# Introduction of lab project
--- ELEC 454

(Design and realization of a Two-Stage, Low-Noise Microstrip Transistor Amplifier)

2004. 01. 21

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## Outline

1. Contact information
2. Brief introduction of this lab project
3. The design goal in this project
4. Theory related to amplifier design
5. Initial design
6. Computer Analysis
7. PCB design
6. Manufacture and measurement
7. Project marking scheme
8. Time schedule

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## Contact information

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Lab section: **ELEC454LS02**

Time: **On Feb.4, Feb.25, Mar. 10, and Mar. 24; 14:30 to 17:30**

Location: **ELW-A359**

You may reach me in my lab or office from 9:30am to 5:00pm on week days.

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## Brief introduction of this lab project

1. In order to reinforce the theories and techniques learnt in an engineering course, the best way is to put them into practice. The purpose of this laboratory project is to realize a complete microstrip transistor amplifier using the design methods discussed in this course as well as employing commercial design software packages.
2. We will design a two-stage low noise amplifier working in the frequency range of 1.4 to 1.6GHz.
3. The active devices are RF bipolar transistors which are easier to match at these frequencies and offer almost the same noise performance as FETs.

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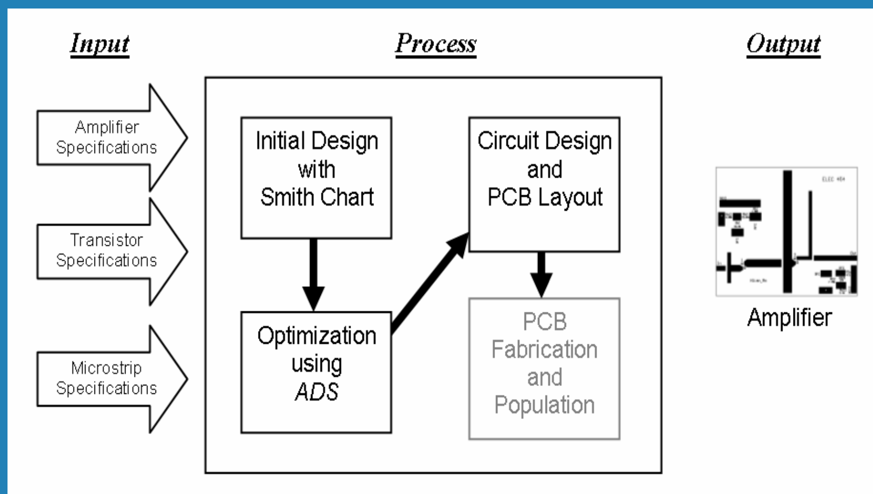
# Design flow of this project

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# The design goal in this project

| Amplifier Specifications | |
|---|---|
| Frequency Band | 1.4 to 1.6GHz |
| Gain | ≥ 20 dB ± 0.5 dB |
| Noise Figure | < 2 dB |
| $S_{11}$ | < -10 dB |
| $S_{22}$ | < -16 dB |

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## Theory related to amplifier design

***Stability Check***

For a two-port device with a 2×2 S-parameter matrix, the stability factor is given as

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21}$$

where $\Delta$ is the determinant of the scattering matrix.
A two-port device is unconditionally stable if $K > 1$ and $|\Delta| \leqslant 1$.

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## Theory related to amplifier design

The stability circles:

Center of output stability circle:

$$C_L = \frac{(S_{22} - \Delta S_{11}^*)^*}{|S_{22}|^2 - |\Delta|^2}$$

Radius of output stability circle:

$$R_L = \left| \frac{S_{12} S_{21}}{|S_{22}|^2 - |\Delta|^2} \right|$$

Center of input stability circle:

$$C_S = \frac{(S_{11} - \Delta S_{22}^*)^*}{|S_{11}|^2 - |\Delta|^2}$$

Radius of input stability circle:

