A Low Noise Amplifier with HF Selectivity

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Abstract

This report describes the design work of a high frequency amplifier with image rejection filter. This amplifier is designed to be used as an input stage in a superheterodyne receiver for the analog FM radio (88-108 MHz). The design includes several areas that a radio designer must have good knowledge about, for example matching, filter design and measurement methods.

The final circuit fulfilled the specifications of image rejection, gain and noise performance.
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1. PREFACE

In this project a Low Noise Amplifier (LNA) with High Frequency (HF) selectivity was constructed. It was designed to be an input stage for an FM receiver and should be able to work within the specified frequency band 88-108MHz. Except for the LNA itself it contains several filters to fulfill the specifications of pre-selection and image rejection.

For the construction procedure the Matlab toolbox deslib0401 (Dept. of Electroscience, Lund University) was used, the layout was created in a PCB tool Eagle and measurements and verifications was performed with a Vector Network Analyzer.

Larger figures are found in the appendices.
2. SPECIFICATION

- Operating frequency: 88-108 MHz
- Noise figure: $F \leq F_{min} + 3$ dB
- Gain: $G \geq |S_{21}|^2$
- Source impedance: 50Ω
- Load impedance: 50Ω
- Image rejection $\geq 20$ dB
- $V_{cc}$: 12V
- Channel bandwidth: 200kHz
- Tunable over the entire frequency range
- Matching network both at input and output

3. THEORY

This section describes some basic theory.

3.1. IMAGE REJECTION

When the modulated signal shall be converted from the carrier frequency to the intermediate frequency the signal can be mixed with a signal from a Local Oscillator. The output frequency from the mixer consists of $f_{\text{out,mixer}} = (f_{\text{signal}} + f_{\text{LO}})$ and $(f_{\text{signal}} - f_{\text{LO}})$. The last term is the down converted signal. The problem is that there is another frequency that also will be down transformed and will overlap with the wanted signal. This frequency is called image frequency and must be filtered out before the mixing stage. If high-side injection is used the image frequency is located at $f_{\text{signal}} + 2(f_{\text{LO}} - f_{\text{signal}})$. In the FM receiver this frequency is $f_{\text{signal}} + 2 \times 10.7$ MHz.
4. CONSTRUCTION PROCEDURE

This section describes the different parts of the construction procedure. The Low Noise Amplifier does not only contain a transistor but also an input matching network and an output matching network for impedance matching between the antenna, the transistor and the output for the next stage. The matching networks also contain filter to select frequency band. Figure 4.1 describes the block diagram of the construction.

![Figure 4.1. Block diagram of the LNA.](image)

4.1. CHOICE OF TRANSISTOR

The first step in the design is to choose a proper transistor. We selected BFR520 because of its good compromises of noise and gain characteristics, but also because it was available on a test board in the lab.

![Figure 4.2. Noise figure as function of collector current.](image)  
![Figure 4.3. Noise figure as function of frequency.](image)

The choice of bias point was made with help of the transistor data sheet [1], see figure 4.2 and figure 4. The bias point $V_{CE} = 6\, \text{V}$ and $I_C = 10\, \text{mA}$ was chosen. This was a good compromise between the added noise and the transistor gain. Some approximations had to be made to find this point because there was no curve for our operation frequency interval. We choose to use the transistor in Common Emitter (CE) mode which offers gain in both current and voltage.
4.2. Stability, gain and noise behavior

To see if the specification of the amplifier is fulfilled the stability, gain and a noise circle was plotted for the chosen bias point with measured $S$-parameters. Our measurement showed that the transistor was conditional stable and could be used if $\Gamma_S$ and $\Gamma_{OUT}$ was chosen in the stable regions. Different input reflection coefficients was tested and $\Gamma_S (Z_S = 50 - j50 \ \Omega)$ which gave $\Gamma_{OUT}$ and $\Gamma_L = \Gamma_{OUT}^* (Z_L = 186 + j104 \ \Omega)$ was finally chosen. Note that $\Gamma_{OUT}$ was located close to the output stability circle, this could cause stability problems if the input was not correctly matched. Figure 4.4 shows all the plotted parameters.

