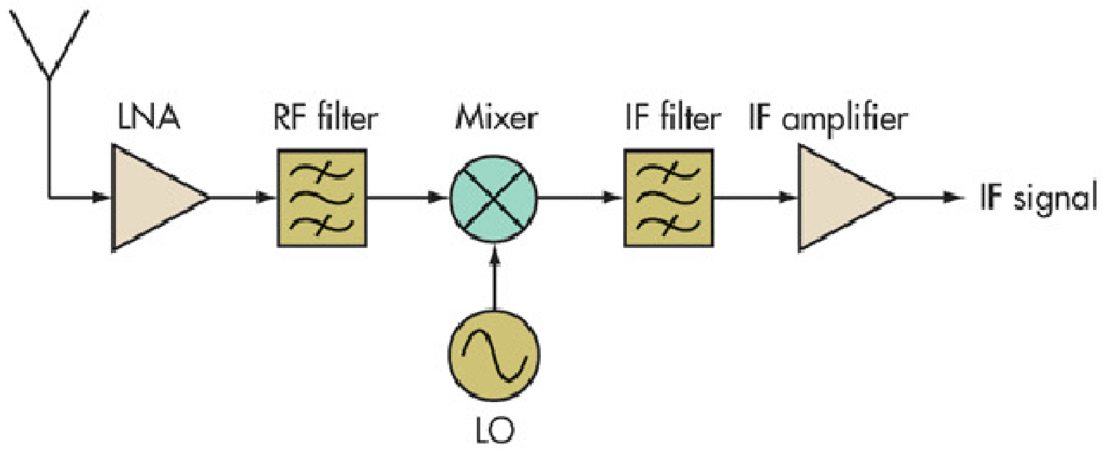
הפקולטה להנדסה

המחלקה להנדסת חשמל ואלקטרוניקה

מעבדת תכנון ומדידות במעגלי MMIC



עבודת סיום בנושא: תכנון ומימוש שרשת קליטה לתדר 2.8 GHz

מגישים:

סמואל נומן - 342785912

עמוס סרוסי - 209324045

חגי פרץ - 207460130

Introduction

This report details the design of a RF receiver optimized for a center frequency of 2.8 GHz, incorporating a patch antenna to ensure high-quality signal reception. The architecture is chosen for its excellent selectivity and sensitivity, ideal for high-frequency RF applications. Key components of the receiver include the Patch Antenna, Low Noise Amplifier (LNA), RF Filter, Mixer, Local Oscillator (LO), IF Filter, and IF Amplifier.

Receiver Components

1. **Patch Antenna**: The receiver uses a patch antenna designed specifically for 2.8 GHz. This type of antenna is chosen for its compact size and ability to provide a high degree of directionality and bandwidth, making it suitable for capturing signals with precision and minimal interference from other sources.
2. **Low Noise Amplifier (LNA)**: Positioned directly after the antenna, the LNA amplifies the received signal with minimal noise introduction. It is engineered with high gain and a low noise figure, employing GaAs or SiGe transistors optimized for 2.8 GHz operations.
3. **RF Filter**: A bandpass filter follows the LNA to only allow signals within a narrow band around 2.8 GHz. This step is critical for minimizing interference and easing the load on the receiver's more sensitive components.
4. **Mixer and Local Oscillator (LO)**: The Mixer downconverts the RF signal to a lower intermediate frequency (IF) by combining it with a frequency generated by the LO. The LO is typically a phase-locked loop (PLL) synthesizer, selected for its stability and minimal phase noise, crucial for maintaining the fidelity of the signal.
5. **IF Filter and Amplifier**: After mixing, the IF Filter refines the selection by narrowing down the bandwidth to the necessary limits, thereby enhancing the receiver's selectivity. The IF Amplifier boosts this filtered signal to sufficient levels for detection, prioritizing the integrity and noise reduction of the signal.

Conclusion

This RF receiver design integrates a patch antenna and other key components, each meticulously selected and optimized for operation at 2.8 GHz. The use of a patch antenna at the forefront of the signal chain is particularly significant, as it efficiently captures the desired RF signals with high specificity and reduced environmental interference. The comprehensive component integration ensures the receiver delivers high selectivity and sensitivity, which are essential for robust performance in complex high-frequency RF environments.

Patch Antenna

A patch antenna with coaxial feeding (vias) is a type of planar antenna that utilizes a rectangular or circular patch of metal on a dielectric substrate.

In a coaxially fed patch antenna, the coaxial cable connects directly to the patch element through a hole in the ground plane. The inner conductor of the coax attaches to the radiating patch, while the outer conductor is connected to the ground plane. This method is commonly used due to its simplicity and effectiveness in transmitting and receiving RF signals.

Building a patch antenna, particularly one with coaxial feeding, involves a straightforward design process focused on a few key components and precise dimensions. Here's a detailed explanation of how to build a patch antenna:

Materials and Components:

1. **Radiating Patch**: This is typically a rectangular or circular piece of conductive material like copper. The size and shape of the patch determine the resonant frequency of the antenna.
2. **Dielectric Substrate**: Positioned directly under the patch, this material supports the patch and affects the antenna's performance. Common substrates include materials like FR4 or RT/duroid, chosen for their specific dielectric constants.
3. **Ground Plane**: The ground plane is a larger sheet of conductive material located on the opposite side of the substrate from the patch. It needs to be at least as large as the patch, though typically it is larger to prevent edge diffraction effects.
4. **Coaxial Cable**: Used for feeding the antenna, consisting of an inner conductor and an outer conductor separated by an insulator.

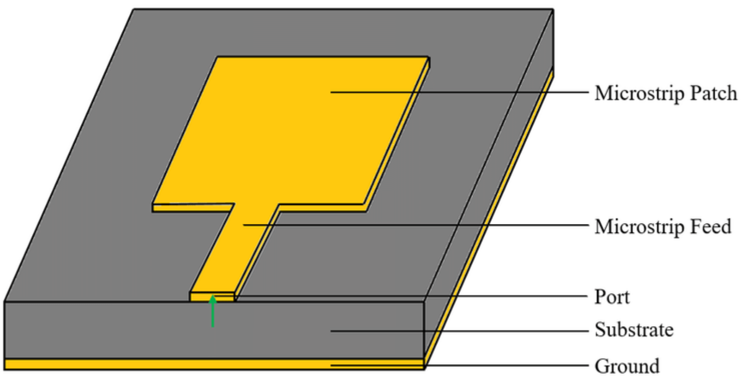


Image 1 – Patch Antenna

Pros:

1. **Simple Design and Implementation:** The coaxial feed is straightforward to construct and integrate with the rest of the RF system, making it a popular choice for many practical applications.
2. **Good Impedance Matching:** Coaxial feeding allows for better control over the impedance matching between the antenna and the transmission line, optimizing the antenna's performance in terms of signal strength and bandwidth.
3. **Low Cost:** The materials and fabrication process for a coaxially fed patch antenna are relatively inexpensive, making it cost-effective for both commercial and hobbyist projects.
4. **Compact Size:** The overall structure is compact, which is advantageous for applications where space is a constraint.