$$R_S = \left| \frac{S_{12} S_{21}}{|S_{11}|^2 - |\Delta|^2} \right|$$

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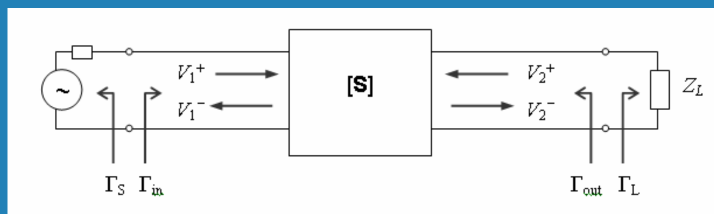
# Theory related to amplifier design

***Gain***

Considering a simple network with a single two-port device, the parameters can be defined as illustrated.




By definition, we have

$$V_2^+ = \Gamma_L V_2^-$$
$$V_1^- = S_{11} V_1^+ + S_{12} V_2^+$$
$$V_2^- = S_{21} V_1^+ + S_{22} V_2^+$$

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# Theory related to amplifier design

Therefore, we can solve for $\Gamma_{in}$ as

$$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11} + \frac{S_{12} S_{21} \Gamma_L}{1 - S_{22} \Gamma_L}$$

Similarly, the output reflection coefficient is given as

$$\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22} + \frac{S_{12} S_{21} \Gamma_S}{1 - S_{11} \Gamma_S}$$

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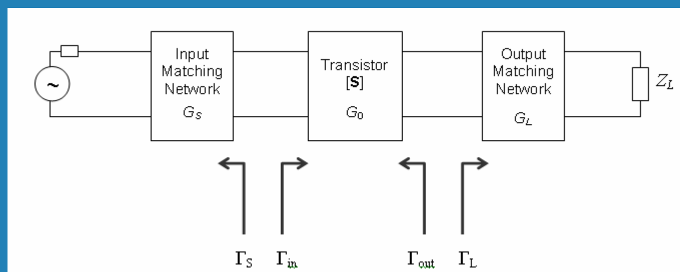
## Theory related to amplifier design

For single transistor amplifier:




the total gain is given by: $G_T = G_S \cdot G_0 \cdot G_L$

$$G_S = \frac{1-|\Gamma_S|^2}{|1-\Gamma_{in}\Gamma_S|^2} \quad G_0 = |S_{21}|^2 \quad G_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}$$

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## Theory related to amplifier design

In order to have the maximum power transferred, we want to use conjugate impedance matching, therefore we have:

$$\Gamma_{in} = \Gamma_S^* \quad \Gamma_{out} = \Gamma_L^*$$

The maximum total gain resulting from this match, assuming lossless sections, becomes:

$$G_{T_{\max}} = \frac{1}{1-|\Gamma_S|^2}|S_{21}|^2 \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}$$

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## Theory related to amplifier design

***For a bilateral device we have:***

$$\Gamma_S = \frac{B_1 \pm \sqrt{B_1^{\,2} - 4|C_1|^2}}{2C_1} \qquad B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2$$

$$B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2$$

$$\Gamma_L = \frac{B_2 \pm \sqrt{B_2^{\,2} - 4|C_2|^2}}{2C_2} \qquad C_1 = S_{11} - \Delta S_{22}^*$$

$$C_2 = S_{22} - \Delta S_{11}^*$$

Once $\Gamma_S$ and $\Gamma_L$ are identified, the input and output matching networks can be built for optimum gain.

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## Theory related to amplifier design

***For a unilateral device we have:*** $S_{12} = 0$

$$\Gamma_S = S_{11}^{\ *} \qquad \Gamma_L = S_{22}^{\ *}$$

In this case, the maximum total transistor gain is given by

$$G_{TU_{\max}} = \frac{1}{1 - |S_{11}|^2} |S_{21}|^2 \frac{1}{1 - |S_{22}|^2}$$

Obviously a unilateral device has much simplified equations, therefore even when $S_{12}$ is small but not exactly zero, it may still be desirable to assume the unilateral case for initial designs if the discrepancy is acceptable.

