RF Amplifier with Mirror Frequency Filter

Qiran Zhou  07SOC  
Lunds tekniska högskola  
Supervisor: Göran Jönsson

Abstract

When using traditional RF filter, we usually need 7 to 8 orders to achieve the goal of mirror frequency rejection. By using the mirror frequency filter introduced in this report in a RF amplifier, we can just only use three components to reject mirror frequency and at the same time amplify the signal at the desired frequency.
# Contents

1 Preface .................................................................................................................. 2

2 Mirror Frequency Filter .......................................................................................... 3
   2.1 Mirror Frequency .............................................................................................. 3
   2.2 Mirror Frequency Rejection ............................................................................ 3

3 RF Amplifier Design and Simulation ...................................................................... 8
   3.1 Transistor Selection ......................................................................................... 8
   3.2 Biasing Circuit Design ..................................................................................... 9
   3.3 Parameters Choosing ...................................................................................... 9
   3.4 Input Matching Network .................................................................................. 10
   3.5 Output Matching Network ............................................................................... 11
   3.6 Prototype of RF Amplifier and Simulation result ......................................... 11
   3.7 PCB Layout ..................................................................................................... 13

4 Results ..................................................................................................................... 14
   4.1 Original Result .................................................................................................. 14
   4.2 Current Result .................................................................................................. 14

5 Conclusion ............................................................................................................... 17

6 Acknowledgements ................................................................................................. 18

7 Reference ................................................................................................................ 18

8 Appendix ................................................................................................................ 19
   8.1 Simulation by Matlab ....................................................................................... 19
1 Preface

In this project an RF amplifier with tunable mirror frequency rejection function should be constructed. It was designed to work within the specified frequency band 88-108MHz. Since the main task is mirror frequency 109.4-129.4MHz rejection, a tunable filter will be implemented at the output stage. Traditionally, an RF filter with 7 to 8 stages will be needed, in order to achieve at least 20dB mirror frequency rejection. But in RF amplifier, it is impractical by using this kind of filter. Here, I will introduce a special filter as a part of the output stage. And the matching networks at both input and output and stability problems will also be considered during the design.

For the whole construction procedure the Matlab toolbox deslib0401 and ADS will be used. Eagle 5.0 will be selected as the tool of PCB layout. Finally, Vector Network Analyzer will perform measurements and verifications.

The general specification is listed as follows:

**Compulsory**
- Operating frequency: 88-108 MHz
- Source impedance: 50Ω
- Load impedance: 50Ω
- $V_{cc}$: +12V
- Image rejection $\geq$ 20 dB
- Tunable over the entire frequency range

**Optional**
- Noise figure: $F \leq F_{\text{min}} +2$ dB
- Gain: $G \geq |S_{21}|^2$
- Matching network both at input and output
2 Mirror Frequency Filter

2.1 Mirror Frequency

In radio reception using heterodyning in the tuning process, the mirror frequency is an undesired input frequency that is capable of producing the same intermediate frequency (IF) that the desired input frequency produces. It is a potential source of interference to proper reception.

In a heterodyne receiver, a mixer fed by a local oscillator whose frequency $f_{LO}$ is tunable converts the desired input frequency $f_{RF}$ to a fixed IF $f_{IF}$ that then passes through selective filter(s), amplification and detection. The output of a simple mixer contains the sum and difference of its two input frequencies. Here if high injection is chose, the mirror frequency equals to the station frequency plus twice the intermediate frequency ($f_{mirror} = f_{RF} + 2f_{IF}$). Because mirror frequency will be down transformed and will overlap with the wanted signal, it must be filtered out before the mixing stage. Mirror frequencies can be eliminated by sufficient attenuation on the incoming signal by the RF amplifier filter of the superheterodyne receiver.

Here FM receiver and should be able to work within the specified frequency band 88-108MHz. Intermediate frequency is defined as 10.7MHz. So the range of mirror frequency is from 109.4MHz to 129.4MHz.