Cons:

1. **Limited Bandwidth:** Patch antennas inherently have narrow bandwidths, which can be a significant limitation if wide-band operation is required.
2. **Physical Intrusion:** The physical presence of the coaxial cable might interfere with the radiation pattern and purity of the antenna design.

Overall, a coaxially fed patch antenna is suitable for applications where simplicity, cost, and compact size are prioritized, and where the limitations in bandwidth are manageable within the operational context.

Equations:

(1) Resonance Frequency:

$$f_0 = \frac{c}{2L\sqrt{\varepsilon_{eff}}}$$

(2) Effective Permittivity:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + 12\frac{h}{w}}}\right)$$

(3) Patch Width (for good impedance matching):

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_{r+1}}{2}}}$$

(4) Effective Length (considering fringing fields):

$$L_{eff} = L + 2\Delta L$$

(5) Fringing Field Extension:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)}$$

Simulation Results:

First we will show effects of changing L as can be seen in simulation results.

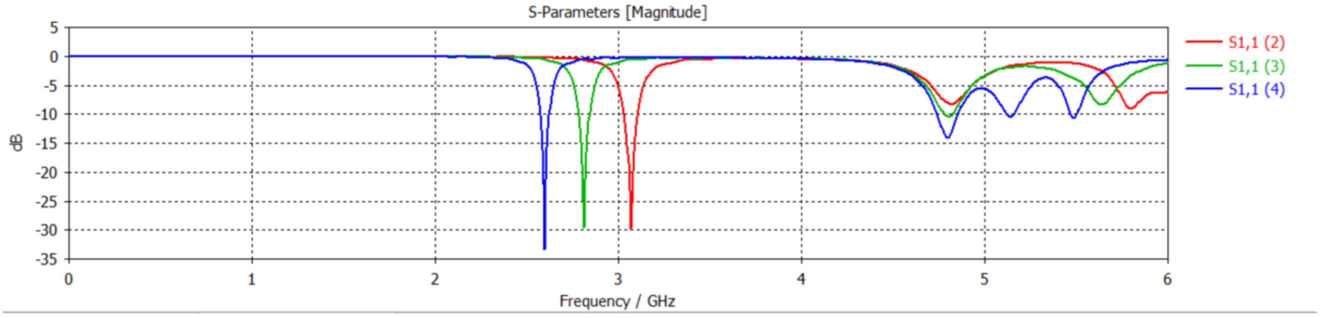


Image 2 – Changing L in Antenna

In a patch antenna, adjusting the length L directly impacts the resonant frequency. Increasing L lowers the resonant frequency, while decreasing L raises it. This occurs because the length L defines the antenna's effective electrical length, thereby setting its frequency of resonance where it most efficiently transmits or receives electromagnetic waves. This can be seen in equation (1) above.

Result Navigator

3D Run ID	w	l	yo
4	40.5	36.9	6.1
3	40.5	33.9	6.1
2	40.5	30.9	6.1

Image 3 – Antenna L Simulation result

Second, the effects of changing W will be shown in the simulation:

In a patch antenna, adjusting the width also affects its resonant frequency, but primarily influences the antenna's bandwidth and impedance characteristics. Increasing the width tends to lower the resonant frequency slightly, but more significantly, it enhances the bandwidth. This broader bandwidth results from the increased surface area which allows the antenna to support a wider range of frequencies effectively. Thus, by modifying the width, one can optimize the antenna for desired impedance matching and operational bandwidth alongside minimal shifts in frequency.

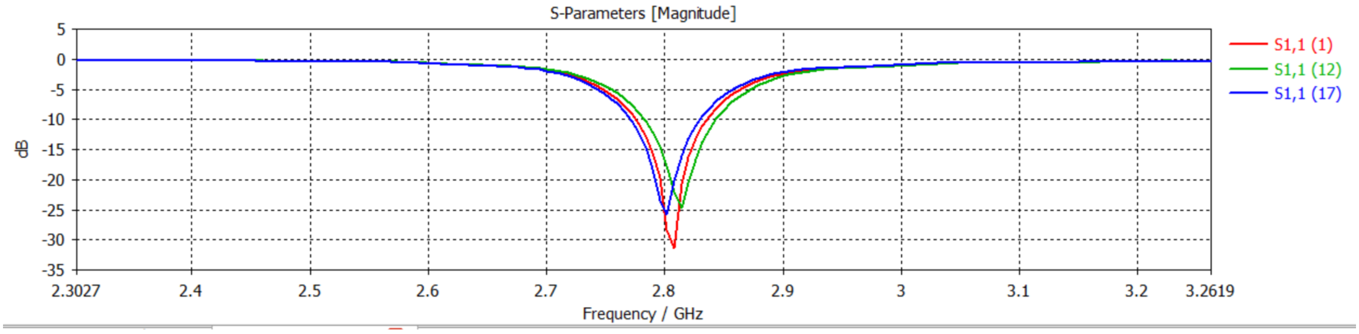


Image 4 – Antenna Changing W Simulation

From the simulation it can be seen as W changes the resonant frequency changes slightly. With different values of W the bandwidth can be seen widening or narrowing as well.

3D Run ID	w	l	yo
17	46.5	33.9	6.3
12	40.5	33.9	6.3
1	43.5	33.9	6.3

Image 5 – Antenna Changing W Simulation Results

Finally the effects of changing y_0 will be tested and shown in the simulation results.

When designing or tuning a patch antenna, adjusting the feed location (y_0) is a practical method to achieve desired impedance levels and to control the radiation characteristics. This adjustment is crucial for optimizing antenna performance for specific applications, ensuring it operates efficiently at the intended frequency and with the desired radiation pattern. This adjustment is done by changing the location of the via on the y-axis of the antenna.

The goal is to get pure impendence matching of 50 Ohm.

