Chapter 4 Noise, Broadband, and High Power Design Methods

4.1 Introduction

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

\[ \downarrow \]

- Draw both constant noise figure circles and 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. Pout or gain) needed.
4.2 Noise in Two-Port Networks

- A microwave amplifier has a small output, even with no input, called amplifier noise power.

- Total noise output = amplified input noise + amplifier noise

\[ N \]

\[ \text{Noisy Two-Port Network} \]

\[ Z_L \]

- The resistor \( R \) at the input models the source of the input noise power due to thermal or Johnson noise.

\[ V_{\text{rms}} = \sqrt{\text{noise power}} = \sqrt{4kTBR} \]

\[ \text{where } k = \text{Boltzmann's Constant} \]
\[ = 1.374 \times 10^{-23} \text{ J/K} \]

\[ T = \text{resistor noise temperature in degrees Kelvin (°K)} \]

\[ B = \text{Noise bandwidth} = f_H - f_L \]

- Since the noise depends on bandwidth rather than a specific frequency, it is called white noise.
The maximum power transfer theorem, the available noise power from \( R \) is
\[ P_N = \frac{V_{n,\text{rms}}^2}{4R} = \frac{(\sqrt{4kTBR})^2}{4R} = kTB \]

This can be put in dBm (decibels referenced to 1mW) as
\[ P_N (\text{dBm}) = 10 \log_{10}\left(\frac{P_N}{1 \times 10^{-3}}\right) \]
ex. Find the available noise power from a 50Ω resistor at 300 K over a 1 MHz bandwidth. Also, find the rms noise voltage.

\[ V_{n,\text{rms}} = \sqrt{4kTBR} = \sqrt{4(1.374 \times 10^{-23})(300)(10^6)} \]

\[ V_{n,\text{rms}} = 0.908 \mu V_{\text{rms}} \]

\[ P_N = \frac{V_{n,\text{rms}}^2}{4R} = \frac{(0.908 \times 10^{-6})^2}{4(50)} = 4.122 \times 10^{-15} \text{ W} \]

\[ = kTBR = (1.374 \times 10^{-23})(300)10^6 = 4.122 \times 10^{-15} \text{ W} \]

\[ P_N (\text{dBm}) = 10 \log_{10} \left( \frac{4.122 \times 10^{-15}}{10^{-3}} \right) = -113.85 \text{ dBm} \]
Noise Figure \( F \) (unitless) is used to quantify the performance of a two-port (e.g., microwave amplifiers)

\[
F = \frac{\text{available noise power @ output}}{(\text{available noise power @ input}) G_A}
\]

\[
= \frac{P_{N_o}}{P_{N_i} G_A}
\]

From \( R \approx T_o = 290 K \)

Using \( G_A = \frac{P_{S_o}}{P_{S_i}} = \frac{\text{available signal power @ output}}{\text{available signal power @ input}} \)

\[
F = \frac{P_{S_i} / P_{N_i}}{P_{S_o} / P_{N_o}} = \frac{\text{SNR}_{in}}{\text{SNR}_{out}}
\]

We want to minimize by proper selection of \( R_s \)

What about multi-stage amplifiers?

E.g., 2-stage

\[
P_{N_0} = 6A_2 \left( G_{A1} P_{N_i} + P_{N_1} \right) + P_{N_2}
\]

\[
= G_{A1} G_{A2} P_{N_i} + G_{A2} P_{N_1} + P_{N_2}
\]
\[ F_{\text{overall}} = F = \frac{P_i}{P_i G A_1 G A_2} = 1 + \frac{P_{i1}}{P_i G A_1} + \frac{P_{i2}}{P_i G A_1 G A_2} \]

Letting \( F_1 = 1 + \frac{P_{i1}}{P_i G A_1} \) \( \in \) Noise Figure for 1st amplifier

\( and \)

\( F_2 = 1 + \frac{P_{i2}}{P_i G A_2} \) \( \in \) Noise Figure for 2nd Amplifier

we can set

\[ F = F_1 + \frac{F_2 - 1}{G A_1} = F_2 \]

\( \Rightarrow \) Noise from stage 2 is irrelevant if \( G A_1 \) is large!