2.2 Mirror Frequency Rejection

When doing a detailed research, we chose the following circuit as a filter at the output stage. At the desired frequency the paralleled circuit consisting of $L_2$ and $C_2$ has the maximum impedance. At the mirror frequency the series circuit consisting of $L_1$ and $C_2$ has the minimum impedance, so that the mirror frequency can be effectively suppressed.

![Figure 1. Circuit of mirror frequency filter](image)

Here the distance between amplitude tip and dip can be adjusted by
both $L_1$ and $L_2$. $L_1$ will set the dip of the amplitude and $L_2$ will set the tip of the amplitude. Then by adjusting $C_2$ the whole filter characteristic can be tuned in frequency, this is able to tune in a specific radio channel and efficiently reject the mirror frequency. Here the specified frequency band is 88-108MHz. Mirror frequency from 109.4MHz to 129.4MHz should be suppressed.

After comparing various parameters of inductors and capacitor, we choose the following prototype of the mirror frequency filter (100MHz).

![Figure 2. Prototype of the mirror frequency filter](image)

Then we can see the results figures of simulation based on the software ADS2006A. The format of the figures is ‘Gain as a function of frequency’. We just need to change $C_1$ from 570pF to 800pF, so that the tip will change from 88MHz to 108MHz and dip will change from 109.4MHz to 129.4MHz.
Figure 3. Mirror frequency filter at 88MHz ($C=570\text{pF}$)

Figure 4. Mirror frequency filter at 100MHz ($C=650\text{pF}$)

Figure 5. Mirror frequency filter at 108MHz ($C=800\text{pF}$)

From the charts above, we can see the tip and top frequencies are very
accurate and the mirror frequency rejection is far more than 20dB. So the mirror frequency filter perfectly fulfills the specification. Because the simulation results above are based on the ideal components, we should do further simulation. From the components specification, we can get Q factors of two inductors. With the help of ADS2006A, we can do the more accurate simulation.

Figure 6. Mirror frequency filter at 88MHz (C=570pF)

Figure 7. Mirror frequency filter at 100MHz (C=650pF)
Figure 8. Mirror frequency filter at 108MHz (C=800pF)
From the figures above, we can see the tip and dip frequencies change a little compared to the ideal ones and the mirror frequency rejection is reduced to around 20dB when considering Q of inductors. But the mirror frequency filter still fulfills the specification. As a result, we can foresee that the mirror frequency filter will have a good performance when integrated in the RF amplifier.
3 RF Amplifier Design and Simulation

3.1 Transistor Selection

In this project, I select Philips BFG520x which is recommended as the transistor of RF amplifier. From the data sheet, we can get some practical information.

![Minimum noise figure and associated available gain as functions of collector current](image1)

Figure 9. Minimum noise figure and associated available gain as functions of collector current

From the figure above, we can choose 5mA and 6V as DC working current and voltage, so that we can get the best noise figure and proper transducer gain. Here we can use the noise figure at 500MHz. So we can get $F_{\text{min}} = 0.8\text{dB}$.

![DC current gain as a function of collector current](image2)

Figure 10. DC current gain as a function of collector current.
Here we have chosen $V_{CE} = 6V$ and $I_C = 5mA$, so we can get $\beta_0 = 125$ according to the figure above.

### 3.2 Biasing Circuit Design

![Biasing Circuit Diagram](image)

3.2 Biasing Circuit Design

There are some different biasing circuits: current driven biasing, voltage driven biasing and active biasing. In the project, a current driven biasing circuit is used which is shown in figure 11. It has moderate bias stability, less sensitive to current gain and high loop gain.

We have already chosen $V_{CE} = 6V$ and $I_C = 5mA$, the current gain $\beta_0 = 125$. According to the formula in the textbook and the real available components, we can get the parameters of the transistors: $R_C = 1.1k\Omega$ $R_{B1} = 9.1k\Omega$ $R_{B2} = 3k\Omega$ $R_{B3} = 20k\Omega$.