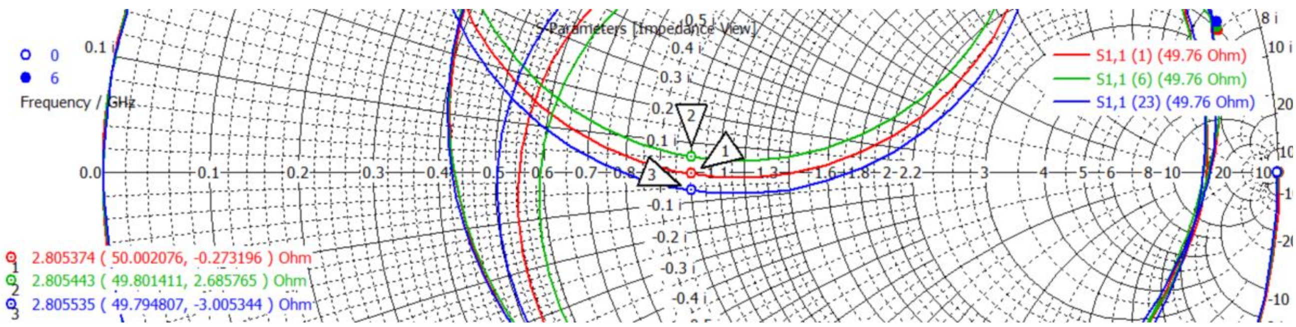


Image 6 – y_0 Simulation

3D Run ID	w	l	yo
6	43.5	33.9	6.1
1	43.5	33.9	6.3
23	43.5	33.9	6.5

Image 7 – Antenna feed level simulation

After some fine tuning the best results are shown below:

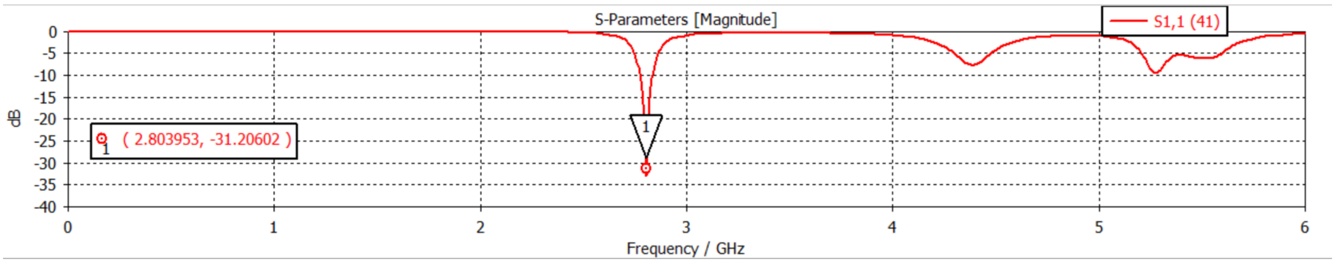


Image 8 – Antenna Resonance Frequency

This shows that at the required frequency of 2.8GHz there is little to no reflection in the source.

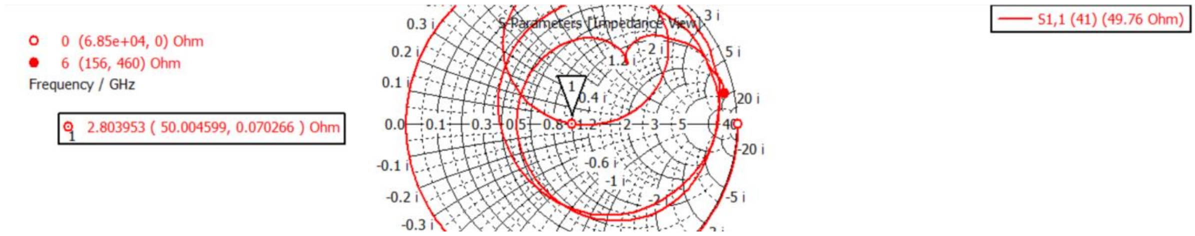


Image 9 – Antenna Matching

The antenna matching shows that the antenna gets areal pure impudence at the required frequency.

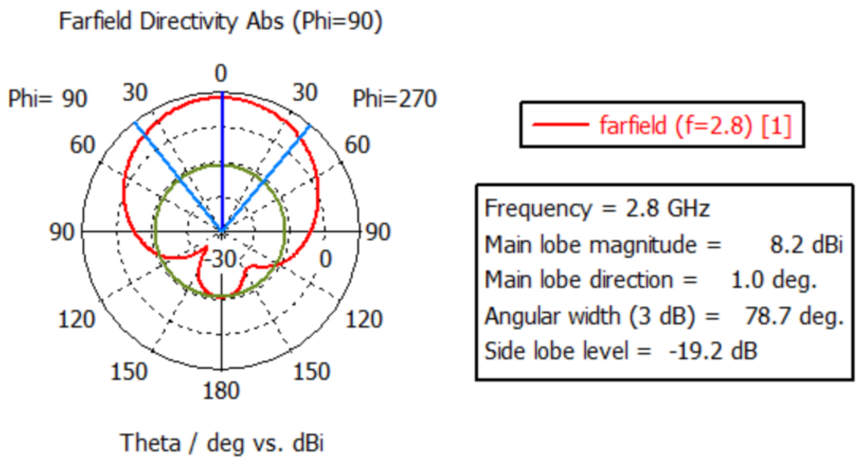


Image 10 – Antenna Farfield Directivity

The Farfield Directivity shows the radiation of the antenna in 2D.

Parameter List

Name	Expression	Value
w	= 44.5	44.5
l	= 33.9	33.9
t	= 0.035	0.035
h	= 1.6	1.6
d2	= 2.2	2.2
yo	= 6.4	6.4
d1	= 0.6387	0.6387

Image 11 – Antenna Final Parameters

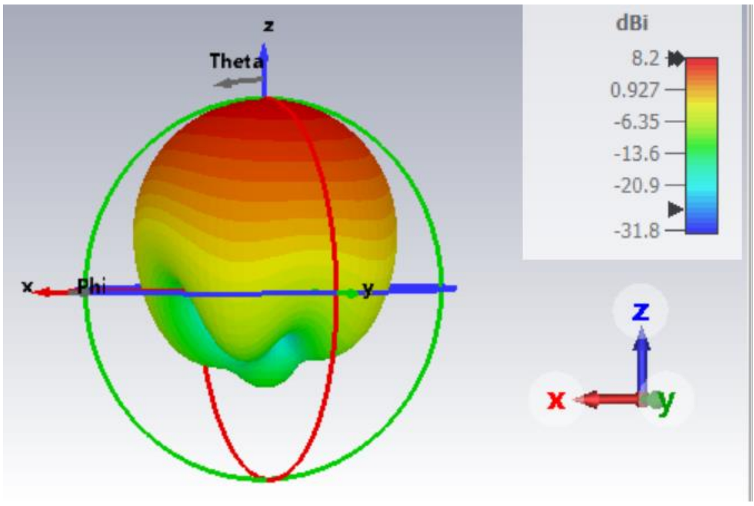


Image 12 – 3D Antenna Radiation Gain

The final image shows the 3D radiation of the antenna (its gain).

