MISRTRONICS

DIGITAL FREQUENCY MEASUREMENT SYSTEM DESIGN

FOR THE FT-101 RECEIVER

Dr. Aladdin Assisi

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This document describes in detail the new unit that has been designed to measure the instantaneous value of the signal frequency being received by the FT-101 HF transceiver. The new unit consists of two main sub-units; the Frequency Measurement Unit (RFMU) and the Counter Unit (CU). The RFMU builds up a rectangular wave with the same frequency of the signal being received by the FT-101, while the CU counts and displays the number of pulses received every second. Many design challenges have been solved and thorough simulation techniques have been repeatedly applied to assure that the frequency to be measured exactly equal that being received by the FT-101.

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DIGITAL FREQUENCY MEASUREMENT SYSTEM DESIGN

FOR THE FT-101 RECEIVER

1. INTRODUCTION

1. The design task is to design a unit that can measure both the transmitted signal frequency and the received signal frequency of the FTY-101 HF Transceiver.

2. Measuring the transmitted signal frequency is straightforward. A sample of the transmitted signal is taken from the leftmost point of the rear panel. It is the RF signal output of the driver stage. This signal can be directly driven to the CU input.

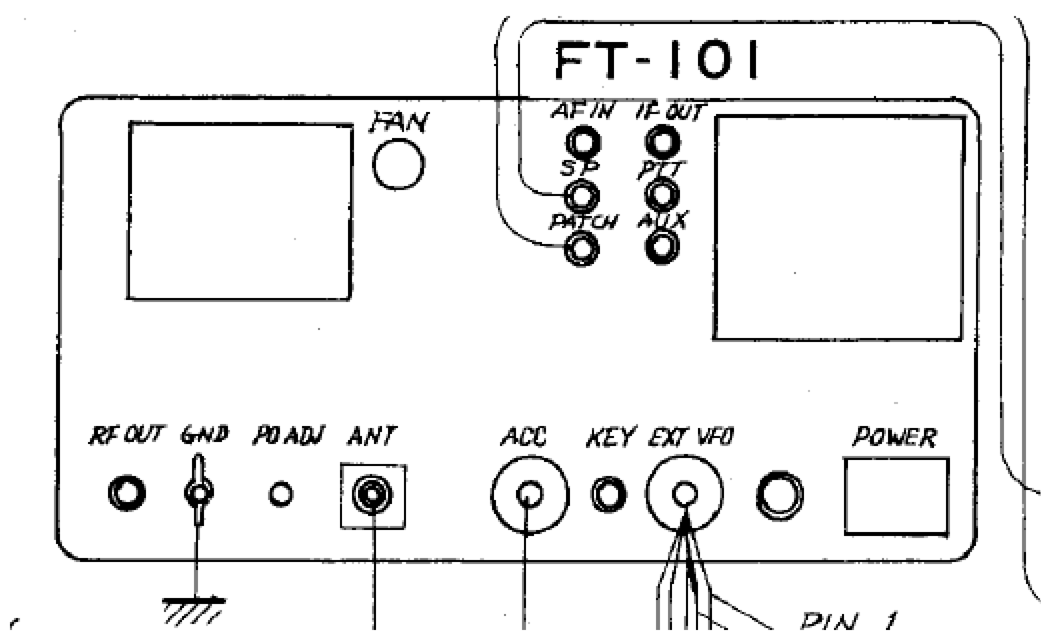


Figure 1. Rear of the FT-101

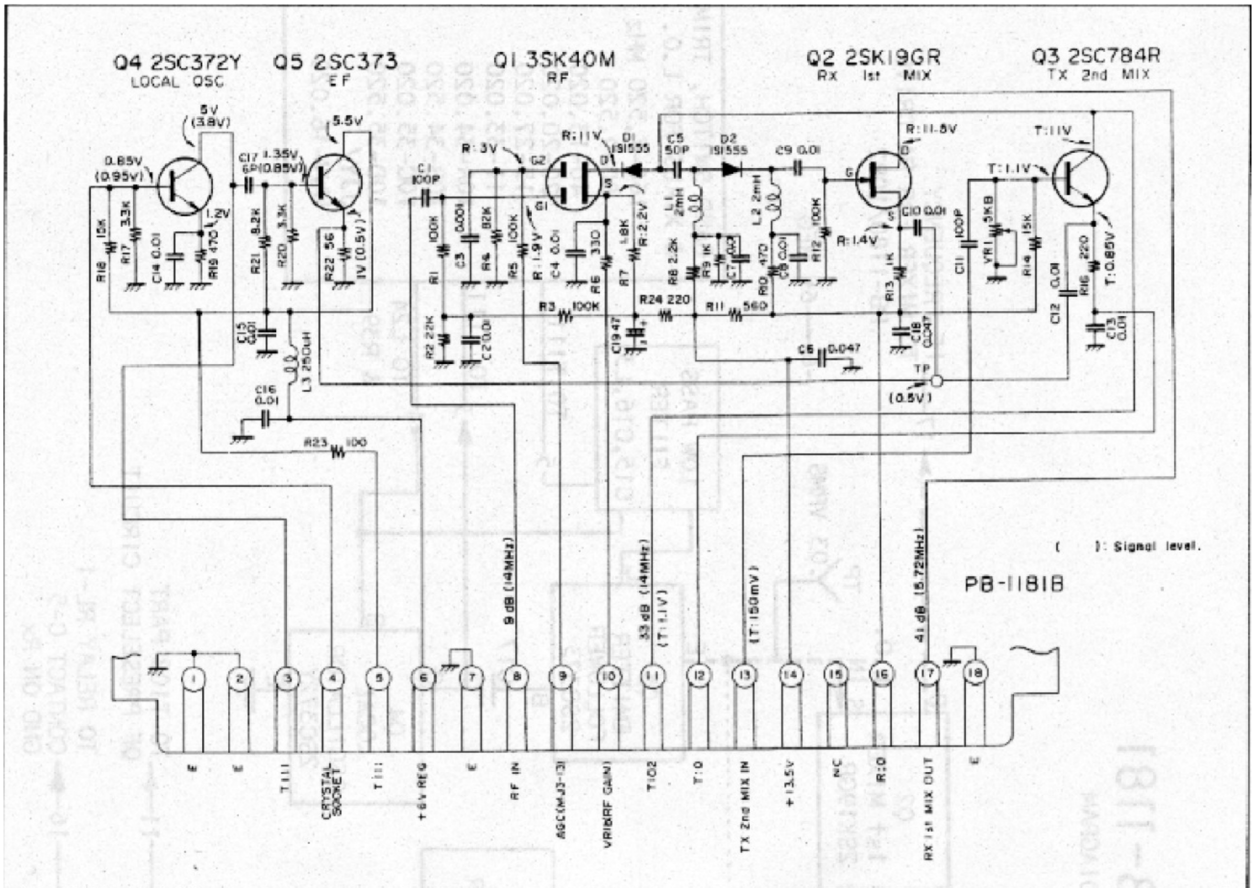


Figure 2. The PB1181 RF Unit

3. To measure the received signal frequency is a big challenge for the following reasons:

    a. There are many RF signals at the receiver input. It is not possible to know which one is currently selected by the user without reading the current values of the course and the fine local oscillators

    b. The instantaneous signal being received is a very weak signal at the RF unit receiving input.

