混合訊號與射頻積體電路實作

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Design Flow

- Specification
- Decide Circuit Topology
- Pre-simulation
- Layout
- Post-simulation
- Tape-out
- Measurement

Consideration:
- Pad, bonding wire,
- SMD, Tr lines

Measurement
Measurement Consideration

- On-board or On-chip?

Properly modeled?
PCB design

Layout Considerations

RFIC Measurement
Protect your chips and Instruments

- ESD and what else?

ESD to IC’s

ESD protection circuit for IC’s

Lightning to the buildings

Lightning Rod for Buildings
Protect your chips and Instruments

Don’t feed DC current into RF instrument!!
LNA measurement

- DC measurement
  - Power supply
  - Current meter/Voltage meter
  - DC probing pad
  - Bias method
  - …
LNA measurement

- S-parameters
  - Network analyzer, 8753ES, E8362B
LNA measurement
LNA measurement

- S-parameters
  - Calibration -> TRL
  - Biasing, Balun, etc.
  - $S_{11}, S_{22}$ -> input/output matching
  - $S_{21}$ -> gain
  - $S_{12}$ -> reverse isolation
LNA measurement (Calibration)

Figure 4.20  (p. 193)
Block diagram of a network analyzer measurement of a two-port device.

three or more known loads: shorts, opens, matched loads
LNA measurement (Calibration)

Figure 4.21a (p. 194)  Block diagram and signal flow graph for the *Thru* connection.

Symmetry: $T_{22} = T_{11}$

Error box is reciprocal:

- $S_{12} = S_{21}$, $T_{12} = T_{21}$
- $T_{11} = \frac{b_1}{a_1}_{a_2=0} = S_{11} + \frac{S_{22}S_{12}^2}{1 - S_{22}^2}$
- $T_{12} = \frac{b_1}{a_2}_{a_1=0} = \frac{S_{12}^2}{1 - S_{22}^2}$
LNA measurement (Calibration)

**Figure 4.21b (p. 194)** Block diagram and signal flow graph for the Reflect connection.

Symmetry: 
\[ R_{22} = R_{11} \]

Decouple: 
\[ R_{12} = R_{21} = 0 \]
\[ R_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} = S_{11} + \frac{S_{12}^2 \Gamma_L}{1 - S_{22} \Gamma_L} \]
**LNA measurement (Calibration)**

**Figure 4.21c (p. 194)**  Block diagram and signal flow graph for the *Line* connection.

**Symmetry:**
\[ L_{22} = L_{11} \]

**Error box is reciprocal:**
\[ S_{12} = S_{21}, \quad L_{12} = L_{21} \]

\[
L_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} = S_{11} + \frac{S_{22} S_{12}^2 e^{-2\gamma l}}{1 - S_{22}^2 e^{-2\gamma l}}
\]

\[
L_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} = \frac{S_{12}^2 e^{-2\gamma l}}{1 - S_{22}^2 e^{-2\gamma l}}
\]
LNA measurement (Calibration)

5 equations for 5 knowns:

\[ S_{11}, S_{12}, S_{22}, \Gamma_L, e^{-\gamma l} \]

\[ e^{-\gamma l} = \frac{L_{12}^2 + T_{12}^2 - (T_{11} - L_{11})^2 \pm \sqrt{[L_{12}^2 + T_{12}^2 - (T_{11} - L_{11})^2]^2 - 4L_{12}^2T_{12}^2}}{2L_{12}T_{12}} \]

\[ S_{22} = \frac{T_{11} - L_{11}}{T_{12} - L_{12}e^{-\gamma l}} \]

\[ S_{11} = T_{11} - S_{22}T_{12} \]

\[ S_{12}^2 = T_{12}(1 - S_{22}^2) \]

\[ \Gamma_L = \frac{R_{11} - S_{11}}{S_{12}^2 + S_{22}(R_{11} - S_{11})} \]