LNA (Low Noise Amplifier)

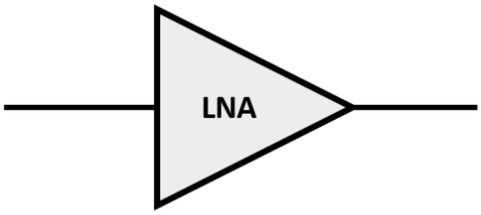


Image 13 - LNA

An LNA operates at the front end of the receiver chain, where it is the first amplifier to encounter the signal after it's received by the antenna. Its main function is to boost the amplitude of signals captured from the antenna to levels suitable for further processing by other circuit components downstream while introducing minimal additional noise. This is critical in scenarios where signals are extremely weak, such as in satellite communications, cellular phones, GPS devices, and other wireless communication systems.

The importance of the LNA cannot be overstated because its performance significantly affects the overall system's sensitivity and effectiveness. A well-designed LNA helps in:

- **Improving the SNR**: By amplifying the signal before it passes through subsequent stages that might introduce more noise, an LNA improves the overall Signal-to-Noise Ration (SNR) of the system. This is crucial in environments with significant background noise or when the signal itself is very weak.
- **Preserving Signal Integrity**: The LNA minimizes the amount of noise added to the signal compared to the original signal's strength, which is essential for maintaining the integrity and quality of the information carried by the signal.

Key Parameters of LNA

- **Gain**: This is the amount by which the LNA amplifies the input signal. It is typically expressed in decibels (dB) and is a critical factor in ensuring that the signal is amplified sufficiently to be processed effectively by subsequent stages without saturation.
- **Noise Figure (NF)**: This parameter indicates how much noise the LNA adds to the signal. A lower noise figure is preferable as it represents less degradation of the SNR after amplification.
- **Linearity**: The linearity of an LNA is also vital, especially in systems where signal fidelity is paramount. Non-linear behavior in an LNA can lead to signal distortion and the generation of unwanted spurious signals or intermodulation products.

Stability Factor:

The Rollet Stability Factor K ensures that the LNA does not oscillate:

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

Where: (7) $\Delta = S_{11}S_{22} - S_{12}S_{21}$

In order to have stability: $K > 1 \; and \; |\Delta| < 1$

If $K < 1$ then the amplifier might be conditionally stable or unstable.

After creating an amplifier using a transistor, the circuit was tested for stability and max gain. Adding a resistor near the output helps stabilize the circuit, but lowers the max gain as a consequence.

GL(Load Gain) and GS(Source Gain) circles were used to visualize and optimize the amplifier's performance in terms of gain, noise, and impedance matching. These circles were plotted on the Smith Chart and helped select the best source and load impedances for maximum or stable gain. With these results, a transmission line with the measured parameters was connected to the source and load of the circuit.

The available power gain describes the ratio of power delivered to the load to the power available from the source. This gain depends on how well the amplifier is matched to the source and load impedances:

(8) $G_A = \frac{P_L}{P_S}$

The **transducer power gain** accounts for mismatches in both the source and load impedances:

(9) $G_T = G_0 \cdot G_S \cdot G_L$

- G_0 = intrinsic gain of the amplifier (assuming perfect matching)
- G_S = source reflection coefficient gain
- G_L = load reflection coefficient gain

These two gains G_S and G_L describe how much power is lost due to mismatches.

$$G_S = \frac{1 - |\Gamma_S|^2}{|1 - S_{11}\Gamma_S|^2}$$
(10)

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0}$$
(11)

S_{11} = input reflection coefficient of the amplifier

$$G_L = \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}$$
(12)

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$
(13)

S_{22} = output reflection coefficient of the amplifier

The total transducer gain, considering input and output mismatches, is:

$$G_T = G_0 \cdot \frac{1 - |\Gamma_S|^2}{|1 - S_{11}\Gamma_S|^2} \cdot \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}$$
(14)

If the amplifier is perfectly matched to both the source and load, GS and GL approach 1, so GT ≈G0. If mismatches exist, the gain is reduced due to reflections.

Using everything mentioned above, a stable LNA was built for the frequency of 2.8GHZ.