    c. The received signal is amplified in the successive heterodyning stages through a double down frequency conversion process where the original RF frequency value is lost.

    d. The only way to measure the received signal frequency is to reconstruct the RF signal from its three components:
        i. The 3.18 MHz detected signal at the receiver output
        ii. The VFO instantaneous output signal.
        iii. The RF oscillator instantaneous output signal

e. It should be considered that:
   i. The 3.18 MHz signal frequency can be incremented or decremented by the side band shift according to the user's selection (USB/LSB)
   ii. The VFO frequency is continuously variable between 8.7 MHz and 9.2 MHz according to the fine tuning under the user's control
   iii. The RF oscillator frequency is user-selectable among ten different positions of the RF band switch in the FT-101 front panel.

Table 1 shows the ten frequency bands of the FT-101and the corresponding frequencies at different stages.

TABLE 1.

FT-101 FREQUENCY BANDS

BAND	Crystal frequency f_x	VFO frequency	Fine IF_1	Final IF $IF_2 = f_{VFO} - IF_1$	Correct RF f_x - IF_2	Undesired spur output frequency $f_x + IF_2$	Required Filter
[m]	**MHz**	**MHz**	**MHz**	**MHz**	**MHz**	**MHz**	**MHz**
160	7.52	8.7 to 9.2	3.18	5.52 to 6.02	**1.50 to 2.00**	13.04 to 13.54	LP5
80	9.52	8.7 to 9.2	3.18	5.52 to 6.02	**3.50 to 4.00**	15.04 to 15.54	LP5
40	13.02	8.7 to 9.2	3.18	5.52 to 6.02	**7.00 to 7.50**	18.54 to 19.04	LP8
20	20.02	8.7 to 9.2	3.18	5.52 to 6.02	**14.0 to 14.5**	25.54 to 26.04	LP15
15	27.02	8.7 to 9.2	3.18	5.52 to 6.02	**21.0 to 21.5**	32.54 to 33.04	LP22
11	33.02	8.7 to 9.2	3.18	5.52 to 6.02	**27.0 to 27.5**	38.54 to 39.04	LP28
10A	34.02	8.7 to 9.2	3.18	5.52 to 6.02	**28.0 to 28.5**	39.54 to 40.04	LP30
10B	34.52	8.7 to 9.2	3.18	5.52 to 6.02	**28.5 to 29.0**	40.04 to 40.54	LP30
10C	35.02	8.7 to 9.2	3.18	5.52 to 6.02	**29.0 to 29.5**	40.54 to 41.04	LP30
10D	35.52	8.7 to 9.2	3.18	5.52 to 6.02	**29.5 to 30.0**	41.04 to 41.54	LP30

