Chapter 4 Noise, Broadband, and High Power Design Methods

4.1 Introduction

- Minimum noise figure and maximum power gain (G_p) are mutually exclusive

  ↓

  Draw both constant noise figure circles <u>and</u> power gain circles on Smith Chart to help select reflection coefficients

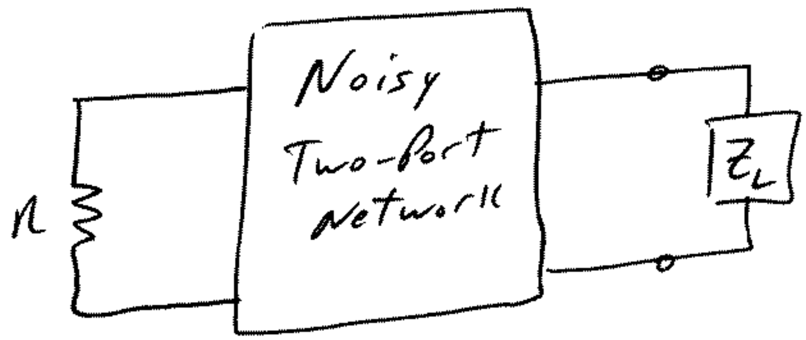
- Broadband amplifiers usually have a design goal of flat gain over a range of frequencies. Useful techniques are compensated matching networks, negative feedback, &/or balance amplifiers

- For high power, the small-signal S parameters are not usable → large signal impedance or reflection coefficient data (vs. P_{out} or gain) needed.

4.2 Noise in Two-Port Networks

→ a microwave amplifier has a small output, even with no input, called <u>amplifier noise power</u>.

→ Total noise output = amplified input noise + amplifier noise



→ The resistor R at the input models the source of the input noise power due to thermal or Johnson noise.

rms noise voltage $\equiv V_{n,rms} = \sqrt{4KTBR}$

where $K \equiv$ Boltzmann's Constant $= 1.374 \times 10^{-23}$ J/°K

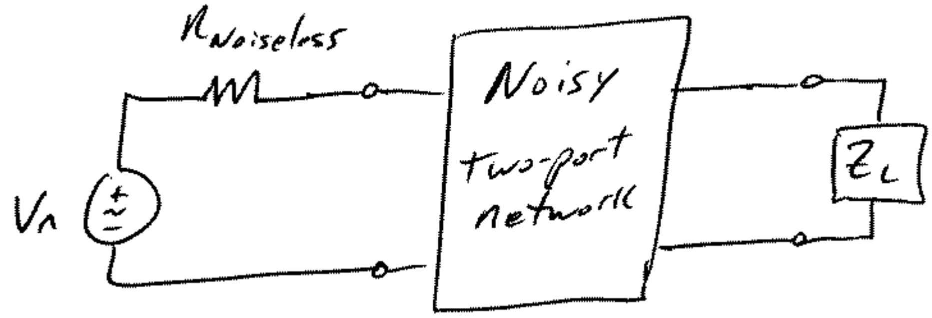
$T \equiv$ resistor noise temperature in degrees Kelvin (°K)

$B \equiv$ Noise bandwidth $= f_H - f_L$

→ Since the noise depends on bandwidth rather than a specific frequency, it is called <u>white noise</u>.

4.2 cont.

Revised model



Per the maximum power transfer theorem, the available noise power from R is

$$P_N = \frac{V_{n,rms}^2}{4R} = \frac{\left(\sqrt{4KTBR}\right)^2}{4R} = KTB$$

This can be put in dBm (decibels referenced to 1mW) as

$$P_N\,(dBm) = 10\log_{10}\left(\frac{P_N}{1\times10^{-3}}\right)$$

4.2 cont.

ex. Find the available noise power from a 50Ω resistor at $300°K$ over a 1 MHz bandwidth. Also, find the rms noise voltage.

$$V_{n,rms} = \sqrt{4KTBR} = \sqrt{4(1.374\times10^{-23})(300)(10^6)50}$$

$$\underline{\underline{V_{n,rms} = 0.908\,\mu V_{rms}}}$$

$$P_N = \frac{V_{n,rms}^2}{4R} = \frac{(0.908\times10^{-6})^2}{4(50} = 4.122\times10^{-15}\,W$$

$$= KTB = (1.374\times10^{-23})(300)10^6 = \underline{\underline{4.122\times10^{-15}\,W}}$$

$$P_N(dBm) = 10\log_{10}\left(\frac{4.122\times10^{-15}}{10^{-3}}\right) = \underline{\underline{-113.85\,dBm}}$$

4.2 cont.