What if we reversed the order of the amplifiers?

\[ F_{21} = F_2 + \frac{F_1 - 1}{G A_2} \]

Usually, we want to choose the order so that \( F_{\text{overall}} \) is minimized.
Assuming \( F_{12} < F_{21} \) or

\[
\left( F_i + \frac{F_{21} - 1}{GA_i} \right) < \left( F_i + \frac{F_{21} - 1}{GA_2} \right),
\]

we can manipulate the expression to get

\[
\frac{F_i - 1}{1 - \frac{1}{GA_i}} < \frac{F_{21} - 1}{1 - \frac{1}{GA_2}}
\]

and define the noise measure \( M \)

\[
M = \frac{F - 1}{1 - \frac{1}{GA}}
\]

to get

\[
M_1 < M_2.
\]

\[\Rightarrow\] Put amplifier w/ lowest \( M \) first!

What about more than two amplifiers?

\[
F = F_i + \frac{F_{21} - 1}{GA_1} + \frac{F_{31} - 1}{GA_1 GA_2} + \frac{F_{41} - 1}{GA_1 GA_2 GA_3} + \ldots
\]

If all amplifiers are identical (same \( F \) + same \( GA \))

\[
F = 1 + \frac{F_i - 1}{1 - \frac{1}{GA_i}} = 1 + M_i
\]
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**
- \( F_A = 3 \text{ dB} \)
- \( G_{A,A} = 10 \text{ dB} \)

**Amplifier B**
- \( F_B = 4 \text{ dB} \)
- \( G_{A,B} = 12 \text{ dB} \)

* Convert the noise figures and gain to be unitless.

\[
F_A = 10 \% = 1.9953 \quad F_B = 10 \% = 2.5119
\]
\[
G_{A,A} = 10 \% = 10 \quad G_{A,B} = 10 \% = 15.8489
\]

\[
M_A = \frac{F_A - 1}{1 - \frac{1}{G_{A,A}}} = \frac{1.9953 - 1}{1 - \frac{1}{10}} = 1.105847
\]
\[
M_B = \frac{F_B - 1}{1 - \frac{1}{G_{A,B}}} = \frac{2.5119 - 1}{1 - \frac{1}{15.8489}} = 1.6137
\]

\( M_A < M_B \)

\( \Rightarrow \) F_{AB} should be less than F_{BA} \( \leftarrow \)

\[
F_{AB} = F_A + \frac{F_B - 1}{G_{A,A}} = 1.9953 + \frac{2.5119 - 1}{10} = 2.14645
\]
\[
F_{BA} = F_B + \frac{F_A - 1}{G_{A,B}} = 2.5119 + \frac{1.9953 - 1}{15.8489} = 2.5747
\]
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:

- $F_{\text{min}}$ = minimum/maximum noise figure.
- $r_n$ = normalized (i.e., $\frac{r_n}{Z_0}$) equivalent noise resistance.
- $\Gamma_{\text{opt}}$ = value of $\Gamma_S$ (source reflection coefficient) which produces $F_{\text{min}}$.

How can the noise parameters be measured?