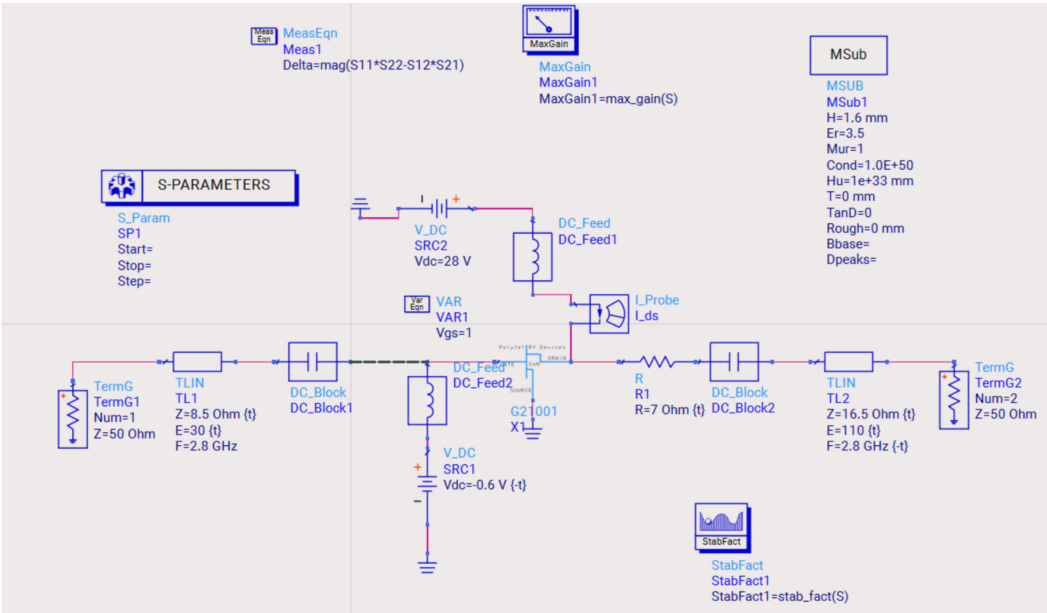


Image 14 – LNA Circuit

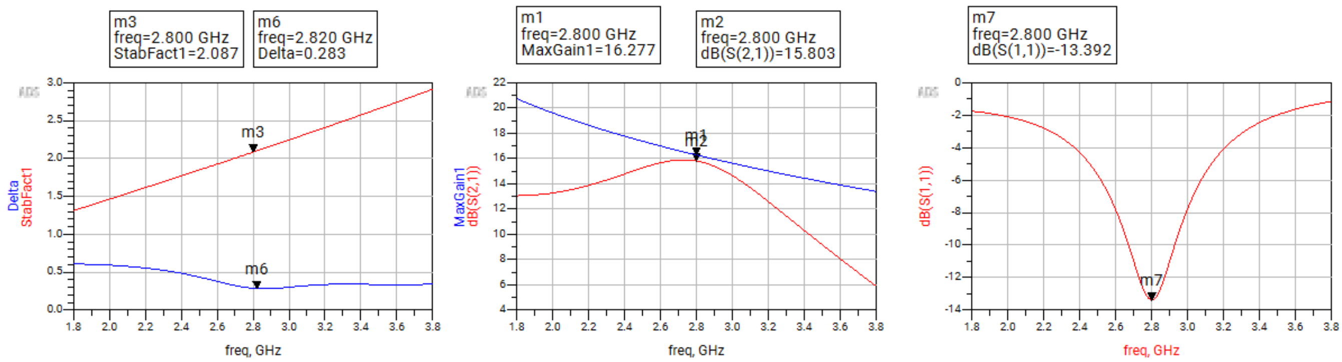


Image 15 – LNA Simulation Results

The graph on the left how how delta is always above 1, while the stability factor always stays below 1. This insures stability in the circuit. The middle graph shows that at the desired frequency a large gain was reached(not quite the max gain but very close). The graph on the right shows that there is little to no refelction in the source, which means a good transfer of power with minimal noise.

Pin 1dB (1dB Compression Point):
This is the input or output power level at which an amplifier or transistor starts to deviate from its ideal (linear) behavior by 1 dB. In other words, when you increase the input power to this point, the gain compresses—meaning the device can't amplify as effectively, which is a sign of nonlinearity.

IP3 (Third-Order Intercept Point):
This is a theoretical value that indicates the level at which the power of third-order intermodulation distortion products would equal the power of the fundamental signal if the trends were extended linearly. Although the actual IP3 is never reached in practice, a higher IP3 value means the device is more linear and better at handling multiple signals simultaneously without significant distortion.

Both parameters are key for evaluating the performance of transistors in RF and communication systems, helping designers balance gain, linearity, and power handling.

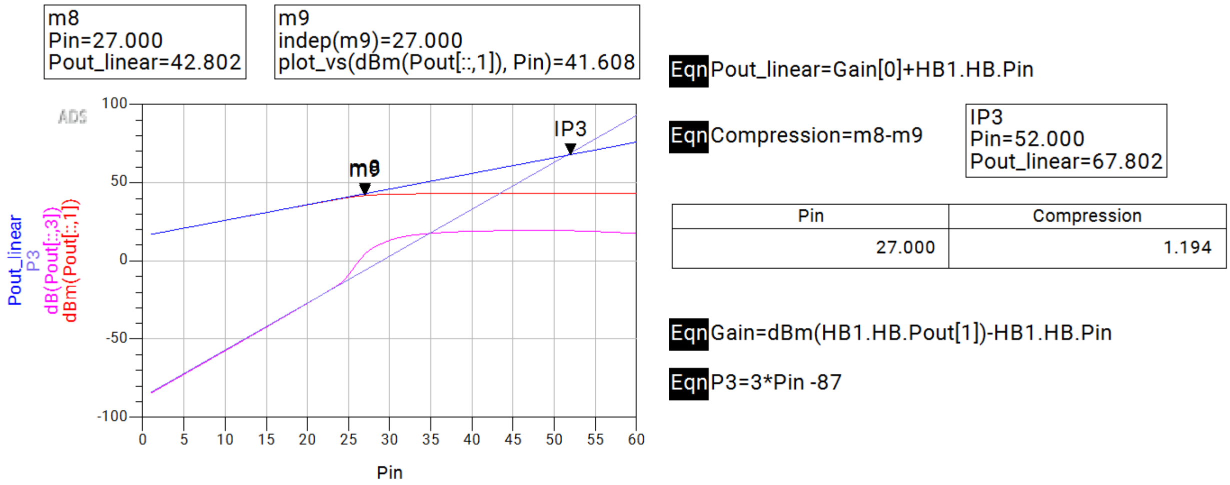


Image 16 – IP3

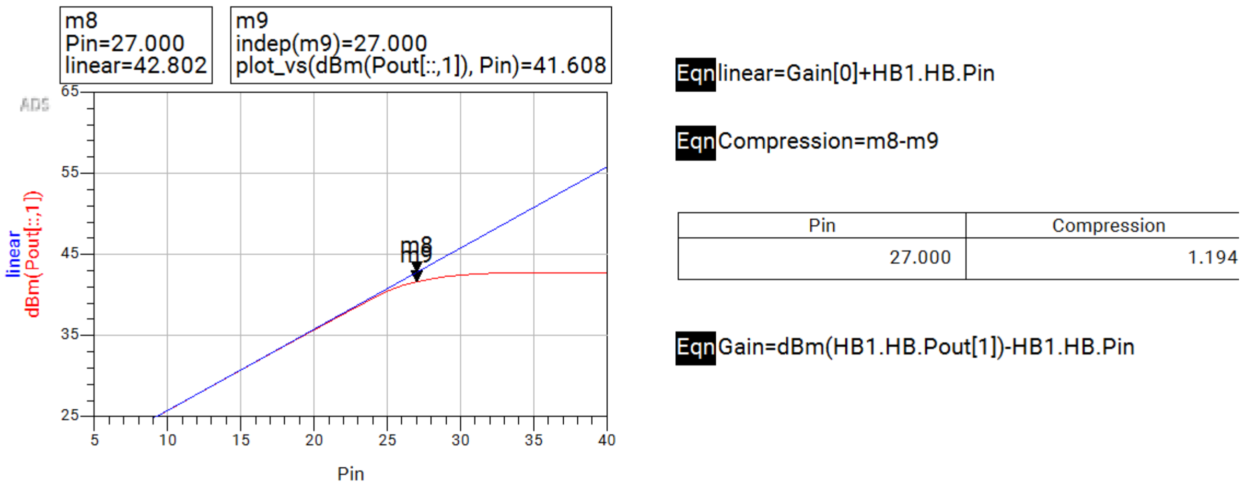


Image 17 – Pin 1dB

BPF (Coupled Lines)

Image 18 – Coupled Line BPF Diagram

The coupled line bandpass filter design operates based on electromagnetic coupling between parallel transmission lines that are closely spaced on a substrate. The core functionality arises from the interactions of the electromagnetic fields between these lines. Each line is precisely calculated to resonate at the desired center frequency of 2.8 GHz, which is crucial because it determines the peak transmission frequency of the filter—essentially the frequency it allows through most effectively.

