Amplifiers

- RF amplifiers used to increase the level of the signal along RX/TX chain
- Made using active devices
  - tubes (tube amplifiers)
  - transistors
    - Silicon/Ge FETs and BJT
    - GaAs FET

...many different devices build up the year to accommodate different frequency ranges, different power and noise figure requirements, etc.

Comparison between different microwave transistors (Table 6.1 in the book)

<table>
<thead>
<tr>
<th>f [GHz]</th>
<th>GaAs FET</th>
<th>GaAs HEMT</th>
<th>Si BJT</th>
<th>GaAs HBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>20</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>1.0</td>
<td>22</td>
<td>0.5</td>
</tr>
<tr>
<td>18</td>
<td>8</td>
<td>1.2</td>
<td>16</td>
<td>0.9</td>
</tr>
<tr>
<td>36</td>
<td></td>
<td>12</td>
<td>1.7</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>8</td>
<td>2.6</td>
<td>-</td>
</tr>
</tbody>
</table>

* Gains and NF are in dB

HEMT - high electron mobility transistors
HBT - heterojunction bipolar transistors
FET - field effect transistors
BJT - bipolar junction transistors
At lower frequencies, transistors are often represented as two-port networks.

**Example**  Consider the amplifier shown in Figure.

\[
\begin{align*}
\text{\textbf{Vcc}} & \quad \text{Supply voltage} \\
R_{B1}, R_{B2}, R_C, R_E & \quad \text{Biasing resistors used to establish operating points of the transistor circuit (i.e., I_{CQ}, I_{BQ}, I_{EQ}, ...)} \\
L_1, L_2, L_3 & \quad \text{"RF chokes". Inductors that decouple biasing circuit components at high operating frequencies} \\
\text{C1, C2, C3} & \quad \text{Coupling capacitors. Connect the signal of interest to the amplifier inputs and outputs. Since } \frac{2\pi f}{C}\text{, } C \rightarrow 0 \text{ as } f \rightarrow \infty. \\
\text{At operating frequency, the capacitors act as short circuits.}
\end{align*}
\]

At higher frequencies, the amplifiers are usually represented as two-port networks. This is due to the fact that lumped element representation given in schematic does not hold as the frequency is increased. Most commonly, the two-port network is represented using smaller parameters or "TSJ parameters".
S-parameters representation of 2-port network (chapter 2)

\[ S_{11} = \frac{V_1^-}{V_1^+} \bigg|\bigg. V_2^+ = 0 \quad \text{for all} \quad k \neq j \]

For example:

\[ S_{11} = \frac{V_1^-}{V_1^+} \bigg|\bigg. V_2^+ = 0 \]
\[ S_{21} = \frac{V_2^-}{V_1^+} \bigg|\bigg. V_2^+ = 0 \]
\[ S_{12} = \frac{V_1^-}{V_2^+} \bigg|\bigg. V_1^+ = 0 \]
\[ S_{22} = \frac{V_2^-}{V_2^+} \bigg|\bigg. V_1^+ = 0 \]

Therefore, for a two-port network, one can establish relationship

\[
\begin{bmatrix}
V_1^- \\
V_2^-
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
\begin{bmatrix}
V_1^+ \\
V_2^+
\end{bmatrix}
\]

or

\[
[V^-] = [S] [V^+] \quad \text{are commonly} \quad V^- = S V^+ \]

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\[
V^- = [S] [V^+] \quad \text{are commonly} \quad V^- = S V^+ \]
Example: Consider the network represented in Fig.

\[
\begin{align*}
S_{11} &= \frac{V_{1-}}{V_{1+}} \bigg|_{V_{2+}=0} = \frac{P^{(1)}}{V_{2+}=0} = \frac{2_{in}-Z_0}{2_{in}+Z_0} \\
2_{in} &= 8.56 + 141.81 \cdot (8.56 + 50) = 8.56 + 41.44 = 50 \Omega \\
\text{Therefore} \quad S_{11} &= \frac{50-50}{100} = 0 \\
S_{21} &= \frac{V_{2-}}{V_{1+}} \bigg|_{V_{2+}=0} = \frac{41.44}{8.56+41.44} \cdot \frac{50}{50+8.56} = 0.707 = \frac{1}{\sqrt{2}} \\
\text{Due to symmetry} \quad S_{22} = S_{11} \quad \& \quad S_{12} = S_{21}
\end{align*}
\]

\[
\begin{bmatrix}
V_{1-} \\
V_{2-}
\end{bmatrix} = 
\begin{bmatrix}
0 & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & 0
\end{bmatrix} \cdot 
\begin{bmatrix}
V_{1+} \\
V_{2+}
\end{bmatrix}
\]

Power at the input of the network

\[
P_i = \frac{V_{1+}^2}{2Z_0}
\]

Power at the output of the network

\[
P_o = \frac{V_{2-}^2}{2Z_0} = \left(\frac{1}{\sqrt{2}} V_{1+}\right)^2 = \frac{1}{2} \cdot \frac{V_{1+}^2}{2Z_0} = \frac{1}{2} P_i
\]

Therefore, the above circuit represents a 3dB attenuator. For a TL line having characteristic impedance of \(Z_0 = 50 \Omega\).
The concept of S parameters can easily be extended to multiport networks. Consider a network given in the figure.

Then, using S parameters,

\[
\begin{bmatrix}
V_1^- \\
V_2^- \\
\vdots \\
V_n^-
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & \cdots & S_{1n} \\
S_{21} & S_{22} & \cdots & S_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
S_{n1} & S_{n2} & \cdots & S_{nn}
\end{bmatrix}
\begin{bmatrix}
V_1^+ \\
V_2^+ \\
\vdots \\
V_n^+
\end{bmatrix}
\]

where \( S_{ij} = \frac{V_i^-}{V_j^+} \big|_{V_k^+ = 0, \text{ except } k \neq j} \)

For example, \( S_{3/5} = \frac{V_3^-}{V_5^+} \big|_{V_k^+ = 0, k \neq 5} \)

To make \( V_k^+ = 0 \), all ports need to be terminated with appropriate matched impedances. For the port \( i \), reflection coefficients \( y \) - transmission coefficients.
Two port power gain

Consider a two port network in the figure.

Three types of gains may be defined:

1) Power gain \( G_p = \frac{P_L}{P_{in}} \)

\( P_L \) - power dissipated at the load
\( P_{in} \) - power delivered to the input of the two port network

2) Available gain \( G_A = \frac{P_{avn}}{P_{avs}} \)

\( P_{avn} \) - power available from the two port network
\( P_{avs} \) - power available from the source

This gain assumes conjugate matching on both ends of the two port network. In other words, \( 2m_1 = 2s^* \) and \( 2m_2 = 2s^* \)

3) Transducer power gain \( G_T = \frac{P_L}{P_{avs}} \)

\( P_L \) - power delivered to the load
\( P_{avs} \) - power available from the source
The gains become different if there is a mismatch between $Z_s$, $Z_o$, and $Z_l$. If there is a conjugate matching, the gains become the same.

It is our desire to express these gains in terms of $S$ parameters of the network. With reference to Figure, the reflection coefficients

$$\Gamma_s = \frac{Z_s - Z_o}{Z_s + Z_o}$$

$$\Gamma_l = \frac{Z_l - Z_o}{Z_l + Z_o}$$

$Z_o$ - characteristic impedance reference for the two-port network.