- $F_{\text{min}}$ → use a noise figure meter to measure.
- $\Gamma_{\text{opt}}$ → vary $\Gamma_S$ until $F_{\text{min}}$ reached, measure $\Gamma_S$ with network analyzer.
- $r_n$ → measure noise figure when $\Gamma_S = 0$, called $F_{\Gamma_S=0}$, then

$$r_n = \left( F_{\Gamma_S=0} - F_{\text{min}} \right) \frac{1 + |\Gamma_{\text{opt}}|^2}{4 |\Gamma_{\text{opt}}|^2}$$

Note: $F_{\text{min}}$ is a function of the transistor operating point, e.g., $I_C$, frequency, ...
As shown in Appendix L, the noise figure of a two-port amplifier is expressed as:

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

where \( y_s = g_s + j b_s \equiv \text{normalized source admittance} \)

\[ y_s = \frac{1 - \Gamma_s}{1 + \Gamma_s} \quad \text{express in terms of source reflection coeff.} \]

\[ y_{\text{opt}} = \frac{1 - \Gamma_{\text{opt}}}{1 + \Gamma_{\text{opt}}} \quad \text{normalized source admittance which yields } F_{\text{min}} \]

Substitute for \( y_s, g_s = \text{Re}(y_s), \) and \( y_{\text{opt}} \) in terms of \( \Gamma_s \) and \( \Gamma_{\text{opt}} \) in the noise figure equation to get

\[ F = F_{\text{min}} + \frac{4r_n \left| y_s - y_{\text{opt}} \right|^2}{(1 - |\Gamma_s|^2)(1 + |\Gamma_{\text{opt}}|^2)} \]

This equation, for a given \( F = F_i \), can be arranged as

\[ \frac{\left| y_s - y_{\text{opt}} \right|^2}{1 - |\Gamma_s|^2} = \frac{F_i - F_{\text{min}}}{4r_n} \left| 1 + \Gamma_{\text{opt}} \right|^2 = \text{constant} \]

Define noise figure parameter \( N_i \)

\[ N_i = \frac{F_i - F_{\text{min}}}{4r_n} \left| 1 + \Gamma_{\text{opt}} \right|^2 \]
4.3 cont.

Then, \[ \frac{|\Gamma_s \mp \Gamma_{\text{opt}}|^2}{1-|\Gamma_s|^2} = N_s \]

can be rearranged as
\[ \left| \Gamma_s - \frac{\Gamma_{\text{opt}}}{1+N_s} \right|^2 = \frac{N_s^2 + N_s (1-|\Gamma_{\text{opt}}|^2)}{(1+N_s)^2} \]

which is the equation of a circle, on the \( \Gamma_s \) plane, of constant noise figure \( F_i \).

Center of \( F_i \) circle
\[ C_{F_i} = \frac{\Gamma_{\text{opt}}}{1+N_s} \] (complex #)

Radius of \( F_i \) circle
\[ R_{F_i} = \frac{1}{1+N_s} \sqrt{N_s^2 + N_s (1-|\Gamma_{\text{opt}}|^2)} \]

Notes:
1) \( \Gamma_s = \Gamma_{\text{opt}} \) results in \( N_s = 0 \) (\( F_i = F_{\text{min}} \))
and \( C_{F_i} = \Gamma_{\text{opt}} \) \( \Rightarrow \) \( R_{F_i} = 0 \)
2) Must choose \( F_i \geq F_{\text{min}} \)
3) all \( C_{F_i} \) along line of \( \times \Gamma_{\text{opt}} \)
Procedure for drawing constant noise figure circle

1) For a given transistor and operating conditions, obtain/measure the noise parameters: $F_{\text{min}}$, $R_{\text{opt}}$, and $r_n$.

2) Plot $F_{\text{min}}$ at $P_s = P_{\text{opt}}$ on $\Gamma_s$ Smith Chart and $P_{\text{opt}}$ line.

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

4) Plot $F_i$ circle on $\Gamma_s$ Smith Chart.
In this example, we will map noise figure circles on the $\Gamma_S$ 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.

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

\[
\Delta := S_{11}\cdot S_{22} - S_{12}\cdot S_{21} \\
|\Delta| = 0.19989 < 1, \text{ good}
\]

\[
K := \frac{1 - (|S_{11}|)^2 - (|S_{22}|)^2 + (|\Delta|)^2}{2 |S_{12}\cdot S_{21}|} \\
K = 1.3511 > 1, \text{ good}
\]

Stability Conditions ARE met at 2 GHz.