The specific spacing and width of these lines are adjusted to control the filter's bandwidth, which is the range of frequencies around the center frequency that the filter allows to pass. This project's bandwidth is set to 200 MHz, targeting frequencies from 2.7 GHz to 2.9 GHz. The input and output of the filter are also designed to match the typical impedance of RF systems, usually 50 ohms, to ensure minimal signal reflection and optimal power transfer.

The filter itself is built on a substrate material that supports high-frequency operation. A substrate with a high dielectric constant was chosen in order to help reduce the overall size of the filter while maintaining good performance. The actual filtering elements are microstrip lines, which are thin strips of conductive material like copper, printed onto the substrate. These lines are the active components that perform the filtering based on their dimensions and the electromagnetic interactions between them.

The current coupled line bandpass filter was designed for a 2.8 GHz center frequency with a 200 MHz bandwidth, using CST Microwave Studio for all calculations. A substrate with a high dielectric constant was chosen to keep the filter compact while optimizing performance. The simulations in CST helped accurately determine the right spacing between the lines to hit the proper bandwidth and impedance targets, ensuring the filter worked efficiently at the desired frequency.

Summary of Design Adjustments:

Parameter	Effect on f_0	Effect on Bandwidth
Line Length	Shorter = Higher f_0	Small effect
Line Spacing	Small effect	Closer = Wider BW
Number of Sections	More = Better selectivity	More = More control over BW
Substrate ε_r	Higher = Lower f_0	Higher = More coupling = Wider BW

Image 19 – Coupled Filter Parameters

Simulations:

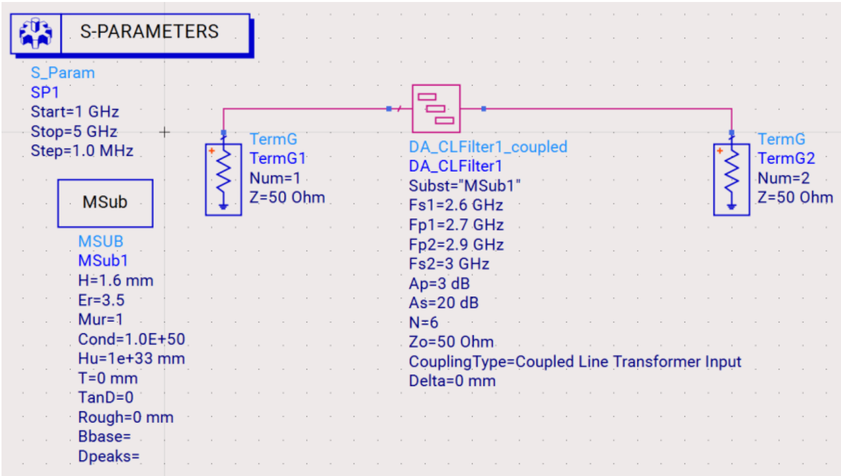


Image 20 – Coupled BPF Simulation

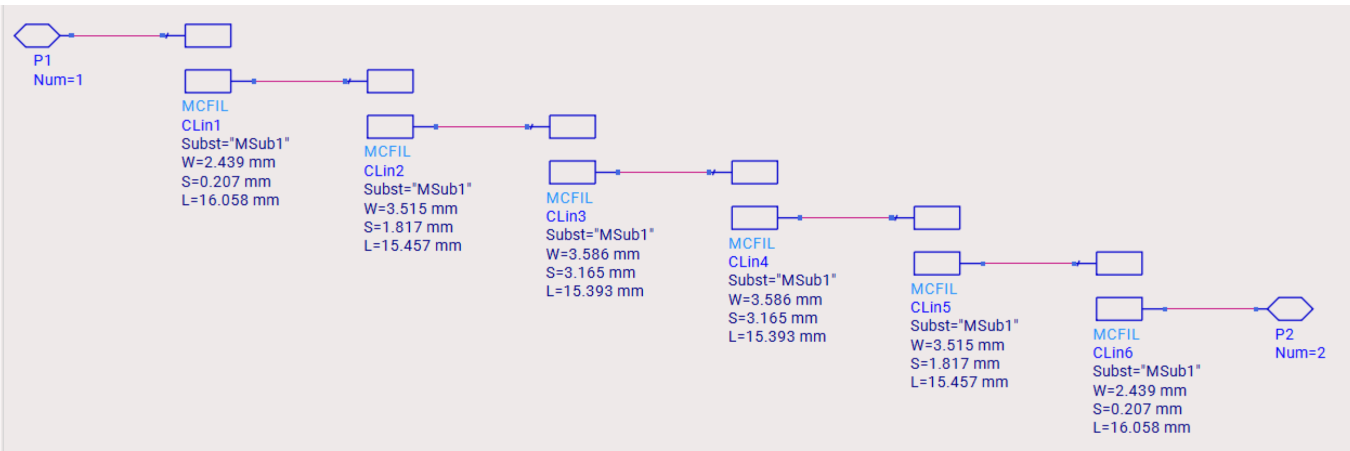


Image 21 – Coupled BPF Simulation inside Look

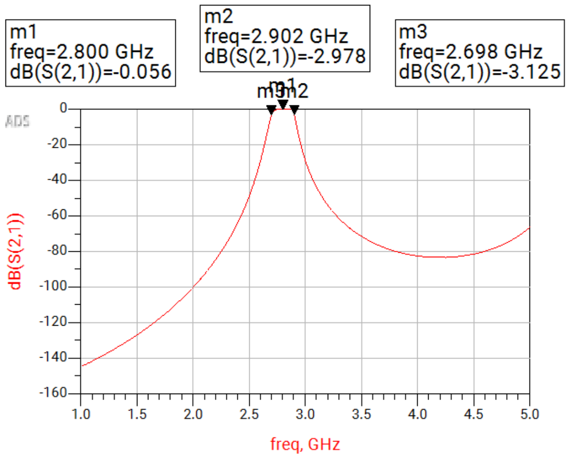


Image 22 – Coupled BPF Simulation Frequency

Mixer

In the receiver line, a mixer is employed to blend a signal of 2.8 GHz with a Local Oscillator (LO) signal of 2.7 GHz. The primary function of the mixer is to both add and subtract the frequencies of these input signals. The result of this mixing process includes a sum frequency (5.5 GHz) and a difference frequency (100 MHz), with the latter being the focus for further applications.