### 3.3 Parameters Choosing

The S-parameters will change slightly when the frequency is changing from 88MHz to 129.4MHz. So in initially design, we can just use the S-parameter of transistor BFG520x at 100MHz. According to the available data sheet, we can get the following parameters: $r_n = 0.27$ $\Gamma_{opt} = 0.439\angle29^\circ$ $F_{min} = 0.9dB$ $F < 2.9dB$. Then we can draw all the input and output stability, noise figure, available gain circles in matlab.
According to the figure, we can see $\Gamma_{S\text{Gain}}$ is among the 22.8dB Gain Circle and 2.9dB Noise Circle, so if we design a good input and output matching network, the noise and gain of the RF amplifier will perfectly fulfill the specification. The problem is that the $\Gamma_{L\text{Gain}}$ is in the unstable region, it will be easy to cause the instability problem. Although we can choose $\Gamma_{S\text{Gain}}$ outside the 22.8dB Gain Circle, so that $\Gamma_{L\text{Gain}}$ will be located in the stable region. The simulation result by using ADS2006A indicates that there will be instable problem at the input. After a long time simulation, we finally choose the above $\Gamma_{S\text{Gain}}$ and $\Gamma_{L\text{Gain}}$ according to the available components and the specification. There is no stability problem at both input and output. It will have a good performance on mirror frequency rejection, but it will get a comparably lower gain.

### 3.4 Input Matching Network

One of the reasons why we choose $\Gamma_{S\text{Gain}}$ at that point is that we can just simply use a capacitor to match the input. The simple
matching network will cause fewer problems on matching and stability. Another important reason is that we should also choose GammaS according to the behavior of mirror frequency filter at the output. Here we use a 68pF capacitor as input matching network.

3.5 Output Matching Network

We directly use mirror frequency filter as the output matching network. Simple is one reason. And the stability is another reason. Although by using mirror frequency filter as the output matching network will cause a comparably huge loss at the gain, it will have a good performance on mirror frequency rejection and stability.

3.6 Prototype of RF Amplifier and Simulation result

Now we can get the final prototype of RF amplifier as follows:

![Figure 13. Prototype of RF amplifier](image-url)
Then we can see the simulation result based on both Matlab and ADS2006A.

Figure 14. Simulation result based on Matlab (100MHz)

Figure 15. Simulation result based on ADS2006A (100MHz)
Simulation result from Matlab is simply based on the ideal components. And the simulation result from ADS2006A is based on the more actual components, so it is more reliable. From the simulation result based on ADS2006A, we can see there is no stability problem at both input and output and the performance of mirror frequency rejection is also perfect. The only drawback of the design is the comparably low gain. The reason is that although we can design a perfect RF amplifier theoretically, we can not achieve it at the real environment due to the confine of the real components and other real problems.

3.7 PCB Layout

Considering the usability, I choose Eagle 5.0 as the PBC Layout tool. After carefully design, we get the final PCB Layout of the RF amplifier as follows.

Figure 16. PCB layout of RF amplifier
4 Results

4.1 Original Result

When I do the measurement using the circuit according to my original design, I find the actual result is so different from the simulation result. The filter actually works during the frequency range between 60MHz – 80MHz. And the distance between tip and dip is also less than 21.4MHz. There are two reasons I can find. The first one is the different behavior of the real components compared to the ideal ones. And the second is mismatch between the collector of the transistor and the filter. So here I must do some changes in the filter. Because here I can not depend on the simulation software, I just can change the components according to my experience when designing the filter and the actual situation.

4.2 Current Result

After trying several times, I change $L_1$ from 8.2nH to 4.7nH. At the same time, $C_2$ can be adjusted from 270pF to 330pF. Now we can get the following results.

\[ L_1 \text{ from 8.2nH to 4.7nH} \]
\[ C_2 \text{ from 270pF to 330pF} \]

From the figure above, we can see the mirror frequency rejection is
about 17.5dB, so close to 20dB. And it is obvious that the filter has a good desired frequency selection function at 88MHz. Moreover, it can get almost 16dB gain at 88MHz.