4. The received signal frequency measurement procedure consists of the following stages:

   a. Get the instantaneous 3.18 MHz received signal from the receiver output. (pin 4 of the Noise Blanker Unit). See Figure 3.

   b. Mix it with the VFO 8.7-9.2 MHz output fine tuning LO signal (Look at Figure 4).

   c. Pass the mixer output from a 5.52-6.02 MHz BPF to suppress the Upper Side Band (USB) output.

   d. Mix the resulting signal with the output of the RF Local Oscillator from the RF Unit (Figure 5).

   e. Filter out the Upper Side Band (USB) output. This was the greatest challenge; since the RF signal frequency changes between 1.5 MHz and 30 MHz, while the second local oscillator signal changes between 7.52 MHz and 35.52 MHz. It means that the USB signal to be suppressed changes between 13.04 MHz and 41.54 MHz. It means that the variation ranges of the desired signal and the spurious signal are interleaved, as it can be seen in Table 2 below.

TABLE 2

FILTER SPECIFICATIONS

Second Solution

BAND	Band Name	Crystal Freq.	Crystal Detection Criteria	Correct RF from	Correct RF to	Undesired Image Spur from	Undesired Image Spur to	Required Image Suppression Filter	S21>-1 for
	[m]	MHz	MHz	MHz	MHz	MHz	MHz		MHz
1	**160**	7.52	f < 15	1.5	2.0	13.04	13.54	BS13-20	f <7.5
2	**80**	9.52	f < 15	3.5	4.0	15.04	15.54	BS13-20	f <7.5
3	**40**	13.03	f < 15	7.0	7.5	18.54	19.04	BS13-20	f <7.5
4	**20**	20.02	f = 20.02	14	14.5	25.54	26.04	BS20-30	f <15
5	**15**	27.02	40>f > 25	21	21.5	32.54	33.04	BS32-42	f <21
6	**11**	33.02	40>f > 25	27	27.5	38.54	39.04	BS32-42	f <21
7	**10A**	34.02	40>f > 25	28	28.5	39.54	40.04	BS32-42	f <21
8	**10B**	34.52	40>f > 25	28.5	29	40.04	40.54	BS32-42	f <21
9	**10C**	35.02	40>f > 25	29	29.5	40.54	41.04	BS32-42	f <21
10	**10D**	35.52	40>f > 25	29.5	30	41.04	41.54	BS32-42	f <21

f. The first solution was to use an image rejection mixer to suppress the USB at every selected RF band. After many design trials, this solution was excluded since it was impossible to design an image rejection mixer with such an ultra wide band with a 20:1 BW (1.5 to 30 MHz output frequency band).

g. The second approach to this problem was to divide the RF frequency band into three sub-bands, design three different band-pass filters each passing a certain desired frequency band and suppressing the corresponding spurious band as shown in Table 2; and switch the resulting signal among the three BPF's according to the RF frequency band being selected by the user. The problem of detecting the band switch position was solved by detecting the instantaneous value of the LO frequency and use it to control the switch. The system was completely designed with this solution.

h. In order to decrease the system complexity and size, a third solution has been adopted with a single specially designed LPF instead of the three switched filters of the second solution. The LPF has been optimized such that the desired signal is higher than the spur by more than 12 dB for each value of the different ten LO frequencies.

i. It was assured through thorough simulation trials in time and frequency domains that an output comparator will ignore the spur if it is lower than the desired signal by more than 10 dB.

j. The third solution has been fully designed and fully simulated in time and frequency domains for the ten frequency bands. The system gain and frequency response have been repeatedly optimized for perfect operation at the ten frequency bands.

k. A zero detection precision comparator has been added at the output of the Frequency Measurement Unit (RFMU) to extract a rectangular pulse from every cycle of the sine wave at the final filter output.

l. A fully hardware based counter has been designed with six digits of 7-segment display. The counter will display the measured frequency up to 30 MHz with 100 Hz resolution. Two decimal points will be always displayed at kHz and MHz beginning range.

m. A 2D layout has been accurately designed for the system, from which an accurate 3D design has been generated. The 3D layout shows where the connectors between every two subsequent modules should be located.