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## Theory related to amplifier design

The range of the error introduced by this assumption can be approximated by the *unilateral figure of merit*:

$$U = \frac{|S_{12}||S_{21}||S_{11}||S_{22}|}{(1-|S_{11}|^2)(1-|S_{22}|^2)}$$

$$\frac{1}{(1+U)^2} < \frac{G_T}{G_{TU}} < \frac{1}{(1-U)^2}$$

If the requirements specified allow such error range, the device can be assumed unilateral for a quicker design.

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## Theory related to amplifier design

***Noise Figure:***

Circles of constant noise figure:

Center: $C_F = \frac{\Gamma_{opt}}{N+1}$

Radius: $R_F = \frac{\sqrt{N\left(N+1-|\Gamma_{opt}|^2\right)}}{N+1}$

$$N = \frac{F - F_{min}}{4R_N / Z_0}|1+\Gamma_{opt}|^2$$

for a cascaded system with several two-port devices like the one we have, the overall noise figure is given as

$$F_{overall} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots$$

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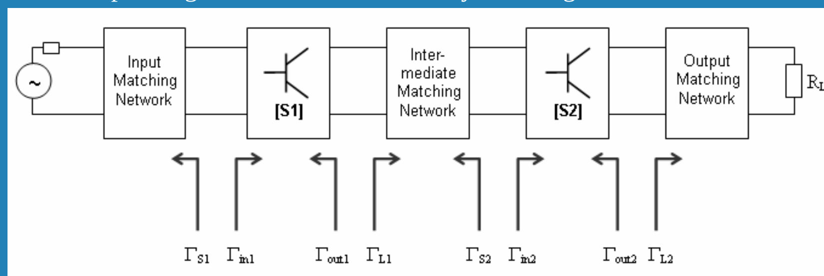
## Initial design

The objective of our project is to design a two-stage amplifier operating in the 1.4 to 1.6 GHz range. Both the minimum noise figure and maximum transducer power gain should be achieved by the design.




The design should employ two bipolar transistors, NE85639: the first one should operate at $V_{CE}$ = 10V and $I_C$ = 7mA for low noise condition, the second one should be optimized for power amplification at $V_{CE}$ = 10V and $I_C$ = 20mA.

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## Initial design

The S-parameters of the transistor for the two bias conditions at 1.5GHz and $Z_0$ = 50 Ω were provided by the manufacturer. So we can proceed according to the theory presented in the previous slides:

***1. Stability Check***
***2. Noise Figure Check***
***3. Input Matching Network design***
***4. Inter-Stage Matching Network design***
***5. Output Matching Network design***

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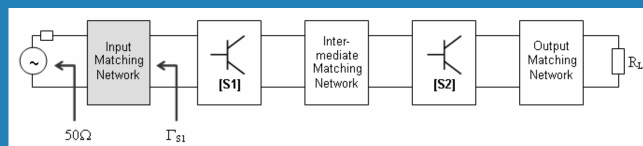
# Input Matching Network




The first stage has the dominant effect on the overall system noise; therefore, we want it to be as small as possible. The noise is minimized when $\Gamma_{S1} = \Gamma_{opt}$.

- $\Gamma_{opt}$ is given ($0.43e\text{-}j174°$) so by using a Smith Chart, we can match $\Gamma_{S1}$ to the characteristic impedance of 50Ω to get the input matching network.
- In order to make the stub susceptance less sensitive to frequency changes, we change the L-section network to a T-section by replacing the single shunt stub by two shorter stubs.

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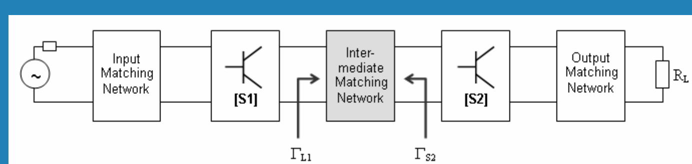
# Inter-stage Matching Network




The inter-stage matching network should ensure that maximum power output from transistor 1 is transmitted to transistor 2.