Noise Figure $\equiv F$ (unitless) is used to quantify the performance of a two-port (e.g., microwave amplifiers)

$$F \equiv \frac{\text{available noise power @ output}}{(\text{available noise power @ input})\, G_A}$$

from R @ $T_0 = 290°K$

$$= \frac{P_{N_o}}{P_{N_i} G_A} \qquad P_{N_i} = K T_o B$$

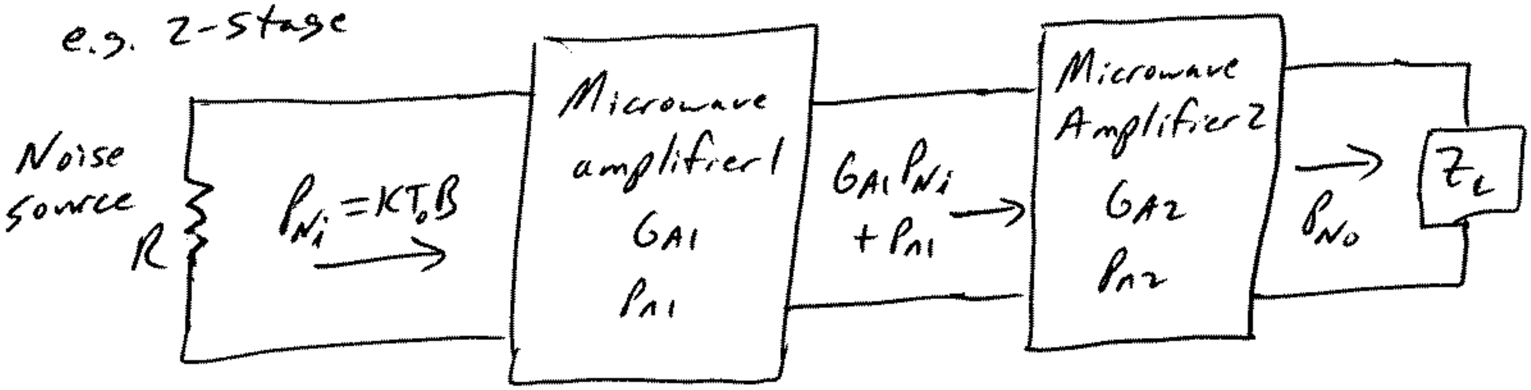
Using $G_A = \dfrac{P_{S_o}}{P_{S_i}} = \dfrac{\text{available signal power @ output}}{\text{available signal power @ input}}$

$$F = \frac{P_{S_i}/P_{N_i}}{P_{S_o}/P_{N_o}} = \frac{SNR_{IN}}{SNR_{OUT}}$$

want to minimize by proper selection of Γ_S

What about multi-stage amplifiers?

e.g. 2-stage



$$P_{N_o} = G_{A2}\left[G_{A1}P_{N_i} + P_{A1}\right] + P_{A2}$$

$$= G_{A1} G_{A2} P_{N_i} + G_{A2} P_{A1} + P_{A2}$$

4.2 cont.

ex. 2-stage cont.

$$F_{overall} = F = \frac{P_{No}}{P_{Ni} G_{A1} G_{A2}} = 1 + \frac{P_{n1}}{P_{Ni} G_{A1}} + \frac{P_{n2}}{P_{Ni} G_{A1} G_{A2}}$$

Letting $F_1 = 1 + \frac{P_{n1}}{P_{Ni} G_{A1}}$ ← Noise Figure for 1st amplifier

and $F_2 = 1 + \frac{P_{n2}}{P_{Ni} G_{A2}}$, ← Noise Figure for 2nd Amplifier

we can set

$$F = F_1 + \frac{F_2 - 1}{G_{A1}} = F_{12}$$

→ Noise from stage 2 is irrelevant if G_{A1} is large!

What if we reversed the order of the amplifiers?

$$F_{21} = F_2 + \frac{F_1 - 1}{G_{A2}}$$

Usually, we want to choose the order so that $F_{overall}$ is minimized.

4.2 cont.