![Graph showing filter effects at 98MHz](image1)

**Figure 18. Filter effects at 98MHz (source power -35dBm)**

Based on the figure above, when it has been changed to 98MHz, the mirror frequency rejection is about 11.5dB. It is a little bit far from 20dB. This is because the ratio between inductors and capacitor has not been optimized. Although the performance is not so good here, the filter is still working. It can also get 15dB gain at 98MHz.

![Graph showing filter effects at 108MHz](image2)

**Figure 19. Filter effects at 108MHz (source power -35dBm)**
From the figure above, we can see the mirror frequency rejection finally achieves 20dB at 108MHz and it has a very good desired signal selection function. Moreover, it can also get 16.74dB gain at 108MHz. Here, the filter works very well.

By analyzing the measurement results, we can get the following conclusion. First of all, if I can add a perfect matching network between collector of the transistor and the mirror frequency filter, maybe I will not need to change the circuit. Initially, the reason why I remove the matching network is that it will easily cause the instability at the input. Secondly, the performance of the filter is mostly decided by the ratio between inductors and capacitor. So it should be optimized. Thirdly, you should use fewer components as possible as you can and try your best to make the circuit less complex. So that it will bring you less problem. At the end, you should always notice the difference between the ideal and real components.
5 Conclusion

The RF amplifier with mirror frequency filter almost fulfills the specification. Because of the time limitation and my limited design experience, this RF amplifier with mirror frequency filter is not so perfect. In the future, I can optimize it.

It is obvious that the prototype of mirror frequency filter is very good. It only needs three components to achieve the function that could be done by traditional filter of more than 7 orders. And after a deep research, I grabbed the basic behavior of this kind of filter. With the help of the ADS and MATLAB, I find maybe the best components’ values of the filter to fulfill the mirror frequency rejection during the range between 88MHz and 108MHz according the available real components.

When I design the RF amplifier by using the transistor of BFG520X, I find it is vulnerable to the instability problem at the low frequency range. So the perfect matching networks at both input and output are needed in order to avoid such problems. Initially, I just design the matching network at both input and output. But it will cause the instability problem at the input according to the simulation result of ADS. So I remove the matching network at output and put the filter directly at the output stage. It doesn’t suffer the instability problem again. But it losses 7dB gain compared to the initially one because of the mismatch at the output. Maybe the mismatch is the main reason that I must change the circuit of the filter. So in the future design, I should balance the filter function and the matching at the output to get the more perfect amplifier.

When designing both filter and the amplifier, I should also consider the real components. The value of available real components and the different behavior between real and ideal components is a big limitation. I can theoretically design a perfect filter and amplifier. But I can not get such things in the real environment. Here, I think good simulation ability and rich design experience is so important. Maybe there is some thing I have not considered when doing simulation by ADS. Moreover I have little experience of RF design. So it causes the problem of the totally difference between simulation result and actual measurement result. In the future, I believe I can gradually avoid such problem when designing the relative thing.

Through ironing the PCB board, I also gain a lot practical experience. Especially when initially I finish the work, the amplifier doesn’t work.
With the help of Göran, I try to find the problem by measuring the voltage at the different places. Finally, I find the problem is caused by the broken of the transistor and unsolid soldering. After that I solve the problem and make the amplifier work properly.

The whole process of the radio project gives me a precious experience of how to do the RF design. I enjoyed the whole process and have learnt a lot from this course.

6 Acknowledgements

I would like to give my greatest thanks to Göran Jönsson, who gave me a lot of help and guidance during the whole project. Moreover, I also want to give my thanks to Lars Hedenstjerna, who helped me fabricate the PCB board.

7 Reference

8 Appendix

8.1 Simulation by Matlab

Figure 20. Mirror frequency filter at 88MHz (C=570pF)

Figure 21. Mirror frequency filter at 100MHz (C=650pF)
Figure 22. Mirror frequency filter at 108MHz (C=850pF)