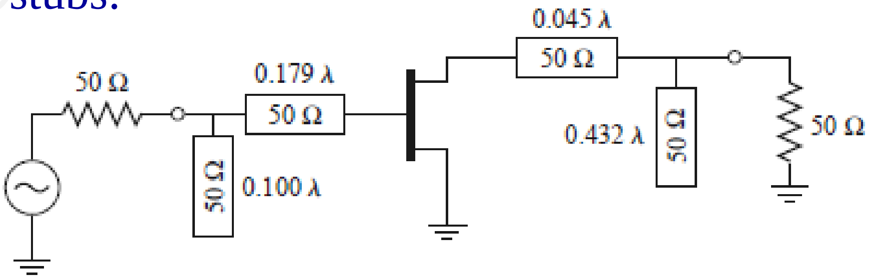
- The gain of mismatched transistor: $G_o = |S_{21}|^2 = 6.25 = 8dB$

5. Constant Gain Circles and Specified Gain Amplifier

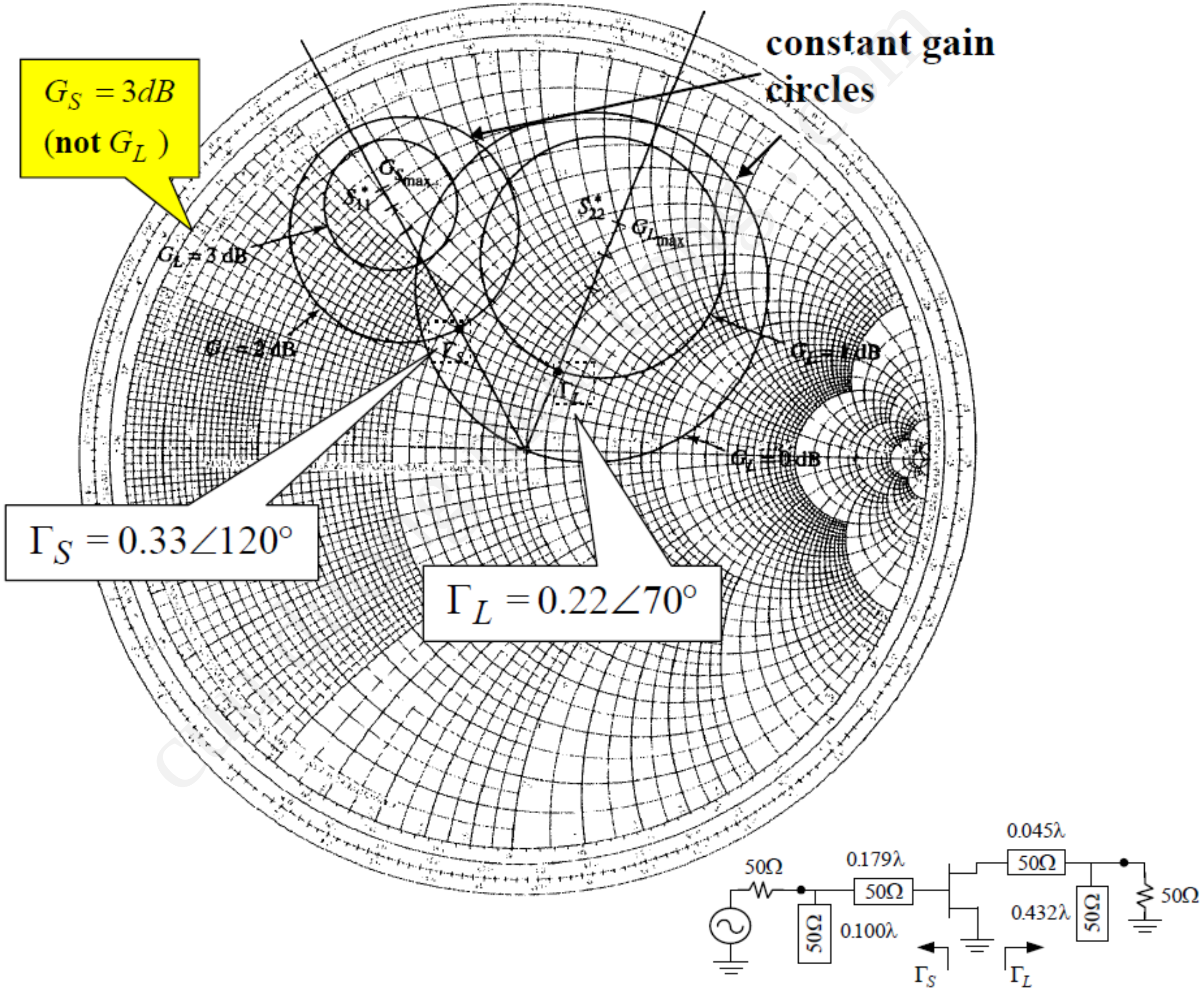
- The maximum unilateral transducer gain is: $G_{TUmax} = 3.6 + 1.9 + 8 = 13.5dB$
- We have 2.5dB more available gain than is required by the specifications.
- Constant-gain circles:

$$\begin{array}{llll} G_S = 3\text{ dB} & g_S = 0.875 & C_S = 0.706\angle 120^\circ & R_S = 0.166 \\ G_S = 2\text{ dB} & g_S = 0.691 & C_S = 0.627\angle 120^\circ & R_S = 0.294 \\ G_L = 1\text{ dB} & g_L = 0.806 & C_L = 0.520\angle 70^\circ & R_L = 0.303 \\ G_L = 0\text{ dB} & g_L = 0.640 & C_L = 0.440\angle 70^\circ & R_L = 0.440 \end{array}$$

- Choose $G_S = 2dB$ and $G_L = 1dB$ then the overall gain: $G_T = 2 + 8 + 1 = 11dB$.
- Select Γ_S and Γ_L along these circles to minimize the distance from the center of the Smith Chart: $\Gamma_S = 0.33\angle 120^0$ and $\Gamma_L = 0.22\angle 70^0$. Matching network can be designed using shunt stubs:



5. Constant Gain Circles and Specified Gain Amplifier



$G_S = 3dB$

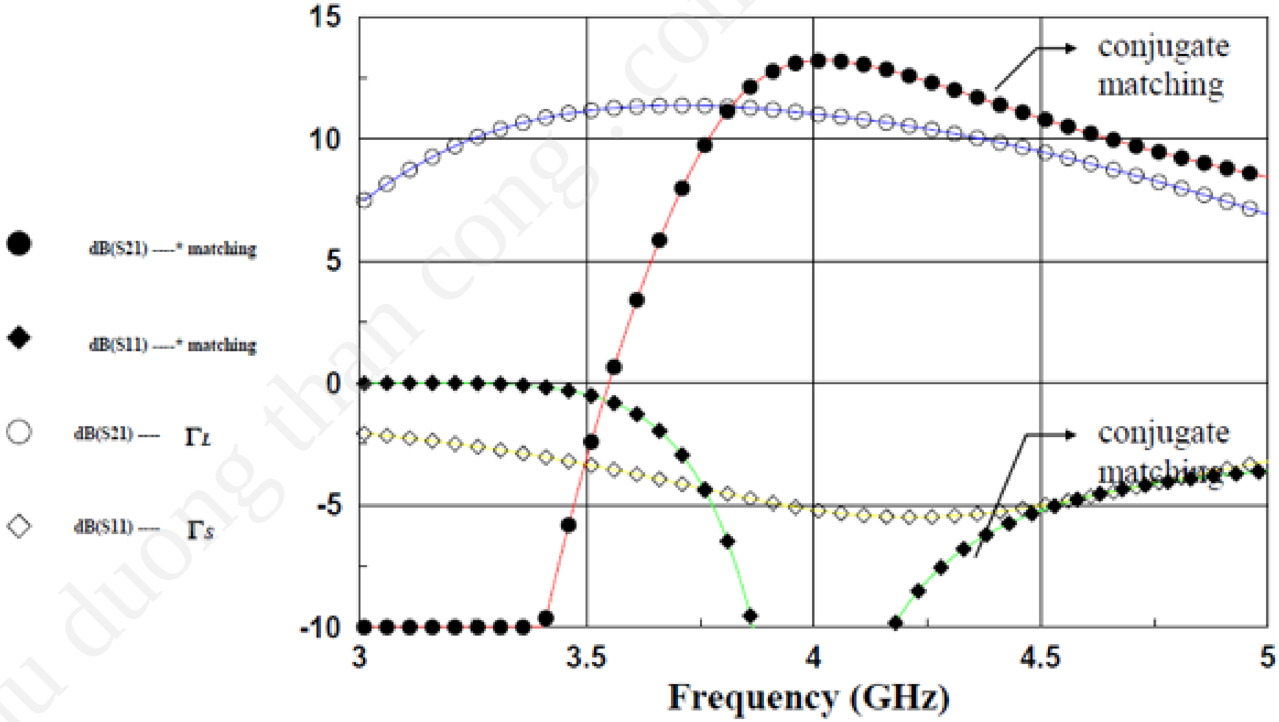
(**not** G_L)