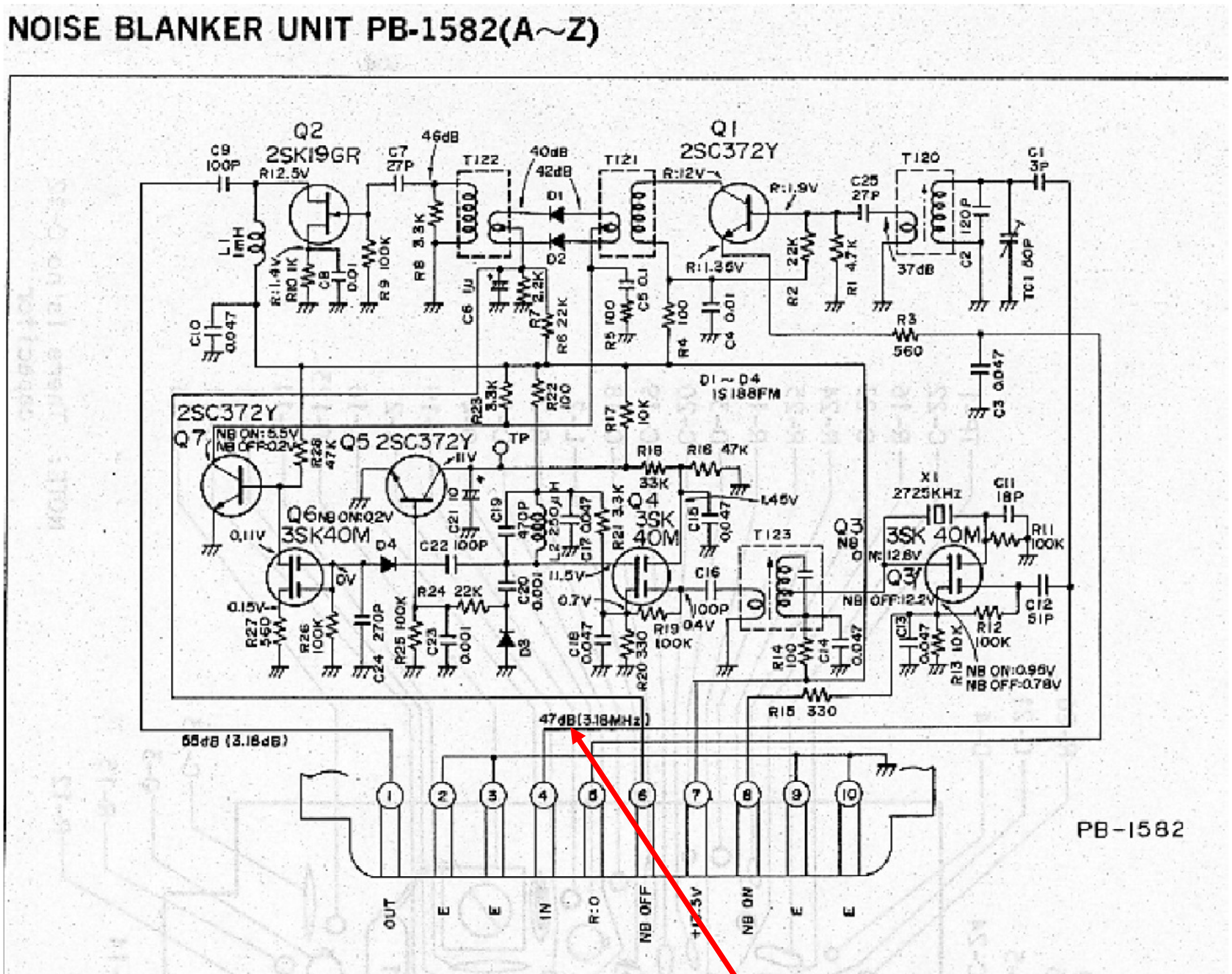


Figure 2. Noise Blanker Unit Output.