Assuming $F_{12} < F_{21}$ or

$$\left(F_1 + \frac{F_2 - 1}{G_{A1}}\right) < \left(F_2 + \frac{F_1 - 1}{G_{A2}}\right),$$

we can manipulate the expression to get

$$\frac{F_1 - 1}{1 - \frac{1}{G_{A1}}} < \frac{F_2 - 1}{1 - \frac{1}{G_{A2}}}$$

and define the noise measure M

$$M = \frac{F - 1}{1 - \frac{1}{G_A}}$$

to get

$$M_1 < M_2 .$$

$\Rightarrow$ Put amplifier w/ lowest M first!

* What about more than two amplifiers?

$$F = F_1 + \frac{F_2 - 1}{G_{A1}} + \frac{F_3 - 1}{G_{A1} G_{A2}} + \frac{F_4 - 1}{G_{A1} G_{A2} G_{A3}} + \cdots$$

If all amplifiers are identical (same F + same G_A),

$$F = 1 + \frac{F_1 - 1}{1 - \frac{1}{G_{A1}}} = 1 + M_1$$

4.2 cont.

ex. Given amplifiers A and B described, determine the overall cascaded noise figures w/ A first (F_{AB}) and w/ B first (F_{BA}).

Amplifier A	Amplifier B
$F_A = 3\,dB$	$F_B = 4\,dB$
$G_{A,A} = 10\,dB$	$G_{A,B} = 12\,dB$

* Convert the noise figures and gain to be unitless.

$F_A = 10^{3/10} = 1.9953$ $\qquad F_B = 10^{4/10} = 2.5119$

$G_{A,A} = 10^{10/10} = 10$ $\qquad G_{A,B} = 10^{12/10} = 15.8489$

$$M_A = \frac{F_A - 1}{1 - 1/G_{A,A}} = \frac{1.9953 - 1}{1 - \frac{1}{10}} \qquad M_B = \frac{F_B - 1}{1 - \frac{1}{G_{A,B}}} = \frac{2.5119 - 1}{1 - \frac{1}{15.85}}$$

$\underline{M_A = 1.105847} \quad < \quad \underline{M_B = 1.6137}$

$\Rightarrow$ F_{AB} should be less than F_{BA} $\Leftarrow$

$$F_{AB} = F_A + \frac{F_B - 1}{G_{A,A}} = 1.9953 + \frac{2.5119 - 1}{10} = \underline{\underline{2.14645}}$$

$$F_{BA} = F_B + \frac{F_A - 1}{G_{A,B}} = 2.5119 + \frac{1.9953 - 1}{15.8489} = \underline{\underline{2.5747}}$$

4.3 Constant Noise Figure Circles

For a microwave transistor meant to be used in applications where noise is a concern, we need (datasheet or measurement) the noise parameters –

F_{min} ≡ minimum/optimum noise figure

r_n ≡ normalized (i.e., $\frac{R_n}{Z_0}$) equivalent noise resistance

Γ_{opt} ≡ value of Γ_s (source reflection coefficient) which produces F_{min}

How can the noise parameters be measured?

F_{min} → use a noise figure meter to measure

Γ_{opt} → vary Γ_s until F_{min} reached, measure Γ_s w/ network analyzer.

r_n → measure noise figure when $\Gamma_s = 0$, called $F_{\Gamma_s=0}$, then

$$r_n = \left[F_{\Gamma_s=0} - F_{min}\right] \frac{|1+\Gamma_{opt}|^2}{4|\Gamma_{opt}|^2}$$

Note: F_{min} is a function of the transistor operating point, e.g., I_c, frequency, ...

4.3 cont.

As shown in Appendix L, the noise figure of a two-port amplifier is expressed as:

$$F = F_{min} + \frac{r_n}{g_s} \left| y_s - y_{opt} \right|^2$$

where $y_s = g_s + j b_s \equiv$ normalized source admittance

$$= \frac{1 - \Gamma_s}{1 + \Gamma_s}$$ ~ express in terms of source reflection coeff.

$$y_{opt} = \frac{1 - \Gamma_{opt}}{1 + \Gamma_{opt}}$$ ~ normalized source admittance which yields F_{min}

Substitute for y_s, $g_s = Re\{y_s\}$, and y_{opt} in terms of Γ_s and Γ_{opt} in the noise figure equation to get

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

This equation, for a given $F = F_i$, can be arranged as

$$\frac{\left| \Gamma_s - \Gamma_{opt} \right|^2}{1 - |\Gamma_s|^2} = \frac{F_i - F_{min}}{4 r_n} \left| 1 + \Gamma_{opt} \right|^2 = \text{constant!}$$

Define <u>noise figure parameter N_i</u>:

$$N_i = \frac{F_i - F_{min}}{4 r_n} \left| 1 + \Gamma_{opt} \right|^2$$

4.3 cont.