![Figure 4.4. Stability, Gain, Noise circles and reflection coefficients.](image)

4.3. Matching network at input

The purpose of the input matching network is both to match the 50Ω antenna to the input of the transistor and to filter out unwanted signals. This filter is necessary to filter out strong signals that could drive the transistor into compression and thereby create intermodulation products. The filter topology was chosen as a PI-network bandpass filter with a bandwidth of 40 MHz to minimize the attenuation within the wanted frequency band. The circuit layout of the input network is shown in figure 4.5, where $Z_S$ is the antenna impedance and $Z_L$ the chosen input of the transistor 50 – j50 Ω.

![Figure 4.5. Input matching network.](image)

A simulation of the filter characteristic showed that it had the wanted appearance with a $B_{3db}$ bandwidth of (115.2 - 75.14) MHz = 40.06MHz.
4.4. Matching network at output

The output network contains the image rejection filter and should also match $\Gamma_L = \Gamma_{\text{OUT}}^* (Z_L = 186 + j104 \, \Omega)$ to 50Ω in the next stage.

The constructed filter consists of three components, one capacitor and two inductors, see figure 4.6. At the wanted signal frequency the parallel circuit has maximum impedance and consist of $L_2$ and $C_2$. At the image frequency the series circuit consisting of $L_1$ and $C_2$ has minimum impedance and forces this frequency directly to signal ground. See the filter shape in figure 4.7.

![Image rejection filter](image)

Figure 4.6. Image rejection filter, a part of the output matching network.

The distance between impedance tip and dip can be adjusted by $L_2$. By adjusting $C_2$ the whole filter characteristic can be tuned in frequency, this to be able to tune in a specific radio channel and efficiently reject its image. By implementing $C_2$ with a variable capacitance diode the frequency adjustments can be coordinated with the adjustments in the local oscillator. The channel bandwidth in FM radio is 200 kHz. The ideal filter does not fulfill this specification but when the filter is connected to the rest of the circuit, the total resistance lowers the Q value and thereby gives a greater bandwidth. This hopefully will fulfill the specifications.

![Filter characteristic](image)

Figure 4.7. 10log₁₀ |Z| of image rejection filter.

4.5. Transistor biasing

For the biasing network a passive voltage driven biasing was chosen, see figure 4.8. This type of transistor biasing has the advantage of low temperature dependency in the collector current, it has excellent bias stability and the resistor $R_C$ can be replaced by a Radio Frequency Choke. The drawback of this biasing configuration is that the transistor may be instable for high frequencies (GHz), but in our case it will operate at lower frequencies (100 MHz), so it should not be a problem. In this case a part of the image rejection filter can be used for the RFC. The feedback is
provided by $R_F$ that converts the current through the resistor to a voltage that is fed back to the transistors base. When a RFC is used, the resistor $R_C = 0$, this gives the following equations for the circuit [2]:

\[
\begin{align*}
R_C &= 0 \\
R_E &= \frac{V_{CE} - V_{CE}}{I_C(1 + \frac{1}{\beta_0})} \\
R_{B1} &= \frac{V_{CE} - V_{BE} - I_E R_E}{I_D} \\
R_{B2} &= \frac{V_{BE} + I_E R_E}{I_D}
\end{align*}
\]

The data sheet showed that at $V_{CE} = 6V$ and $I_C = 10mA$ the current gain $\beta_0 \approx 120$. One design criteria for this bias configuration is that $I_D \gg I_B$ so for simplicity $I_D = I_C = 10mA$ was chosen. When all bias currents and voltages was known, the resister values could be determined. $R_C = 0\Omega$, $R_E = 595\Omega$, $R_{B1} = 560\Omega$, $R_{B2} = 670\Omega$.

### 4.6. Circuit Layout

![Total amplifier circuit.](image)

### 4.7. PCB Layout

![PCB layout.](image)
When the components were placed on the PCB-board we first started with the input filter and performed measurements on that part to be sure that the filter was correctly designed. The same type of measurements was performed on the image rejection filter. This was done to be able to eliminate possible error sources when everything was put together.