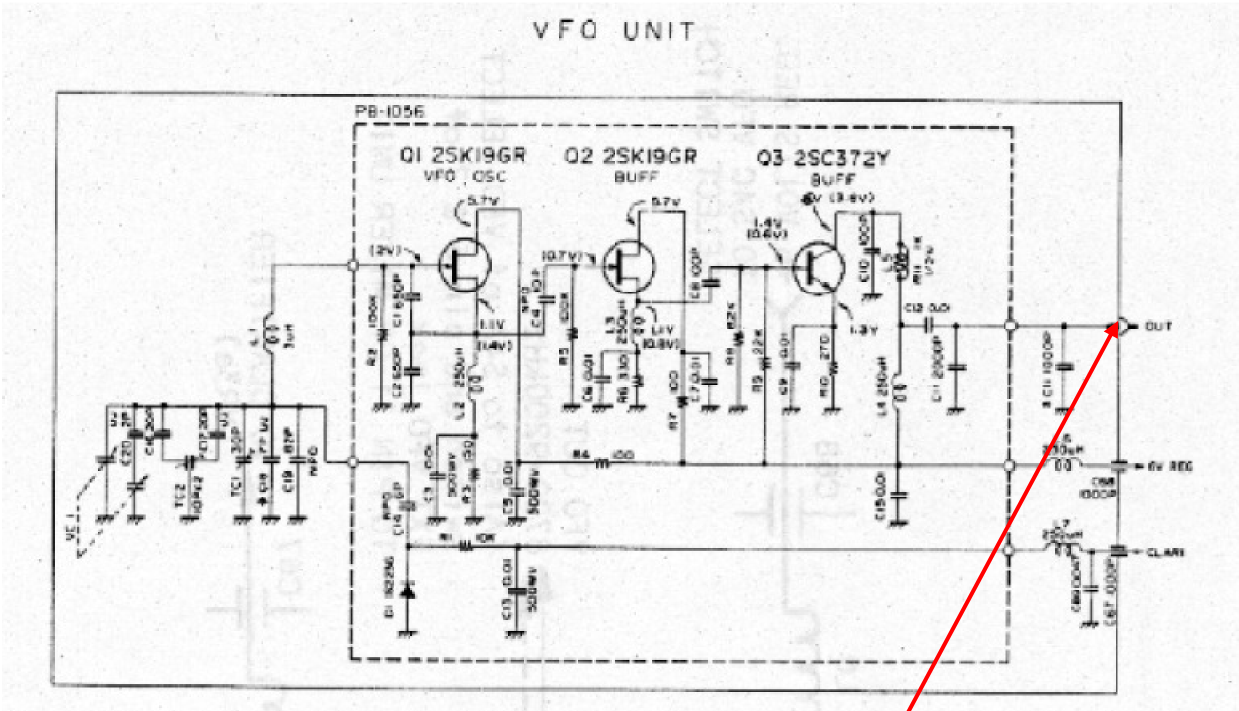


Figure 4. The PB-1056 VFO Unit Output Signal

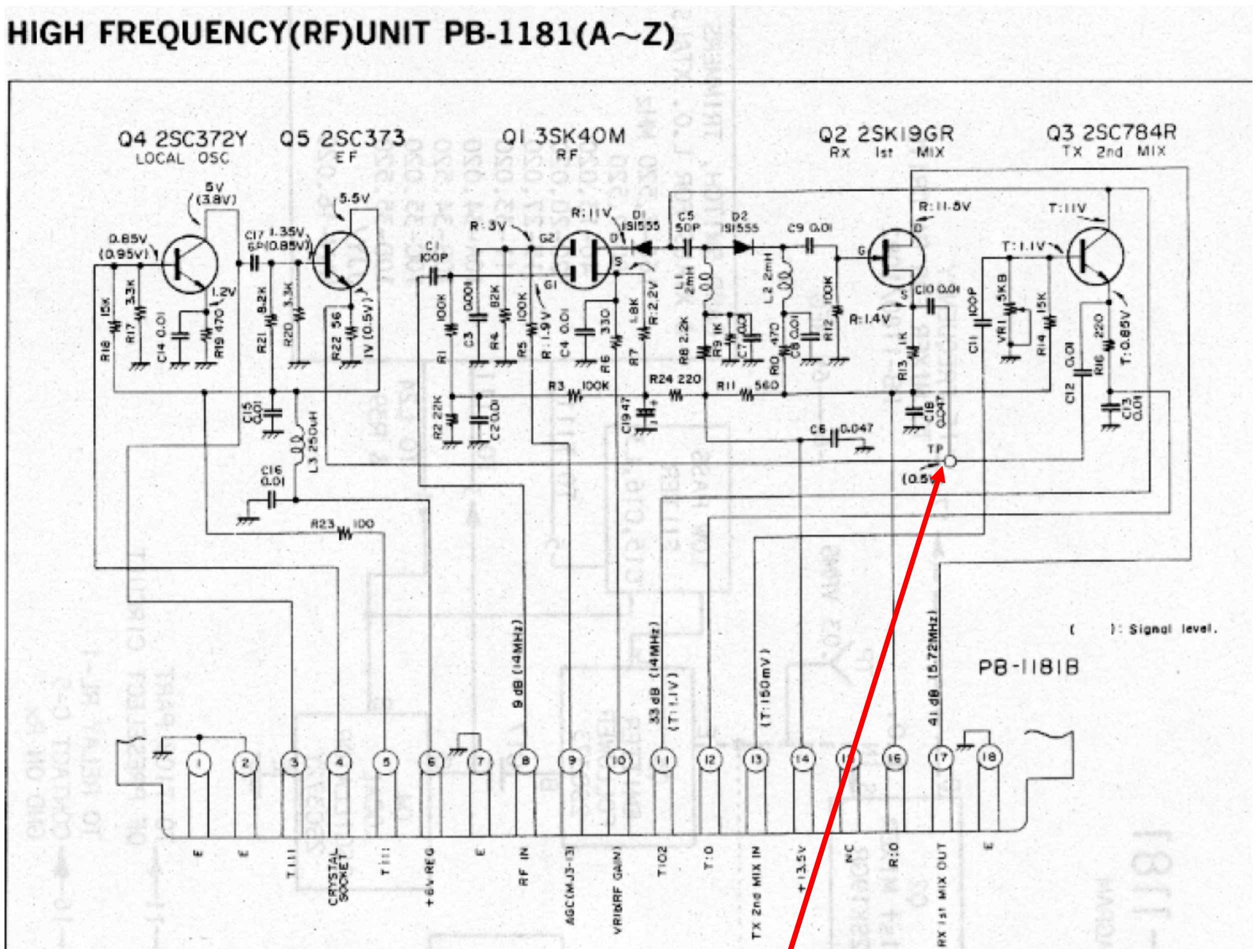


Figure 5. The PB-1181 RF Unit LO2 Signal

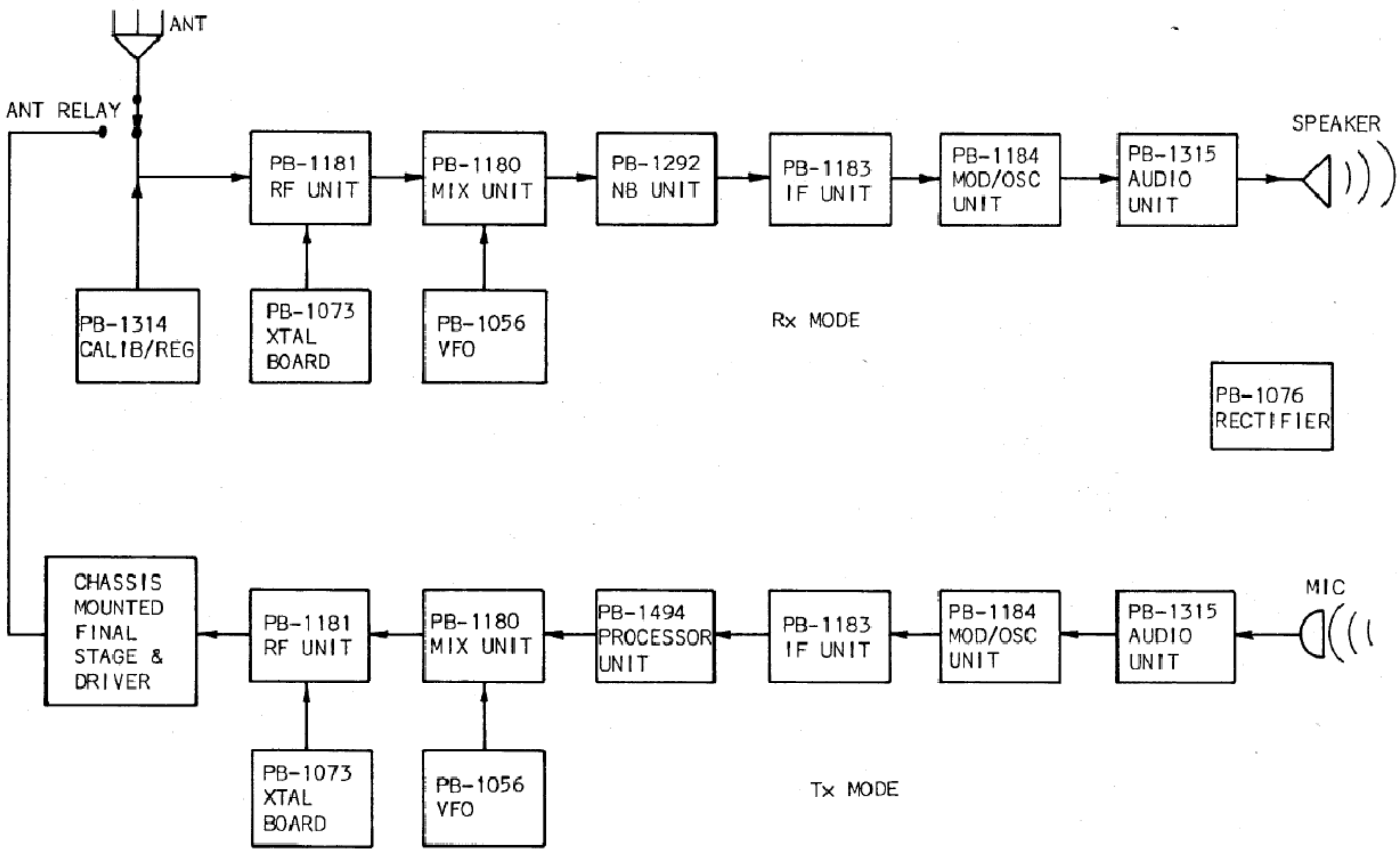


Figure 6. FT-101 Simplified Block Diagram

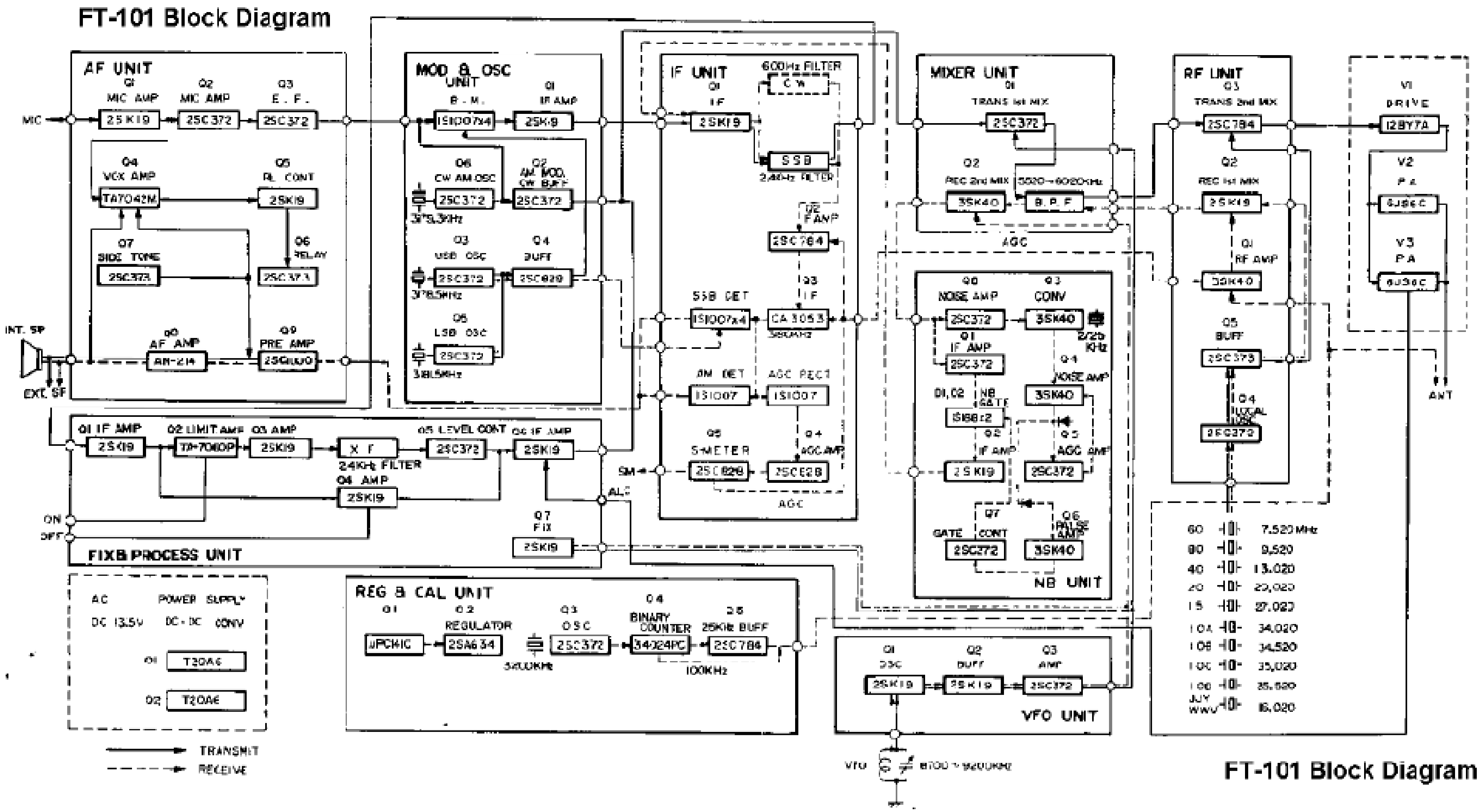


Figure 7. FT-101 Detailed Block Diagram

2. How the FT-101 Selects the Received Frequency

Figures 6 and 7 show the original simplified and detailed block diagrams of the FT-1014 drawn by Yaesu engineers. They describe in detail all exchanged signals among different modules of the transceiver.

From these two figures, the two stage heterodyne process can be understood as follows:

1. The received RF signal is mixed with the selected crystal oscillator output in the **PB1181 RF Unit.**

2. In the **PB1180 MIXER Unit**, the mixer output is filtered by a selective (5.52 - 6.02) MHz BPF. The BPF output is mixed with the VFO output which is fine tuned by the user to the required frequency.

3. The VFO output frequency, generated by the **1056 VFO Unit**, can be manually changed between 8.7 and 9.2 MHz.

4. In the PB1292 NB Unit, the second mixer output is filtered by a second BPF tuned to 3.18 ±0.25 MHz. The 3.18 MHz signal is further processed and demodulated in next IF and audio stages of the receiver.

I have redrawn these frequency management stages by GENESYS. A simplified block diagram of the FT-101 concentrating on the received frequency processing is shown in Figure 8.