Then,
$$\frac{|\Gamma_s - \Gamma_{opt}|^2}{1-|\Gamma_s|^2} = N_i$$

can be rearranged as
$$\left|\Gamma_s - \frac{\Gamma_{opt}}{1+N_i}\right|^2 = \frac{N_i^2 + N_i(1-|\Gamma_{opt}|^2)}{(1+N_i)^2}$$

which is the equation of a circle, on the Γ_s plane, of constant noise figure F_i.

Center of F_i circle $\equiv C_{F_i} = \frac{\Gamma_{opt}}{1+N_i}$ ← complex #

radius of F_i circle $\equiv r_{F_i} = \frac{1}{1+N_i}\sqrt{N_i^2 + N_i(1-|\Gamma_{opt}|^2)}$

Notes: 1) $\Gamma_s = \Gamma_{opt}$ results in $N_i = 0$ ($\underline{F_i = F_{min}}$) and $C_{F_i} = \Gamma_{opt}$ w/ $r_{F_i} = 0$

2) Must choose $F_i \geq F_{min}$

3) all C_{F_i} along line of $\measuredangle \Gamma_{opt}$

4.3 cont.

Procedure for drawing constant noise figure circle

1) For a given transistor and operating conditions, obtain/measure the noise parameters – F_{min}, Γ_{opt}, & r_n.

2) Plot F_{min} at $\Gamma_s = \Gamma_{opt}$ on Γ_s Smith Chart and $\angle \Gamma_{opt}$ line.

3) Select $F_i > F_{min}$, Convert to unitless form $\left(F_i = 10^{F_i/10}\right)$ if necessary, and calculate noise figure parameter N_i, C_{F_i}, and r_{F_i}.

4) Plot F_i circle on Γ_s Smith Chart.

In this example, we will map noise figure circles on the Γ_S plane based on a M-Pulse Microwave MP42141 silicon npn BJT low noise microwave transistor operating at 2 GHz with V_{CE} = 10 V and I_C = 5 mA.

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Transistor info:

$FdB := 3.4$ dB (typical) $Rn := 4\ \Omega$ $\Gamma opt := 0.5 \cdot e^{j \cdot 160 \cdot \frac{\pi}{180}}$

$Z0 := 50\ \Omega$ $rn := \frac{Rn}{Z0}$ $rn = 0.08$

$F := 10^{\frac{FdB}{10}}$ $F = 2.188$

$S11 := 0.561 \cdot e^{j \cdot 166.2 \cdot \frac{\pi}{180}}$ $S12 := 0.078 \cdot e^{j \cdot 32.6 \cdot \frac{\pi}{180}}$

$S21 := 1.894 \cdot e^{j \cdot 43.2 \cdot \frac{\pi}{180}}$ $S22 := 0.571 \cdot e^{j \cdot -63.6 \cdot \frac{\pi}{180}}$

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Out of curiosity, is this transistor stable at 2 GHz?

$\Delta := S11 \cdot S22 - S12 \cdot S21$ $\boxed{|\Delta| = 0.19989}$ < 1, good

$$K := \frac{1 - (|S11|)^2 - (|S22|)^2 + (|\Delta|)^2}{2\,|S12 \cdot S21|}$$ $\boxed{K = 1.3511}$ > 1, good

Stability Conditions ARE met at 2 GHz.

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Let's calculate noise figure circles for F = 3.5, 3.7, 4, & 4.5 dB.

