Case Study Amp2: Wideband Amplifier Design

Design of an 8–12 GHz hJFET Amplifier with 14 dB gain

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Starting Point

Specifications

- 8–12 GHz
- 14 ± 1 dB gain. This is transducer gain: $G_T = \frac{P_L}{P_{Ai}}$
- Maximum noise figure of 1 dB
- Topology
```plaintext
! FILENAME: N32400A.2P VERSION: 5.0.
! NEC PART NUMBERS: NE32400 DATE:06/91
! BIAS CONDITIONS: VDS=2V, IDS=10mA
! NOTE: S-PARAMETERS INCLUDES BOND WIRES.
! GATE: TOTAL 2 WIRES, 1 PER BOND PAD, EACH WIRE 0.0132"(335um) LONG.
! DRAIN: TOTAL 2 WIRES, 1 PER BOND PAD, EACH WIRE 0.0094"(240um) LONG.
! SOURCE: TOTAL 4 WIRES, 2 PER SIDE, EACH WIRE 0.0070"(178um) LONG.
! WIRE: 0.0007"(17.8um) DIAMETER, GOLD

# GHZ S MA R 50

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```
$S_{11}, S_{12}, S_{22}$
$S_{11}, S_{12}, S_{22}, S_{21}$
Input matching network

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

$S_{12}$ is small so $\Gamma_{in}$ is close to $S_{11}$.

We want small so $\Gamma_S = \Gamma_{in}^*$ for maximum power transfer (optimum M1).
Approximate Input Matching Network

\[ \Gamma_S = \Gamma_{in}^* \] for optimum M1.

Curve B is approximate optimum \( \Gamma_S \).
Case Study: Wideband Amplifier Design Using the Negative Image Model. Part B, Image Model
Design approach preview

\( \Gamma_S \) for optimum M1.

What does this look like?

A resistor and negative capacitor in series.
Looking ahead: amplifier design using a negative image model

$$R \vartriangle (-C)$$
Looking ahead: amplifier design using a negative image model
Case Study: Wideband Amplifier Design Using the Negative Image Model. Part C, Gain
Gains

**Maximum Available Power Gain**

\[
G_{MA} = \left| \frac{S_{21}}{S_{12}} \right| \left( k - \sqrt{k^2 - 1} \right)
\]

\[
k = \left( \frac{1 - |S_{11}|^2 - |S_{22}|^2 + \Delta}{2|S_{12}| |S_{21}|} \right)
\]

**Transducer Gain**

\[
G_T = \frac{P_L}{P_{Ai}}
\]

**Maximum Stable Gain**

\[
G_{MS} = \left| \frac{S_{21}}{S_{12}} \right|
\]

Like \(G_{MA}\) at edge of stability \(k = 1\).
Transistor properties

- $G_{MA}$ is undefined from 8 to 12 GHz
  - The amplifier is not unconditionally stable

- $G_{MS}$
  - @8GHz: 16.4 dB
  - @10GHz: 15.8 dB
  - @12GHz: 14.8 dB

- Target transducer gain is 14 dB
  - Achieved by detuning the matching networks

Maximum Stable Gain

$$G_{MS} = \left| \frac{S_{21}}{S_{12}} \right|$$

Like $G_{MA}$ at edge of stability $k = 1$. 
Case Study: Wideband Amplifier Design Using the Negative Image Model. Part D, Noise
Noise

Noisy amplifier model with noisy active device.

Noisy amplifier model with noise-free active device.

- $e_n$ and $i_n$ are partially correlated for a transistor.
- The source admittance determines how they combine.
  - Noise could be minimized with right $Y_S$. 
Noise performance of a two port is described by noise factor $F$ (Noise figure, $NF = 10 \log F$).

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

$r_n$ is the equivalent noise resistance

$y_s = Y_S / Y_0 \quad g_s = \Re\{y_s\}$

$y_{\text{opt}}$ is the optimum value of $y_s$

$F_{\text{min}}$ is $F$ when $y_s = y_{\text{opt}}$
Noise

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

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

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

Circles have increasingly higher NF.