$\Gamma_S = 0.33\angle 120°$

$\Gamma_L = 0.22\angle 70°$

5. Constant Gain Circles and Specified Gain Amplifier

- Constant-gain matching has wider bandwidth than maximum gain (by conjugate matching).



Exercise: Pozar 12.9, 12.10, 12.11, 12.12

6. Low Noise Amplifier

- Besides stability and gain, noise figure (NF) is another important design consideration for a RF/microwave amplifier.
- As shown in Chapter 2, 1st stage RF amplifier in a receiver has the dominant effect on the noise performance. This is the idea of Low Noise Amplifier design.

$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \cdots$$

- The values of the gain and NF of a LNA depend on the communication system design, typical values for wireless communication handset are $\mathrm{G} \simeq 20dB$ and $NF \leq 2 - 3dB$.

6. Low Noise Amplifier

- It can be shown that

$$F = F_{min} + \frac{R_N}{G_S}\left|Y_S - Y_{opt}\right|^2$$

$Y_S = G_S + jB_S$: source admittance presented to transistor.

Y_{OPT} : optimum source admittance that results in minimum noise.

F_{min} : minimum noise figure of transistor, attained when $Y_S = Y_{opt}$

R_N : equivalent noise resistance of transistor.

Note that $Y_S = \frac{1}{Z_0}\frac{1-\Gamma_S}{1+\Gamma_S}$ and $Y_{opt} = \frac{1}{Z_0}\frac{1-\Gamma_{opt}}{1+\Gamma_{opt}}$

- Then: $\left|Y_S - Y_{opt}\right|^2 = \frac{4}{Z_0^2}\frac{\left|\Gamma_S-\Gamma_{opt}\right|^2}{|1+\Gamma_S|^2\left|1+\Gamma_{opt}\right|^2}$

$$G_S = \mathbb{Re}\{Y_S\} = \frac{1}{2Z_0}\left(\frac{1-\Gamma_S}{1+\Gamma_S} + \frac{1-\Gamma_S^*}{1+\Gamma_S^*}\right) = \frac{1}{Z_0}\frac{1-|\Gamma_S|^2}{|1+\Gamma_S|^2}$$

- The noise figure can be written as

$$F = F_{min} + \frac{4R_N}{Z_0}\frac{\left|\Gamma_S - \Gamma_{opt}\right|^2}{(1-|\Gamma_S|^2)\left|1+\Gamma_{opt}\right|^2}$$

6. Low Noise Amplifier

- For a fixed noise figure F, we define *the noise figure parameter N (a constant)*:

$$N = \frac{\left|\Gamma_S - \Gamma_{opt}\right|^2}{1 - |\Gamma_S|^2} = \frac{F - F_{min}}{\frac{4R_N}{Z_0}}\left|1 + \Gamma_{opt}\right|^2$$

- Then the above equation can be rewritten as

$$\left(\Gamma_S - \Gamma_{opt}\right)\left(\Gamma_S^* - \Gamma_{opt}^*\right) = N(1 - |\Gamma_S|^2)$$

$$\rightarrow \Gamma_S\Gamma_S^* - \left(\Gamma_S\Gamma_{opt}^* + \Gamma_S^*\Gamma_{opt}\right) + \Gamma_{opt}\Gamma_{opt}^* = N - N|\Gamma_S|^2$$

$$\rightarrow \Gamma_S\Gamma_S^* - \frac{\left(\Gamma_S\Gamma_{opt}^* + \Gamma_S^*\Gamma_{opt}\right)}{N+1} = \frac{N - \left|\Gamma_{opt}\right|^2}{N+1}$$

$$\rightarrow \left|\Gamma_S - \frac{\Gamma_{opt}}{N+1}\right| = \frac{\sqrt{N\left(N + 1 - \left|\Gamma_{opt}\right|^2\right)}}{N+1}$$