$F35 := 10^{\frac{3.5}{10}}$ $F35 = 2.239$

$$N35 := \frac{F35 - F}{4 \cdot rn} \cdot (|1 + \Gamma opt|)^2$$ $N35 = 0.049$

$$CF35 := \frac{\Gamma opt}{1 + N35}$$ $\boxed{|CF35| = 0.47646}$ $\boxed{\arg(CF35) \cdot \frac{180}{\pi} = 160}$ deg

$$rF35 := \frac{1}{1 + N35} \cdot \sqrt{N35^2 + N35 \cdot \left[1 + (|\Gamma opt|)^2\right]}$$ $\boxed{rF35 = 0.2415}$

$F37 := 10^{\frac{3.7}{10}}$ $F37 = 2.344$

$N37 := \frac{F37 - F}{4 \cdot rn} \cdot \left(\left| 1 + \Gamma opt \right| \right)^2$ $N37 = 0.152$

$CF37 := \frac{\Gamma opt}{1 + N37}$ $\boxed{\left| CF37 \right| = 0.4341}$ $\boxed{\arg(CF37) \cdot \frac{180}{\pi} = 160}$ deg

$rF37 := \frac{1}{1 + N37} \cdot \sqrt{N37^2 + N37 \cdot \left[1 + \left(\left| \Gamma opt \right| \right)^2 \right]}$ $\boxed{rF37 = 0.4004}$

$F40 := 10^{\frac{4}{10}}$ $F40 = 2.512$

$N40 := \frac{F40 - F}{4 \cdot rn} \cdot \left(\left| 1 + \Gamma opt \right| \right)^2$ $N40 = 0.314$

$CF40 := \frac{\Gamma opt}{1 + N40}$ $\boxed{\left| CF40 \right| = 0.3804}$ $\boxed{\arg(CF40) \cdot \frac{180}{\pi} = 160}$ deg

$rF40 := \frac{1}{1 + N40} \cdot \sqrt{N40^2 + N40 \cdot \left[1 + \left(\left| \Gamma opt \right| \right)^2 \right]}$ $\boxed{rF40 = 0.5335}$

$F45 := 10^{\frac{4.5}{10}}$ $F45 = 2.818$

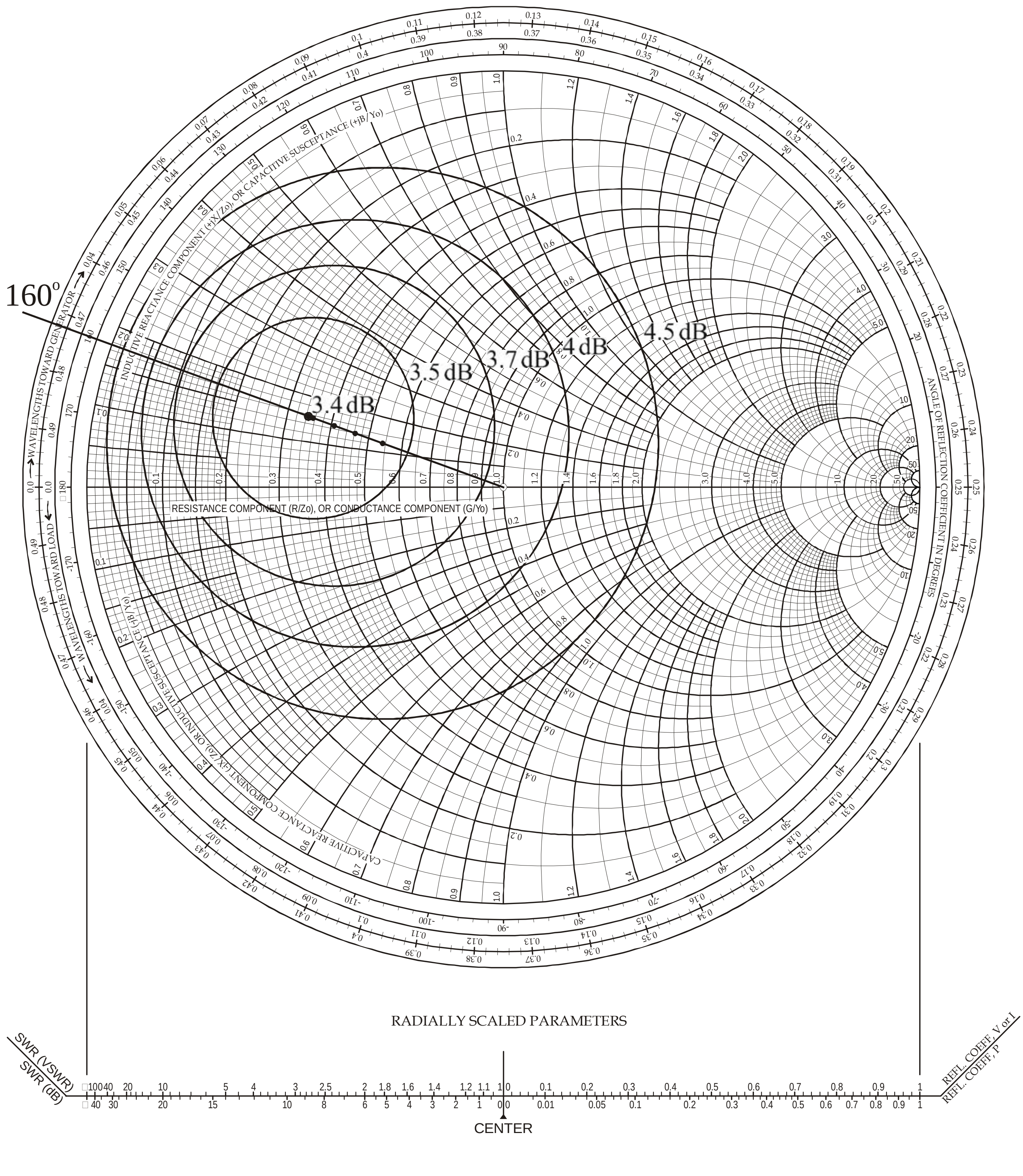
$N45 := \frac{F45 - F}{4 \cdot rn} \cdot \left(\left| 1 + \Gamma opt \right| \right)^2$ $N45 = 0.612$