(8) $f_{IF} = |f_{RF} - f_{LO}|$

(9) $f_{SUM} = |f_{RF} + f_{LO}|$

$IF = |2.8 - 2.7| = 100MHz$

$Sum = 2.8 + 2.7 = 5.5GHz$

The difference frequency, commonly referred to as the Intermediate Frequency (IF), is particularly significant because it is easier to manage, filter, and amplify than the original high RF frequencies. In the case presented, the 100 MHz IF is advantageous for further signal processing within communication systems. Mixers are indispensable in applications such as superheterodyne receivers, where they facilitate the conversion of high-frequency received signals to lower IFs. This conversion process allows for enhanced filtering and amplification, leading to better selectivity and sensitivity in receiver designs. Thus, the mixer not only serves as a critical component for frequency conversion but also significantly improves the overall efficiency and performance of RF communication systems.

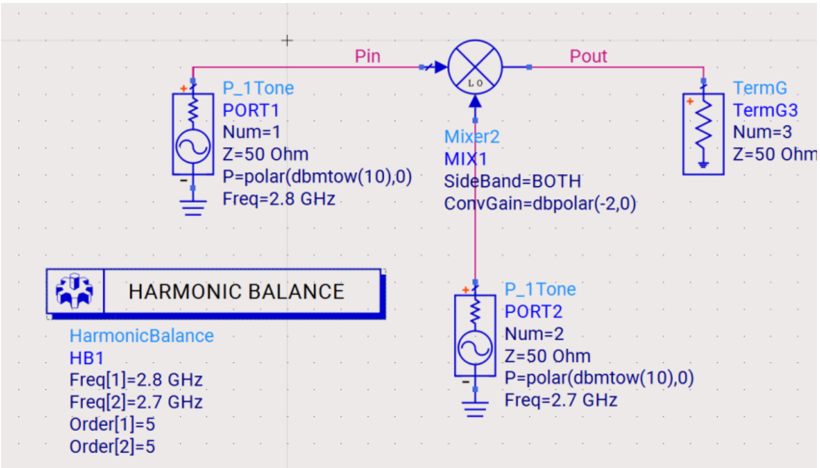


Image 23 – Mixer Circuit

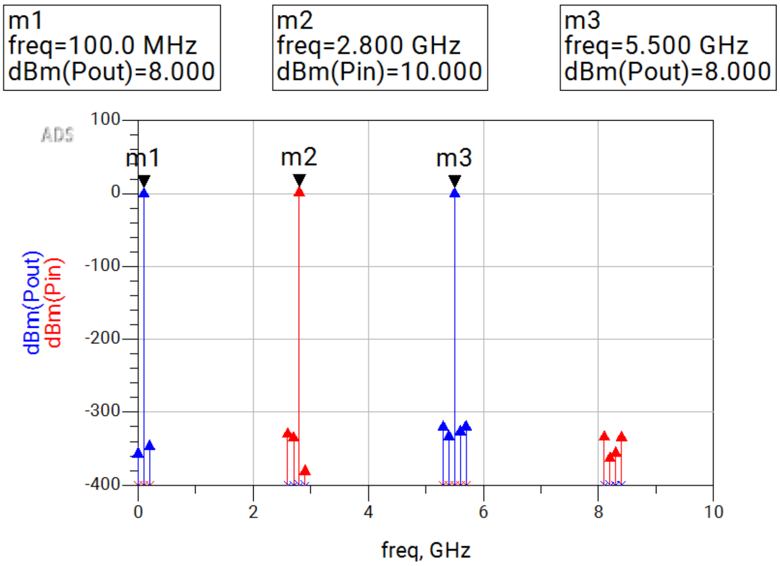


Image 24 - Mixer frequencies

From the Simulation, the IF(left), input (middle) , and Sum (right) frequencies can all be seen.

LPF

A Low Pass Filter (LPF) designed for Intermediate Frequency (IF) applications, specifically targeting a cutoff frequency of 100 MHz, was built at the end of the receiver.

The LPF is designed using a Butterworth filter configuration, which is favored for its flat response in the passband, ensuring minimal signal distortion within the frequency range up to 100 MHz. The cutoff frequency is defined at 100 MHz, which means the filter will effectively allow frequencies below this threshold to pass while attenuating frequencies above it. This type of filter is particularly useful in radio frequency applications for eliminating higher frequency noise or interference that can affect the desired signal. The design ensures a smooth transition from passband to stopband by achieving maximum flatness at the cutoff frequency, making it ideal for applications requiring precise frequency demarcation without sharp oscillations in response.

The LPF filter was built to filter out the high Sum frequency (5.5GHZ) and only allow the IF frequency (100MHz) to pass. The IF signal still carries the same modulation, data and waveform of the original 2.8GHz signal. One reason for this is that modern receivers convert signal to baseband (near 0Hz) or low IF for efficient digital processing.

Simulations:

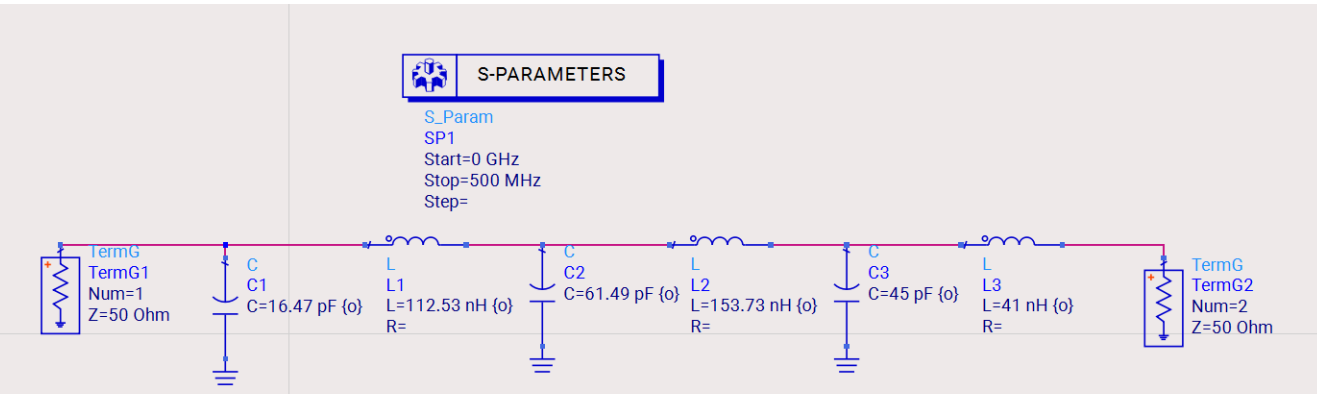


Image 25 – LPF Circuit

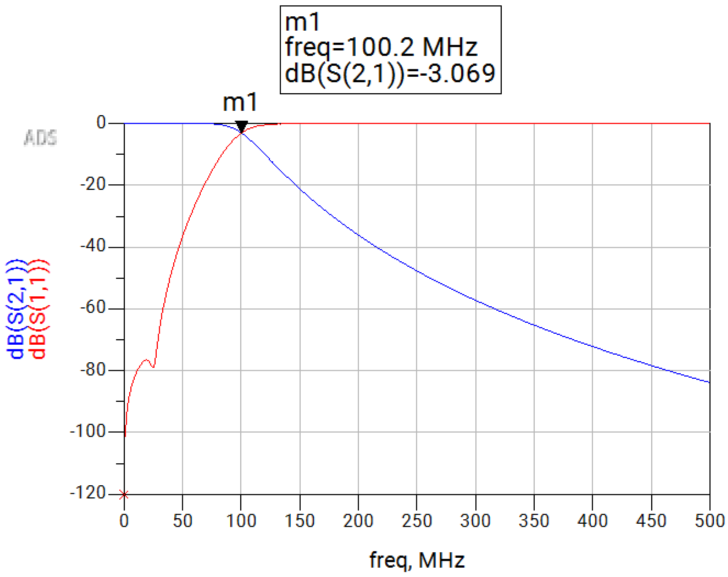


Image 26 – LPF Simulation

It can be seen from the simulation that frequencies up to 100MHz are passed, while higher frequencies are not. This filters out the sum frequencies and any other unwanted high frequencies. This will insure proper conversion to digital.

Summary:

All the different components built where connected into one circuit created the RF Receiver Network for 2.8GHZ. The circuit of the Receiver can be seen below:

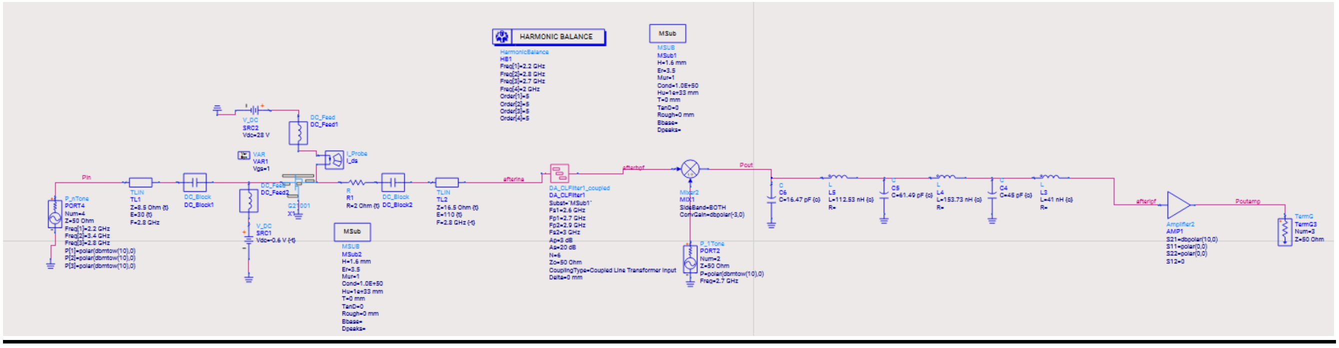


Image 27 – RF Receiver Network Circuit

The network was tested for gain (before and after the LNA, BPF, and LPF). The Output Power was also tested at required frequencies. At our output, our information is not lost, but rather transferred to a lower frequency.

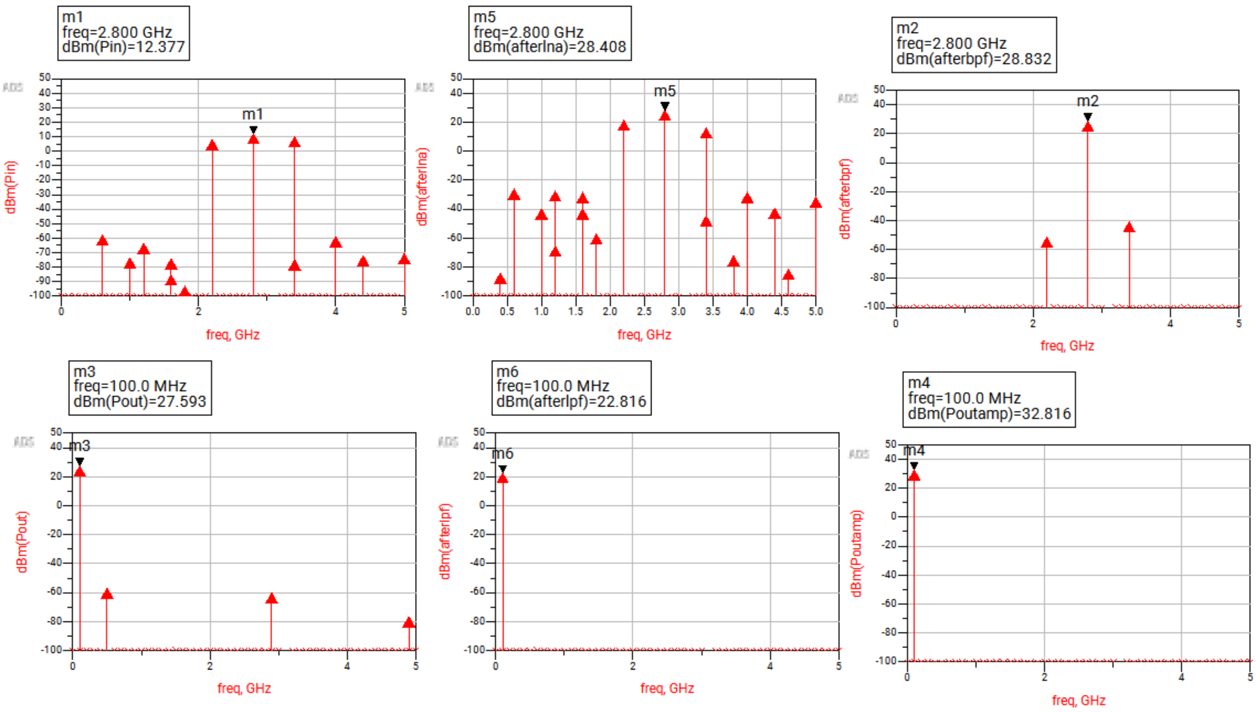


Image 28 – Receiver Network Simulation Results

The outputs above represent the outputs of the system after each step of the receiver. First there are 3 input frequency signals in the system. Next they are amplified, with the 2.8GHz being the most amplified due to the tuning of the LNA. The next step is the Coupled Line BPF which filters out the noise and leaves us with the input signals. The Fourth graph shows the different Sum and IF after the mixer. Then these signals are sent though the LPF which leaves just the desired IF. Finally the signal is amplified by the last LNA. At this point the IF output signal can be processed in different ways according to the discretion of the user.