The input matching network showed the desired filter characteristic with a band pass shape and a $B_{3db}$ bandwidth of approximately 40MHz. Also the image rejection filter at output showed the desired characteristics. Before constructing the whole output matching network the image rejection filter was tuned to the center frequency (98MHz). Measurements showed that to match the output to 50Ω we needed a shunt coil and a series capacitor (also used as a coupling capacitor). Note that the shunt coil must be connected to the same potential as the filter to avoid short circuiting of the power supply.

Then the whole circuit was put together measurements and verifications was performed. It showed that the input was stable in the entire measured frequency range (50-150MHz), but there was an instability problem at the output at 87MHz, see figure 5.1. This can be observed in the Smith chart for $S_{22}$, where the reflection coefficient is outside the unity circle, but also in $S_{12}$ and $S_{21}$ as an amplitude top at the instability frequency.

To make the amplifier stable for all wanted frequencies the transistor could be changed, a redesign of the matching networks could be performed or a change of the biasing point could be done. We chose to change the bias point. Measurements showed that the amplifier was stable if the collector current was reduced to 2mA. The problem was that the S-parameters of the transistor depend on the bias point, this affect the input and the output matching network so they no longer are optimal. Measurements showed that the matching actually got better after this change of bias point, see figure 5.2. The total characteristic for the amplifier is
showed in $S_{21}$, where it is seen that the image rejection is almost 20dB which was the specified value. The gain was $15\text{dB} \geq |S_{21}|^2$ which also fulfills the specifications.

![Figure 5.2. S-parameters with reduced biasing current.](image)

The noise performance was measured in a shielded room to avoid disturbance from the surroundings. Measurements showed that the noise was almost constant below 3dB in the frequency band 88-108MHz. This noise performance was not optimal because there was no redesign of the matching networks after reducing the collector current. Better performance could be achieved, but this was not necessary because the specification was already fulfilled with the present design, see figure 5.3.

![Figure 5.3. Noise performance measurement.](image)

As a final verification a measurement of compression point was performed, see figure 5.4. At the center frequency 98MHz the compression point referred to the output was $-12.7\text{dBm}$. Because of the amplifier gain, the maximum input power was
-27.7dBm. This should not be a problem because the received signal power was much lower.

Figure 5.4. Compression point measurement.

6. CONCLUSIONS

The designed circuit fulfilled the specification but there are some improvements that could been performed.

The choice of bias point should be selected more carefully to avoid problems with stability. This could easily have been performed by measurements at several bias points to find the bias currents and voltages that give the most stable operation. If these have been done properly from the beginning there would not be any stability problems because of the high collector current.

The input matching network has two functions, it should work both as a matching network between the antenna and the transistor and as a band pass filter between 78-118 MHz. In the filter design we had to take into account the transistor input capacitance and use it as a part of the filter to obtain a proper filter function. We succeeded with both matching and the bandwidth of the filter, but when we introduced a change in bias current this effected the matching and thereby the noise performance. The noise performance could be improved if the input matching network had been redesigned but this was not necessary because the specification was already fulfilled.

Worth to note is that there are great stability problems with the chosen bias network. To be able to offer a stable signal ground a lot of coupling capacitors is needed, especially critical is the coupling capacitors on the transistor emitter.

The part of the design that was most successful was the image rejection filter that fulfilled the specification of 20dB rejection. An ordinary Butterworth or Chebychev filter would be of an order that requires a great number of components, which is unpractical. This filter was also a part of the output matching network, and
because of the complexity of this filter the output matching network was difficult to calculate. Instead we used the network analyzer to determine how the output matching network should be constructed. Measurements showed that a shunt inductor and a series capacitor were needed to match the output to 50Ω. The capacitor was tuneable to make it possible to adjust the output matching.

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8. References


9. APPENDICES

9.1. FIGURE 4.4

[Frequency response diagram with various markers and labels, including $F = F_{min} + 3\text{dB}$, $F = 1.8\text{dB}$, $G \geq |S_{21}|^2$, and other annotations.]
Appendices

9.2. **Figure 5.1**

9.3. **Figure 5.2**
9.4. FIGURE 5.3

9.5. FIGURE 5.4