$CF45 := \frac{\Gamma opt}{1 + N45}$ $\boxed{\left| CF45 \right| = 0.3103}$ $\boxed{\arg(CF45) \cdot \frac{180}{\pi} = 160}$ deg

$rF45 := \frac{1}{1 + N45} \cdot \sqrt{N45^2 + N45 \cdot \left[1 + \left(\left| \Gamma opt \right| \right)^2 \right]}$ $\boxed{rF45 = 0.6621}$

Plot the circles on a Γ_S plane / Γ_S Smith Chart.

Γ_S Smith Chart



Silicon Bipolar Low Noise Microwave Transistors

MP42141

Features

- Low Intrinsic Noise Figure (2.3dB Typical @ 1.0 GHz)
- High Power Gain At 1.0 GHz – 18.0 dB Typical
- Gold Metalization
- Hermetic and Surface Mount Packages Available
- Can be Screened to JANTX, JANTXV Equivalent Levels
- ION Implanted arsenic Emitter for Consistent Performance

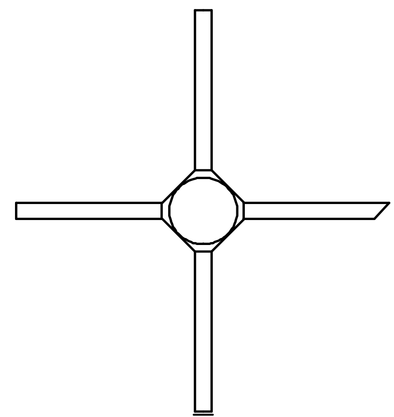
Description

This NPN Silicon transistor finds applications in low noise and medium power microwave amplifier circuitry. The MP42141 exhibits an excellent noise figure characteristic over the frequency range of .5 to 2 GHz. This transistor also features good high frequency current gain at medium current levels.

Applications

RF amplifiers and low level oscillators.

Case Styles



Micro-X

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Absolute Maximum Ratings
MP42141 Series

Collector-Base Voltage	V_{CBO}	27 V
Collector-Emitter Voltage	V_{CEO}	20 V
Emitter-Base Voltage	V_{EBO}	1.5 V
Collector Current	I_C	50 mA
Junction Operating Temperature	T_j	200°C
Storage Temperature Chip or Ceramic Packages Plastic Packages		 -65°C to +200°C -65°C to +125°C
Total Power Dissipation at 25°C 509 Case Style 510 Case Style 35 Case Style		 400 mW 700 mW 700 mW