- This result defines circles of constant noise figure with center and radii as follow

$$C_F = \frac{\Gamma_{opt}}{N+1} \qquad R_F = \frac{\sqrt{N\left(N + 1 - \left|\Gamma_{opt}\right|^2\right)}}{N+1}$$

6. Low Noise Amplifier

Example 6: A GaAs MESFET is biased for minimum noise figure, with the following scattering parameters and noise parameters at 4 GHz ($Z_0 = 50\Omega$):

$$S = \begin{bmatrix} 0.6\angle -60^0 & 0.05\angle 26^0 \\ 1.9\angle 81^0 & 0.5\angle -60^0 \end{bmatrix}$$

$F_{min} = 1.6dB$, $\Gamma_{opt} = 0.62\angle 100^0$ and $R_N = 20\Omega$. For design purposes, assume the device is unilateral, and calculate the maximum error in G_T resulting from this assumption. Then design an amplifier having a $2.0dB$ noise figure with the maximum gain that is compatible with this noise figure.

- Stability: $K = 2.78$, $\Delta = 0.37$: the device is unconditionally stable.
- The center and radius of the 2dB noise figure circle:

$$N = \frac{F - F_{min}}{\frac{4R_N}{Z_0}}\left|1 + \Gamma_{opt}\right|^2 = \frac{1.58 - 1.445}{4 \times 20/50}|1 + 0.62\angle 100^0|^2 = 0.0986$$

$$C_F = \frac{\Gamma_{opt}}{N+1} = 0.56\angle 100^0 \qquad R_F = \frac{\sqrt{N\left(N + 1 - \left|\Gamma_{opt}\right|^2\right)}}{N+1} = 0.24$$

6. Low Noise Amplifier

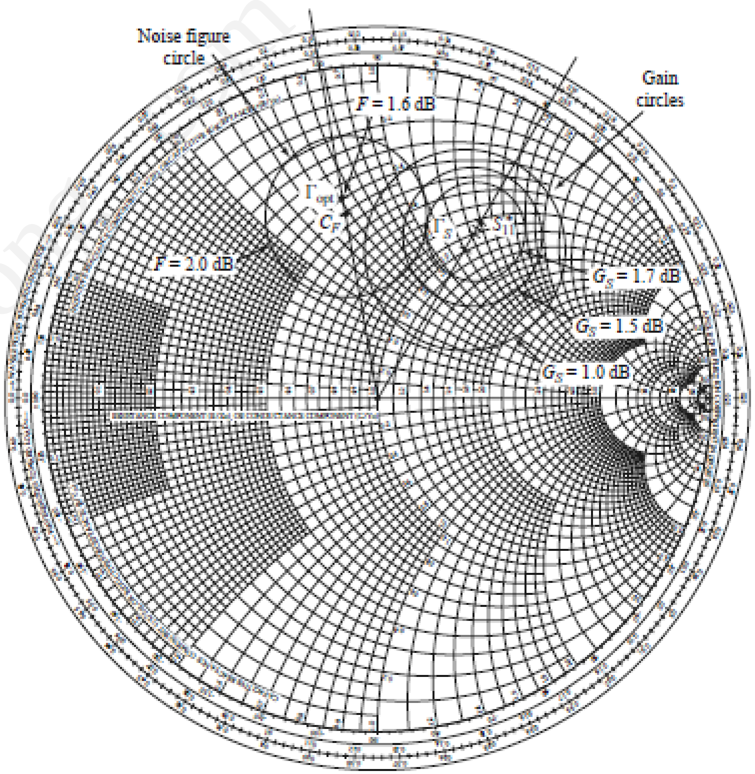
- Draw constant gain circles

G_S (dB)	g_S	C_S	R_S
1.0	0.805	$0.52\angle 60^\circ$	0.300
1.5	0.904	$0.56\angle 60^\circ$	0.205
1.7	0.946	$0.58\angle 60^\circ$	0.150

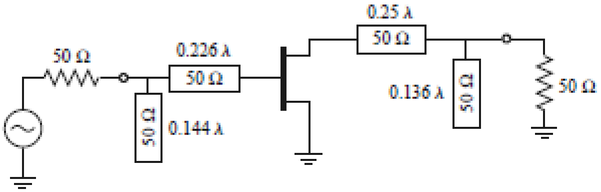
- The $G_S = 1.7dB$ gain circle intersects the $F = 2dB$ noise figure circle. Any higher gain will result in a worse noise figure.
- The optimum solution is $\Gamma_S = 0.53\angle 75^0$ yielding $G_S = 1.7dB$ and $F = 2dB$.
- For the output section, $\Gamma_L = S_{22}^* = 0.5\angle 60^0$ is chosen for a maximum G_L

$$G_L = \frac{1}{1 - |S_{22}|^2} = 1.25dB$$

- The transistor gain: $G_0 = |S_{21}|^2 = 5.58dB$
- Overall transducer gain: $G_{TU} = 8.53dB$.