Noise file

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! WIRE: 0.0007"(17.8um) DIAMETER, GOLD

| 0.1 | .999 | -1 | 5.04 | 179 | .002 | 89 | .62 | -1 |
| 0.2 | .999 | -3 | 5.02 | 178 | .004 | 89 | .62 | -1 |
| 0.5 | .999 | -6 | 4.97 | 175 | .008 | 87 | .62 | -4 |
| 1.0 | .997 | -12 | 4.88 | 170 | .016 | 84 | .62 | -8 |
| 2.0 | .990 | -23 | 4.70 | 161 | .030 | 77 | .61 | -15 |
| 3.0 | .980 | -34 | 4.54 | 152 | .042 | 71 | .61 | -22 |
| 4.0 | .970 | -44 | 4.38 | 144 | .052 | 65 | .61 | -29 |
| 5.0 | .950 | -53 | 4.22 | 136 | .062 | 59 | .60 | -36 |
| 6.0 | .930 | -62 | 4.08 | 128 | .071 | 53 | .59 | -41 |
| 7.0 | .910 | -71 | 3.93 | 120 | .079 | 48 | .59 | -46 |
| 8.0 | .890 | -79 | 3.80 | 113 | .086 | 43 | .58 | -51 |
| 9.0 | .870 | -87 | 3.67 | 106 | .092 | 38 | .57 | -56 |
| 10.0 | .860 | -94 | 3.54 | 99 | .099 | 34 | .56 | -61 |
| 11.0 | .840 | -102 | 3.42 | 92 | .104 | 30 | .55 | -65 |
| 12.0 | .820 | -108 | 3.30 | 86 | .109 | 27 | .54 | -70 |
| 13.0 | .800 | -115 | 3.19 | 80 | .114 | 24 | .53 | -74 |
| 14.0 | .790 | -121 | 3.08 | 74 | .119 | 21 | .51 | -78 |
| 15.0 | .770 | -128 | 2.97 | 68 | .123 | 18 | .50 | -83 |
| 16.0 | .750 | -134 | 2.87 | 63 | .127 | 16 | .49 | -87 |
| 17.0 | .740 | -139 | 2.77 | 57 | .131 | 14 | .48 | -91 |
| 18.0 | .720 | -145 | 2.68 | 52 | .135 | 12 | .47 | -95 |
| 19.0 | .710 | -150 | 2.59 | 47 | .138 | 10 | .46 | -99 |
| 20.0 | .690 | -155 | 2.50 | 42 | .142 | 8 | .45 | -102 |
| 22.0 | .660 | -165 | 2.32 | 32 | .148 | 6 | .43 | -109 |
| 24.0 | .640 | -175 | 2.16 | 23 | .153 | 4 | .42 | -116 |
| 26.0 | .610 | -177 | 2.01 | 15 | .159 | 3 | .41 | -122 |
| 28.0 | .590 | 168 | 1.87 | 7 | .163 | 1 | .41 | -128 |
| 30.0 | .570 | 160 | 1.73 | -1 | .168 | 0 | .41 | -134 |

! NOISE PARAMETERS
! NOTE: NOISE PARAMETERS FOR 28 & 30 GHZ
! ARE EXTRAPOLATED, NOT MEASURED.

| 0.30 | .31 | 10 | .39 |
| 0.31 | .79 | 17 | .36 |
| 0.33 | .75 | 31 | .33 |
| 0.38 | .72 | 45 | .30 |
| 0.40 | .70 | 59 | .27 |
| 0.50 | .68 | 77 | .24 |
| 0.60 | .64 | 92 | .22 |
| 0.71 | .64 | 108 | .19 |
| 0.85 | .62 | 126 | .18 |
| 1.00 | .58 | 140 | .15 |
| 1.20 | .55 | 153 | .13 |
| 1.50 | .52 | 164 | .11 |
| 1.80 | .49 | 175 | .10 |
| 2.10 | .48 | -176 | .08 |
| 2.40 | .46 | -168 | .07 |
| 2.80 | .46 | -160 | .05 |
## Noise data

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

### Table: Noise Parameters

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<th>Frequency (ns)</th>
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<th>\Gamma_{\text{opt}}</th>
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Frequency

18
Minimum noise figure

$\text{NF}_{\text{min}}$ on the input ($\Gamma_s$) plane

Minimum noise figure, $\text{NF}_{\text{min}}$:

$\text{NF}_{\text{min}} = 0.38$ dB, $0.41$ dB, $0.43$ dB, $0.47$ dB, $0.50$ dB, $0.55$ dB, $0.60$ dB, $0.66$ dB and $0.71$ dB from 7 to 14 GHz in 1 GHz steps.
Noise figure circles

Noise figure circles at 10 GHz where $\text{NF}_{\text{min}} = 0.5 \text{ dB}$.

Circles have 0.1 dB steps so that the inner most circle indicates the values of $\Gamma_S$ that achieves $\text{NF} = 0.6 \text{ dB}$. 

$\text{NF}_{\text{MIN}}$
0.25 dB noise figure circles.

The noise figure on each circle is $\text{NF}_{\text{min}} + 0.25$ dB.

At 10 GHz circle is for $\text{NF} = 0.75$ dB

cf specification is for $\text{NF} \leq 1$ dB
Curve B is approximately the optimum $\Gamma_S$ for maximum gain.

Points indicate optimum $\Gamma_S$ for minimum noise figure.
Noise vs. Input match

$\Gamma_S$ plane

$S_{11}^*$

$NF_{\text{min}}$

14 GHz

7 GHz
Summary, so far

- There is a reasonable trade-off between optimum input match and good noise performance.