Electrical Specifications @ 25°C
MP42141 Series

Parameter of Test	Condition	Symbol	Units	MP4214100 Chip	MP4214135 Micro-X	MP42141-509 TO-72
Gain Bandwidth Product	V_{CE} = 10 volts Fm =1.0 GHz Ic = 15 mA	f_T	GHz	4.1 typ	-----	-----
Insertion Power Gain	V_{CE} = 15 volts I_C = 15 mA f = 1 GHz f = 2 GHz	$\|S_{21E}\|^2$	dB	13 typ 7 typ	13 typ 7 min	11 typ 5 typ
Noise Figure	V_{CE} = 10 volts I_C = 5 mA f = 1 GHz f = 2 GHz	NF	dB	2.0 typ 3.4 typ	2.0 typ 3.4 typ	2.3 typ 3.6 typ
Unilateral Gain	V_{CE} = 10 volts I_C = 15 mA f = 1 GHz	GTU (max)	dB	17 typ	17 typ	14 typ
Power Out at 1 dB Compression Z=OPT	V_{CE} = 10 volts I_C = 10 mA f = 1 GHz	P_{1dB}	dBm	N/A	+7 typ	+4 typ

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Electrical Specifications @ 25°C
MP42141 Series

Parameter	Condition	Symbol	Min	Typical	Max	Units
Collector Cut-off Current	V_{CB} = 10 volts I_E = 0 µA	I_{CBO}	—	—	100	nA
Emitter Cut-off Current	V_{EB} = 1 volt I_C = 0 µA	I_{EBO}	—	—	1	µA
Forward Current Gain	V_{CE} = 10 volts I_C = 5 mA	h_{FE}	20	125	250	—
Collector-Base Junction Capacitance	V_{CB} = 15 volts f = 1 MHz	C_{CB}	—	----	1.0	pF (35)

Typical Scattering Parameters
MP42141-511, V_{CE} = 10 Volts, I_C = 5 mA

Frequency (MHz)	S_{11E} Mag.	S_{11E} Angle	S_{21E} Mag.	S_{21E} Angle	S_{12E} Mag.	S_{12E} Angle	S_{22E} Mag	S_{22E} Angle
400	.626	-112.9	7.563	110.3	.044	43.0	.726	-34.3
500	.618	-125.0	6.425	102.1	.046	38.9	.660	-32.9
800	.577	-150.8	4.363	84.7	.054	34.3	.616	-38.6
1200	.566	-170.1	3.073	67.7	.062	32.9	.577	-43.1
1600	.661	-175.9	2.344	54.1	.069	32.6	.578	-50.4
2000	.561	166.2	1.894	43.2	.078	32.6	.571	-63.6
2400	.597	156.6	1.608	30.6	.084	30.3	.572	-70.8
2800	.506	147.8	1.408	17.9	.093	27.0	.565	-81.4
3200	.630	141.1	1.200	6.8	.099	24.6	.583	-90.7
3600	.651	133.7	1.072	-4.6	.106	21.7	.597	-102.6
4000	.643	132.9	.933	-6.5	.109	24.7	.599	-109.2
4400	.643	127.7	.796	-18.4	.112	21.4	.637	-121.6
4800	.656	122.7	.702	-28.8	.123	17.0	.686	-135.2
5000	.652	120.1	.657	-34.1	.123	14.0	.693	-142.1

MP42141-511, V_{CE} = 15 Volts, I_C = 15 mA

Frequency (MHz)	S_{11E} Mag.	S_{11E} Angle	S_{21E} Mag.	S_{21E} Angle	S_{12E} Mag.	S_{12E} Angle	S_{22E} Mag	S_{22E} Angle
400	.537	-143.2	10.294	100.9	.026	45.4	.608	-31.2
500	.547	-152.2	8.564	93.7	.028	46.0	.569	-29.3
800	.548	-170.2	5.694	79.2	.036	47.2	.562	-33.5
1200	.550	-176.9	3.867	65.9	.046	48.7	.532	-37.3
1600	.562	166.4	2.946	53.6	.056	48.0	.539	-43.9
2000	.579	158.8	2.383	43.8	.067	47.2	.539	-56.9
2400	.601	150.8	2.010	32.1	.074	43.4	.537	-63.4
2800	.608	143.3	1.755	20.0	.083	39.7	.530	-73.5
3200	.643	137.0	1.505	10.4	.091	36.6	.553	-82.5
3600	.657	130.1	1.338	-.0	.098	33.5	.560	-94.1
4000	.654	129.7	1.188	-1.4	.104	36.2	.565	-99.8
4400	.648	124.6	1.017	-13.3	.107	32.5	.600	-112.7
4800	.665	120.1	.905	-23.4	.120	27.5	.648	-125.9
5000	.650	117.2	.849	-28.9	.121	24.4	.657	-133.0

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