(a)

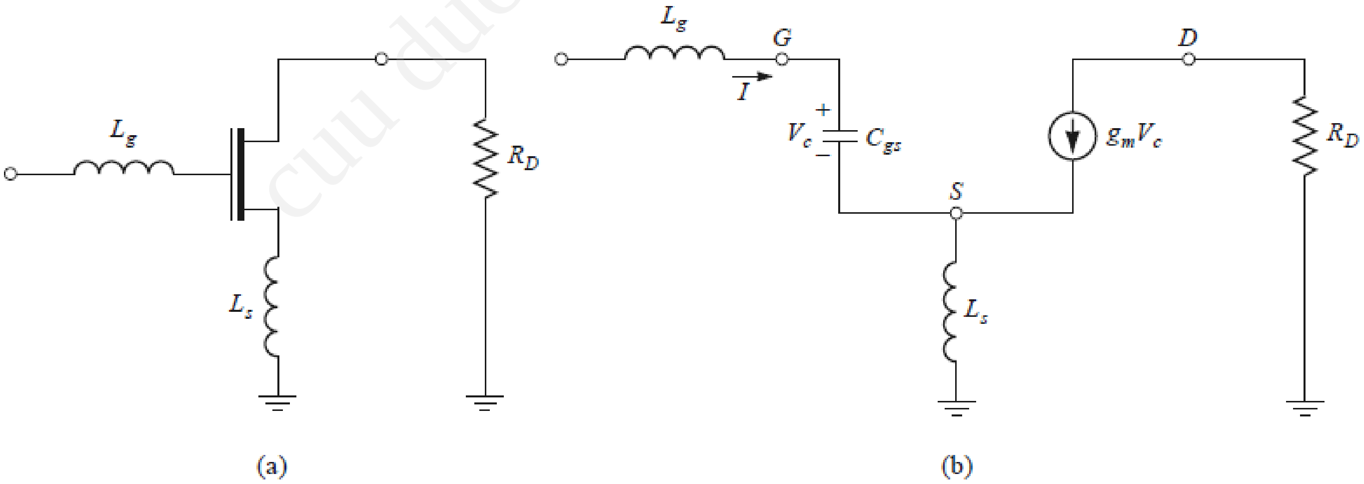


(b)

6. Low Noise Amplifier

- MOSFETs have a relatively low AC input resistance, making them difficult to impedance match.
- An external series resistance can be added to the gate but this increases noise power and degrades efficiency.
- Solution: inductive source degeneration.
- Input impedance of the circuit:

$$Z = \frac{V}{I} = \frac{g_m L_s}{C_{gs}} + j\left(\omega L_s - \frac{1}{\omega C_{gs}}\right)$$



6. Low Noise Amplifier

- Input impedance of the circuit:

$$Z = \frac{V}{I} = \frac{g_m L_s}{C_{gs}} + j\left(\omega L_s - \frac{1}{\omega C_{gs}}\right)$$

- The series inductor L_s can be chosen to match the input resistance of the amplifier to a source impedance Z_0. Then the inductor at the gate, L_g, can then be chosen to cancel the residual input reactance, which is usually capacitive.
- The combination of the series matching inductor, the gate capacitance, and the effective input resistance forms a series RLC resonator. The Q of this resonator is

$$Q = \frac{\omega L_g C_{gs}}{g_m L_s}$$

Example 7: An Infineon BF1005 n-channel MOSFET transistor having $C_{gs} = 2.1pF$ and $g_m = 2.4mS$ is used in a 900 MHz low-noise amplifier with inductive source degeneration. Determine the source and gate inductors, and estimate the bandwidth of the amplifier. Assume a source impedance of $Z_0 = 50\Omega$.

$L_s = 4.37nH$ $L_g = 10.5nH$

Q&A