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix} \leftrightarrow \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\]

\[
\begin{bmatrix}
A^m & B^m \\
C^m & D^m
\end{bmatrix} = \begin{bmatrix}
A & B \\
C & D
\end{bmatrix} \begin{bmatrix}
A' & B' \\
C' & D'
\end{bmatrix} \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}^{-1}
\]

\[
\begin{bmatrix}
A' & B' \\
C' & D'
\end{bmatrix} = \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}^{-1} \begin{bmatrix}
A^m & B^m \\
C^m & D^m
\end{bmatrix} \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\]
LNA measurement (NF)

- Noise Figure meter, Spectrum analyzer

E4440A Spectrum Analyzer
LNA measurement (NF)

Definition of NF

\[ SNR = \frac{\text{signal power}}{\text{total noise power}} \]

noise figure (NF) = \( \frac{\text{SNR}_{in}}{\text{SNR}_{out}} \), (noise factor, \( F \))

\[ NF(\text{dB}) = 10 \log_{10} \left( \frac{N_a + G N_{in}}{G N_{in}} \right) \]
LNA measurement (NF)

- Noise for a resistor
  \[ \nu_n^2 = 4kTBR \]

- Noise power is linear with temperature
  \[ N_{out} = N_a + GN_{in} = N_a + GkT_sB \]

\[ N_{in} \quad G, N_a \]

\[ Z_s @ T_s \]

\[ N_1, N_2 \]

Slope = \( kGB \)
LNA measurement (NF)

Definition of Effective Noise Temperature

\[ N_{out} = N_a + GN_{in} = GkT_eB + GkT_sB \]
\[ = GkB(T_e + T_s) \]

\[ G, N_a = 0 \]

\[ T_e = (F - 1)T_s \]
and
\[ F = \frac{T_e + T_s}{T_s} \]
LNA measurement (NF)

How do we measure Noise Figure?

\[ N_1 = GkB(T_e + T_c) \]

\[ N_2 = GkB(T_e + T_h) \]

\[ Y = \frac{N_1}{N_2} \]

Y factor:

\[ N_{out} \]

Slope = \( kGB \)
LNA measurement (NF)

- Calculating the Noise Factor

\[ Y = \frac{N_1}{N_2} = \frac{GkB(T_e + T_c)}{GkB(T_e + T_h)} = \frac{T_e + T_c}{T_e + T_h} \]

\[ T_e = \frac{T_h - YT_c}{Y - 1} \]

\[ F = \frac{T_e + T_s}{T_s} = \frac{\left( \frac{T_h}{T_s} - 1 \right)}{Y - 1} - Y \left( \frac{T_c}{T_s} - 1 \right) \]

Known Quantities:
\( T_h, T_c, T_s \)

Measured:
\( Y \)
LNA measurement (NF)

- Calculating the Noise Figure
  - Take $T_s = T_c$

$$F = \left( \frac{T_h}{T_s} - 1 \right)$$

$$NF \text{ (dB)} = 10 \log_{10} \left( \frac{T_h}{T_s} - 1 \right) = 10 \log_{10} \left( \frac{T_h}{T_s} \right) - 10 \log_{10}(Y - 1)$$

$$NF \text{ (dB)} = ENR \text{ (dB)} - 10 \log_{10}(Y - 1)$$
LNA measurement (NF)

- Noise Source (Avalanche Diode)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>ENR(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500MHz</td>
<td>8.721</td>
</tr>
<tr>
<td>1GHz</td>
<td>8.823</td>
</tr>
<tr>
<td>2GHz</td>
<td>8.782</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
LNA measurement (NF)
LNA measurement (Linearity)

- SFDR
- P1dB
- IIP3
LNA measurement (Linearity)

- **P1dB**: Signal generator, Spectrum analyzer
- **IIP3**: ESG, Spectrum analyzer
  - Plot 3\textsuperscript{rd} harmonics
  - Use formula

\[ \text{IIP}_3|_{\text{dBm}} = \frac{\Delta P|_{\text{dB}}}{2} + P_{\text{in}}|_{\text{dBm}} \]
Mixer measurement

- DC measurement
- S-parameters (3 ports)
  - $S_{11}$, $S_{22}$ (input matching)
  - Port-to-port isolation
- Conversion gain
  (need 2 RF input)
Mixer measurement
Mixer measurement (IP3)