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

\[
F_{3.5} := 10^{\frac{3.5}{10}} \\
F_{3.5} = 2.239
\]

\[
N_{3.5} := \frac{F_{3.5} - F}{4\cdot m}\left(1 + |\Gamma_{opt}|\right)^2 \\
N_{3.5} = 0.049
\]

\[
CF_{3.5} := \frac{\Gamma_{opt}}{1 + N_{3.5}} \\
|CF_{3.5}| = 0.47646 \\
\text{arg}(CF_{3.5}) \cdot \frac{180}{\pi} = 160 \text{ deg}
\]

\[
rF_{3.5} := \frac{1}{1 + N_{3.5}} \sqrt{N_{3.5}^2 + N_{3.5}\left[1 + (|\Gamma_{opt}|)^2\right]} \\
rF_{3.5} = 0.2415
\]
Plot the circles on a $\Gamma_S$ plane / $\Gamma_S$ Smith Chart.

\[
\begin{align*}
\text{F37} & := 10^{\frac{3.7}{10}} \quad \text{F37} = 2.344 \\
\text{N37} & := \frac{\text{F37} - \text{F}}{4 \cdot \text{r_n}} (|1 + \Gamma_{\text{opt}}|)^2 \quad \text{N37} = 0.152 \\
\text{CF37} & := \frac{\Gamma_{\text{opt}}}{1 + \text{N37}} \quad |\text{CF37}| = 0.4341 \quad \text{arg}(\text{CF37}) \cdot \frac{180}{\pi} = 160 \, \text{deg} \\
\text{rF37} & := \frac{1}{1 + \text{N37}} \sqrt{\text{N37}^2 + \text{N37} \cdot [1 + (|\Gamma_{\text{opt}}|)^2]} \quad \text{rF37} = 0.4004
\end{align*}
\]

\[
\begin{align*}
\text{F40} & := 10^{\frac{4}{10}} \quad \text{F40} = 2.512 \\
\text{N40} & := \frac{\text{F40} - \text{F}}{4 \cdot \text{r_n}} (|1 + \Gamma_{\text{opt}}|)^2 \quad \text{N40} = 0.314 \\
\text{CF40} & := \frac{\Gamma_{\text{opt}}}{1 + \text{N40}} \quad |\text{CF40}| = 0.3804 \quad \text{arg}(\text{CF40}) \cdot \frac{180}{\pi} = 160 \, \text{deg} \\
\text{rF40} & := \frac{1}{1 + \text{N40}} \sqrt{\text{N40}^2 + \text{N40} \cdot [1 + (|\Gamma_{\text{opt}}|)^2]} \quad \text{rF40} = 0.5335
\end{align*}
\]

\[
\begin{align*}
\text{F45} & := 10^{\frac{4.5}{10}} \quad \text{F45} = 2.818 \\
\text{N45} & := \frac{\text{F45} - \text{F}}{4 \cdot \text{r_n}} (|1 + \Gamma_{\text{opt}}|)^2 \quad \text{N45} = 0.612 \\
\text{CF45} & := \frac{\Gamma_{\text{opt}}}{1 + \text{N45}} \quad |\text{CF45}| = 0.3103 \quad \text{arg}(\text{CF45}) \cdot \frac{180}{\pi} = 160 \, \text{deg} \\
\text{rF45} & := \frac{1}{1 + \text{N45}} \sqrt{\text{N45}^2 + \text{N45} \cdot [1 + (|\Gamma_{\text{opt}}|)^2]} \quad \text{rF45} = 0.6621
\end{align*}
\]
Silicon Bipolar Low Noise Microwave Transistors