- Still to consider:
  - Stability
  - Network topology that will lead to counterclockwise rotation on the Smith chart
Case Study: Wideband Amplifier Design Using the Negative Image Model. Part E, Stability

30 GHz

2 GHz

30 GHz

POTENTIALLY UNSTABLE

UNCONDITIONALLY STABLE

UNCONDITIONALLY STABLE
Input stability circles

2 GHz steps

$\Gamma_S$ must be in stable region.
Output stability circles

2 GHz steps

$\Gamma_L$ must be in the stable region.
Noise vs. input match vs. stability

$\Gamma_S$ plane

$S_{11}^*$

14 GHz

$7$ GHz

$2$ GHz

$30$ GHz

$NF_{\text{min}}$
Maximum available gain

\[
G_{\text{MAX}} = \begin{cases} 
G_{\text{MA}} = \left| \frac{S_{21}}{S_{12}} \right| (k - \sqrt{k^2 - 1}) & \text{if } k \geq 1 \\
G_{\text{MS}} = \left| \frac{S_{21}}{S_{12}} \right| & \text{if } k < 1
\end{cases}
\]

\[G_{\text{MAX}} = 17.0 \text{ dB}, 16.5 \text{ dB}, 16.0 \text{ dB}, 15.5 \text{ dB}, 15.2 \text{ dB}, 14.8 \text{ dB}, 14.5 \text{ dB}, 14.1 \text{ dB} \text{ at 7 to 14 GHz in 1 GHz steps.}\]
$G_{\text{MAX}}$ circles at 10 GHz in 1 dB steps

The central circle has $G_{\text{MAX}} = 15.5$ dB

(Recall that the target gain is 14 dB)
Summary

- A tradeoff of stability, and noise and gain performance. Input matching network:

- Similar development for output matching network.
Network design using the negative image model

- Previously reached a tradeoff of stability, and noise and gain performance.

- Tradeoff of stability, noise, and gain performances
Case Study: Wideband Amplifier Design Using the Negative Image Model.
Part F, Image Model-Based Design
Amplifier design using a negative image model
Case Study: Wideband Amplifier Design Using the Negative Image Model. Part G, Completing the Design
Completing the amplifier design

- So far:
  - Designed the input/output matching network using input image model.
  - Design tuning of parameters.

- Final stage:
  - Design “real” input and output matching networks independently
  - Assemble entire amplifier
  - Optimize design
    - Use a few select parameters to optimize
Amplifier designed using the negative image model

PORT P=1
Z=22.9 Ohm
CAP ID=C1
C=-0.294 pF
IND ID=L1
L=-0.67 nH

SUBCKT ID=S2
NET="N32400a"

PORT P=2
Z=68 Ohm

Target:
14 dB gain
NF < 1 dB

Designed using tuning as there are only 5 parameters.

Computer optimization could have been used.
Design step

- Topology that produces counter-clockwise locus (with respect to frequency) on Smith chart.
- Well, perhaps just standstill.
“Real” input network design setup

Now design the “Input Network”
Design goal preview

\[ \Gamma_S \]

8 GHz

12 GHz

\[ Z_S = 22.9 \text{ Ohm} \]

\[ C = -0.294 \text{ pF} \]

PORT P=1

CAP ID=C1

\[ S_{21}, S_{12} \]
Simpler design problem.

Input image model

PORT
P=1
Z=50 Ohm

SUBCKT
ID=S1
NET="Input Network"

CAP
ID=C1
C=0.294 pF

RES
ID=R1
R=22.9 Ohm
Design approach preview
Realization of the Input network
Reflection coefficient looking into input matching network

Γ_{in}

Transistor

PORT
P=1
Z=50 Ohm

SUBCKT
ID=S1
NET="Input Network"

CAP
ID=C1
C

RES
ID=R1
R

Γ_{in}

12 GHz
8 GHz
Input network reflection coefficient from transistor
Input network reflection coefficient from transistor
Realization of the output network

Output image model:

Output network

Approximately $\lambda/4$ at 10 GHz.
Reflection coefficient looking into output matching network

PORT
P=1
Z=50 Ohm

SUBCKT
ID=S1
NET="Output Network"

CAP
ID=C1
C=0.346 pF

IND
ID=L1
L=0.67 nH

RES
ID=R1
R=68 Ohm

PORT
P=1
Z=50 Ohm

Output network.
Final stage of design

- So far:
  - Designed the input matching network using input image model. Used tuning of parameters.
  - Designed output matching network using input image model. Used tuning of parameters.

- Final stage:
  - Assemble entire amplifier
  - Optimize design
    - Use a few select parameters to optimize
Final amplifier

Specification:
8–12 GHz
14 dB gain
NF < 1 dB