- With conjugate matching, matching $\Gamma_{out1}$ to $\Gamma_{in2}$ becomes equivalent to matching $\Gamma_{L1}$ to $\Gamma_{S2}$, because $\Gamma_{L1} = \Gamma_{out1}^*$ and $\Gamma_{S2} = \Gamma_{in2}^*$.
- Since we had determined $\Gamma_{S1}$ to be $0.43e\text{-}j174°$, we can calculate $\Gamma_{out1}$.
- Solving the simultaneous equations we can find $\Gamma_{S2}$ and $\Gamma_{L2}$.
- Therefore our inter-stage matching network should match $\Gamma_{S2} = \Gamma_{out1}^*$ to 50Ω and match $\Gamma_{L1} = \Gamma_{in2}^*$ to 50Ω

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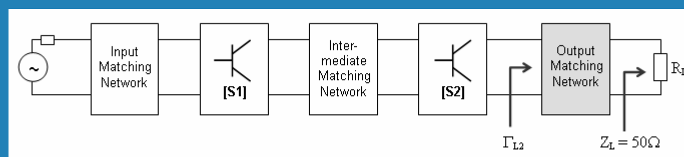
## Output Matching Network




- Finally we design the output matching network. In the same way as we have calculated the inter-stage matching network, we can calculate $\Gamma_{L2} = \Gamma_{out2}{}^*$.

- We can design the output matching network by matching $\Gamma_{L2}$ to the load impedance of 50Ω.

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## Computer Analysis

Using the parameters we found from the Smith Charts, we employ the “ADS” simulation software to validate and optimize our design.

Initial check: stability circles, noise circle

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Initial Results with ideal transmission lines

↓

Initial Results with realistic microstrip elements

↓

Optimization

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Final Parameters

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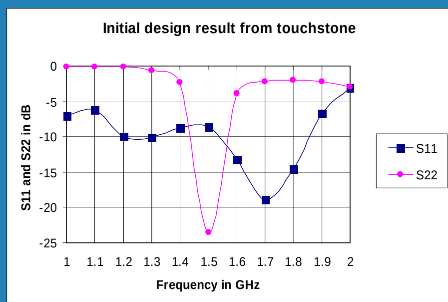
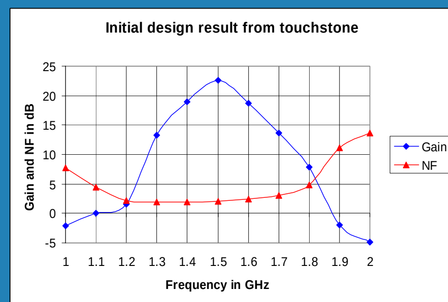
# Computer Analysis

Initial design result with ideal transmission line elements :

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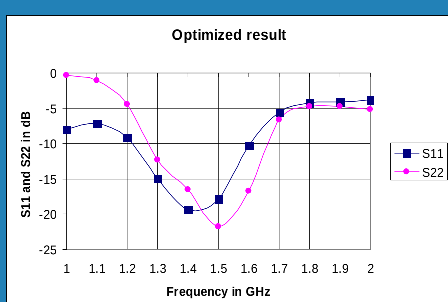
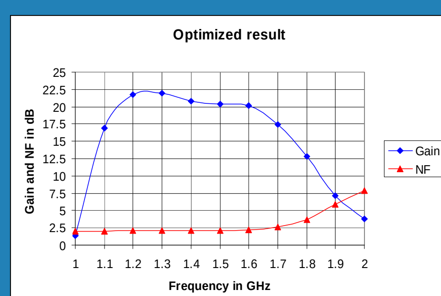
# Computer Analysis

Optimized result:

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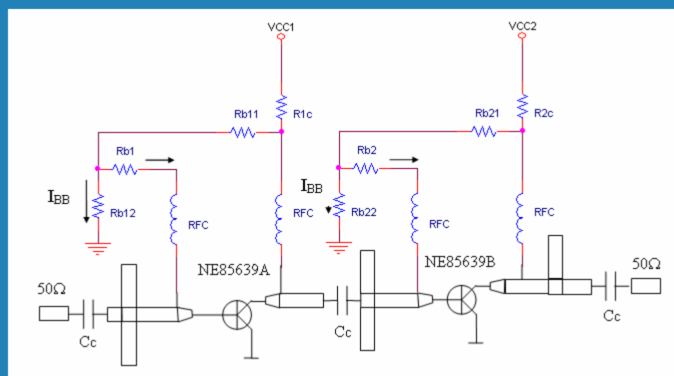
# PCB Design

Overall Circuit Design with Bias Circuits and Matching Networks

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# PCB Design

***Bias Circuit Design:***

| For the first stage | For the second stage |
|---|---|
| $V_{CE}$ = 10V  $I_C$ = 7mA<br>$h_{FE}$ = 120  $V_{CC}$ = 20V | $V_{CE}$ = 10V  $I_C$ = 20mA<br>$h_{FE}$ = 120  $V_{CC}$ = 20V |

Using the assumptions that for both stages: $V_{BE}$ = 0.7V, $I_{BB} = 5I_B$, $V_{BB}$ = 2V, we can calculate:

| For the first stage | For the second stage |
|---|---|
| $Rb_1$ = 22.3k Ω<br>$Rb_{11}$ = 22.84k Ω<br>$Rb_{12}$ = 6.85k Ω<br>$R_{1C}$ = 1.36k Ω | $Rb_2$ = 7.78k Ω<br>$Rb_{21}$ = 10k Ω<br>$Rb_{22}$ = 2.4k Ω<br>$R_{2C}$ = 476 Ω |

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# PCB Design

***Board Layout:***

You can create your layout according to your optimized transmission line parameters and bias circuit design.

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# Manufacture and Measurement

- Our amplifier board will be fabricated by an external company and populated by the lab technician.
- When the board is ready, we will check the bias circuits using a regular power supply and a digital multi-meter.
- We then verify our design by measuring gain and noise figure over the specified frequency band (1.4 to 1.6 GHz).

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## Project marking scheme

| | |
|---|---|
| **Initial Design (using Smith Chart)**<br>Stability circles<br>Noise circle<br>Input matching network<br>Inter-stage matching network<br>Transducer Power Gain | 30 |
| **Computer Analysis (using ADS)**<br>Stability circles<br>Noise circle<br>Analysis of the first design using 'ideal' elements | 10 |
| **Optimization and Final Layout**<br>Replace ideal microstrip line with 'real' microstrip elements<br>Optimize using ADS<br>Bias circuit design<br>Print layout | 25 |

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## Project marking scheme (continued)

| | |
|---|---|
| **Testing**<br>Test bias voltages of completed amplifier<br>Measure gain and noise figure<br>Compare with expectations | 5 |
| **Discussions/Conclusions** | 15 |
| **Overall Report**<br>Introduction<br>Initial design data, observation, discuss difficulties, problems, etc.<br>Touchstone design data, observation, discuss difficulties, problems, etc.<br>PCB design …… | 15 |
| **Total** | 100 |

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## Time schedule

**Lab period 1:** (Feb. 4, 2:30-5:30pm ELW-A359)

Using transistor data, make a preliminary design of the amplifier at 1.5GHz following the steps shown on page a-16 in lab manual.

**Lab period 2:** (Feb. 25, 2:30-5:30pm ELW-A359)

Computer analysis by using ADS

Bias circuit design

**Lab period 3:** (Mar. 10, 2:30-5:30pm ELW-A359)

Optimized amplifier design

Finish final PCB board

**Lab period 4:** (Mar. 24, 2:30-5:30pm ELW-A359)

Testing of the amplifier

**Lab report is due one week after the last lab.**

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