**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
### Absolute Maximum Ratings

**MP42141 Series**

<table>
<thead>
<tr>
<th>Parameter of Test</th>
<th>Symbol</th>
<th>Units</th>
<th>MP4214100 Chip</th>
<th>MP4214135 Micro-X</th>
<th>MP42141-509 TO-72</th>
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</thead>
<tbody>
<tr>
<td>Collector-Base Voltage</td>
<td>$V_{CB0}$</td>
<td>27 V</td>
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<td>-----</td>
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<tr>
<td>Collector-Emitter Voltage</td>
<td>$V_{CEO}$</td>
<td>20 V</td>
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<tr>
<td>Emitter-Base Voltage</td>
<td>$V_{EBO}$</td>
<td>1.5 V</td>
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<tr>
<td>Collector Current</td>
<td>$I_C$</td>
<td>50 mA</td>
<td>400 mW</td>
<td>700 mW</td>
<td>700 mW</td>
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<tr>
<td>Junction Operating Temperature</td>
<td>$T_J$</td>
<td>200°C</td>
<td>-----</td>
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<tr>
<td>Storage Temperature</td>
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<tr>
<td>Chip or Ceramic Packages</td>
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<td>Plastic Packages</td>
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<tr>
<td>Total Power Dissipation at 25°C</td>
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<tr>
<td>509 Case Style</td>
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<td>400 mW</td>
<td>700 mW</td>
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<tr>
<td>510 Case Style</td>
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<td>35 Case Style</td>
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### Electrical Specifications @ 25°C

**MP42141 Series**

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

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**M-Pulse Microwave**

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Specification Subject to Change Without Notice
### Electrical Specifications @ 25°C

#### MP42141 Series

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Symbol</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>Collector Cut-off Current</td>
<td>$V_{CE} = 10$ volts $I_E = 0 \mu A$</td>
<td>$I_{CBO}$</td>
<td>—</td>
<td>—</td>
<td>100</td>
<td>nA</td>
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<tr>
<td>Emitter Cut-off Current</td>
<td>$V_{BE} = 1$ volt $I_C = 0 \mu A$</td>
<td>$I_{EBO}$</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>μA</td>
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<tr>
<td>Forward Current Gain</td>
<td>$V_{CE} = 10$ volts $I_C = 5$ mA</td>
<td>$h_{FE}$</td>
<td>20</td>
<td>125</td>
<td>250</td>
<td>—</td>
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<tr>
<td>Collector-Base Junction Capacitance</td>
<td>$V_{CB} = 15$ volts $f = 1$ MHz</td>
<td>$C_{CB}$</td>
<td>—</td>
<td>—</td>
<td>1.0</td>
<td>pF (35)</td>
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</table>

#### Typical Scattering Parameters

**MP42141-511, $V_{CE} = 10$ Volts, $I_C = 5$ mA**

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$S_{11E}$</th>
<th>$S_{21E}$</th>
<th>$S_{12E}$</th>
<th>$S_{22E}$</th>
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</thead>
<tbody>
<tr>
<td>400</td>
<td>0.626 -122.9</td>
<td>7.563 110.3</td>
<td>0.444 43.0</td>
<td>0.726 -34.3</td>
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<tr>
<td>500</td>
<td>0.618 -125.0</td>
<td>6.425 102.1</td>
<td>0.466 38.9</td>
<td>0.660 -32.9</td>
</tr>
<tr>
<td>800</td>
<td>0.577 -150.8</td>
<td>4.363 84.7</td>
<td>0.545 34.3</td>
<td>0.616 -38.6</td>
</tr>
<tr>
<td>1200</td>
<td>0.566 -170.1</td>
<td>3.073 67.7</td>
<td>0.626 32.9</td>
<td>0.577 -43.1</td>
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<tr>
<td>1600</td>
<td>0.661 -175.9</td>
<td>2.344 54.1</td>
<td>0.699 32.6</td>
<td>0.578 -50.4</td>
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<tr>
<td>2000</td>
<td>0.561 166.2</td>
<td>1.894 43.2</td>
<td>0.786 32.6</td>
<td>0.571 -63.6</td>
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<tr>
<td>2400</td>
<td>0.597 156.6</td>
<td>1.608 30.6</td>
<td>0.848 30.3</td>
<td>0.572 -70.8</td>
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<tr>
<td>2800</td>
<td>0.506 147.8</td>
<td>1.408 17.9</td>
<td>0.938 27.0</td>
<td>0.565 -81.4</td>
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<td>3200</td>
<td>0.630 141.1</td>
<td>1.200 6.8</td>
<td>0.999 24.6</td>
<td>0.583 -90.7</td>
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<tr>
<td>3600</td>
<td>0.651 133.7</td>
<td>1.072 -4.6</td>
<td>1.060 21.7</td>
<td>0.597 -102.6</td>
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<tr>
<td>4000</td>
<td>0.643 132.9</td>
<td>0.933 -6.5</td>
<td>1.090 24.7</td>
<td>0.599 -109.2</td>
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<td>4400</td>
<td>0.643 127.7</td>
<td>0.796 -18.4</td>
<td>1.112 21.4</td>
<td>0.637 -121.6</td>
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<tr>
<td>4800</td>
<td>0.656 122.7</td>
<td>0.702 -28.8</td>
<td>1.123 17.0</td>
<td>0.686 -135.2</td>
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<tr>
<td>5000</td>
<td>0.652 120.1</td>
<td>0.657 -34.1</td>
<td>1.123 14.0</td>
<td>0.693 -142.1</td>
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</table>

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

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$S_{11E}$</th>
<th>$S_{21E}$</th>
<th>$S_{12E}$</th>
<th>$S_{22E}$</th>
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</thead>
<tbody>
<tr>
<td>400</td>
<td>0.537 -143.2</td>
<td>10.294 100.9</td>
<td>0.266 45.4</td>
<td>0.608 -31.2</td>
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<tr>
<td>500</td>
<td>0.547 -152.2</td>
<td>8.564 93.7</td>
<td>0.285 46.0</td>
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<tr>
<td>800</td>
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<td>5.694 79.2</td>
<td>0.305 47.2</td>
<td>0.562 -33.5</td>
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<tr>
<td>1200</td>
<td>0.550 -176.9</td>
<td>3.867 65.9</td>
<td>0.356 48.7</td>
<td>0.539 -37.3</td>
</tr>
<tr>
<td>1600</td>
<td>0.562 166.4</td>
<td>2.946 53.6</td>
<td>0.356 48.0</td>
<td>0.539 -43.9</td>
</tr>
<tr>
<td>2000</td>
<td>0.579 158.8</td>
<td>2.383 43.8</td>
<td>0.367 47.2</td>
<td>0.539 -48.1</td>
</tr>
<tr>
<td>2400</td>
<td>0.601 150.8</td>
<td>2.010 32.1</td>
<td>0.374 43.4</td>
<td>0.537 -63.4</td>
</tr>
<tr>
<td>2800</td>
<td>0.609 143.3</td>
<td>1.755 20.0</td>
<td>0.383 39.7</td>
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<tr>
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<td>1.505 10.4</td>
<td>0.391 36.6</td>
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<tr>
<td>3600</td>
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<td>1.338 -0</td>
<td>0.399 33.5</td>
<td>0.560 -94.1</td>
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<tr>
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<td>1.188 -1.4</td>
<td>0.404 36.2</td>
<td>0.565 -99.8</td>
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<tr>
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<td>1.017 -13.3</td>
<td>0.407 32.5</td>
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<tr>
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<td>0.665 120.1</td>
<td>0.905 -23.4</td>
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<tr>
<td>5000</td>
<td>0.650 117.2</td>
<td>0.849 -28.9</td>
<td>0.412 24.4</td>
<td>0.657 -133.0</td>
</tr>
</tbody>
</table>