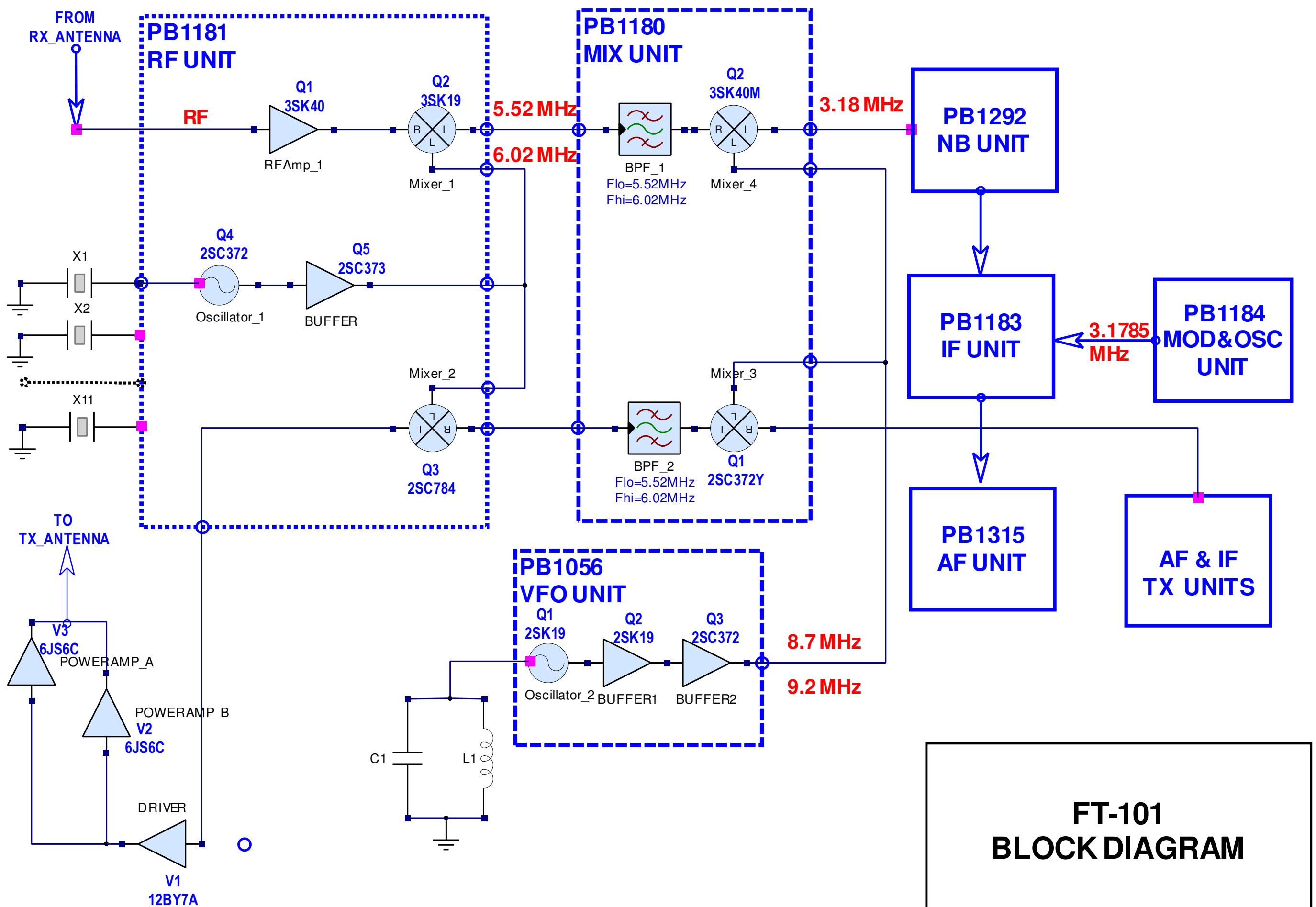


Figure 8. FT-101 Simplified Block Diagram drawn by GENESYS

3. The Rx Frequency Measurement Problem

a. The transmitter frequency can be easily measured by taking a sample of the output signal before the power amplifier to the frequency counter.

b. The situation differs in the receiver; since:
   i. The input signal is too low to be measured
   ii. There are many input signals among which the receiver should select. The selection is done by tuning the receiver to a certain frequency and taking the signal possessing this selected frequency.
   iii. There are two stages of down conversion. In the first stage, the receiver switches in one of ten different crystals as a first local oscillator to determine the frequency sub-band of the receiver. By mixing the input signal with the first local oscillator, the selected signal is down converted to the first IF (5.52 to 6.02 MHz).
   iv. In the second stage, a Variable Frequency Oscillator is fine tuned to the exact required frequency between 8.7 MHz and 9.2 MHz as the second local oscillator. By mixing the first IF with the second local oscillator, the selected signal is down converted to the second IF = 3.18 MHz.

c. Therefore, there is actually no RF signal in the receiver that can be detected and measured.

4. The Adopted Method to Measure the Selected Receiver Frequency

a. The best solution is to create the RF signal to which the receiver desires to select and measure the frequency of this created signal.

b. The RF signal is created in the same two steps:
   i. The 3.18 MHz signal is taken from the PB1292 NB Unit.
   ii. The instantaneous fine LO signal is taken from the PB1056 VFO Unit
   iii. The two signals are mixed and the mixer output is filtered by a 5.52 to 6.02 MHz BPF.
   iv. The resulting signal is mixed with the currently selected crystal oscillator output.
   v. The mixer output is taken to the Frequency Counter Unit.

c. The frequency measuring system is shown in Figure 9.

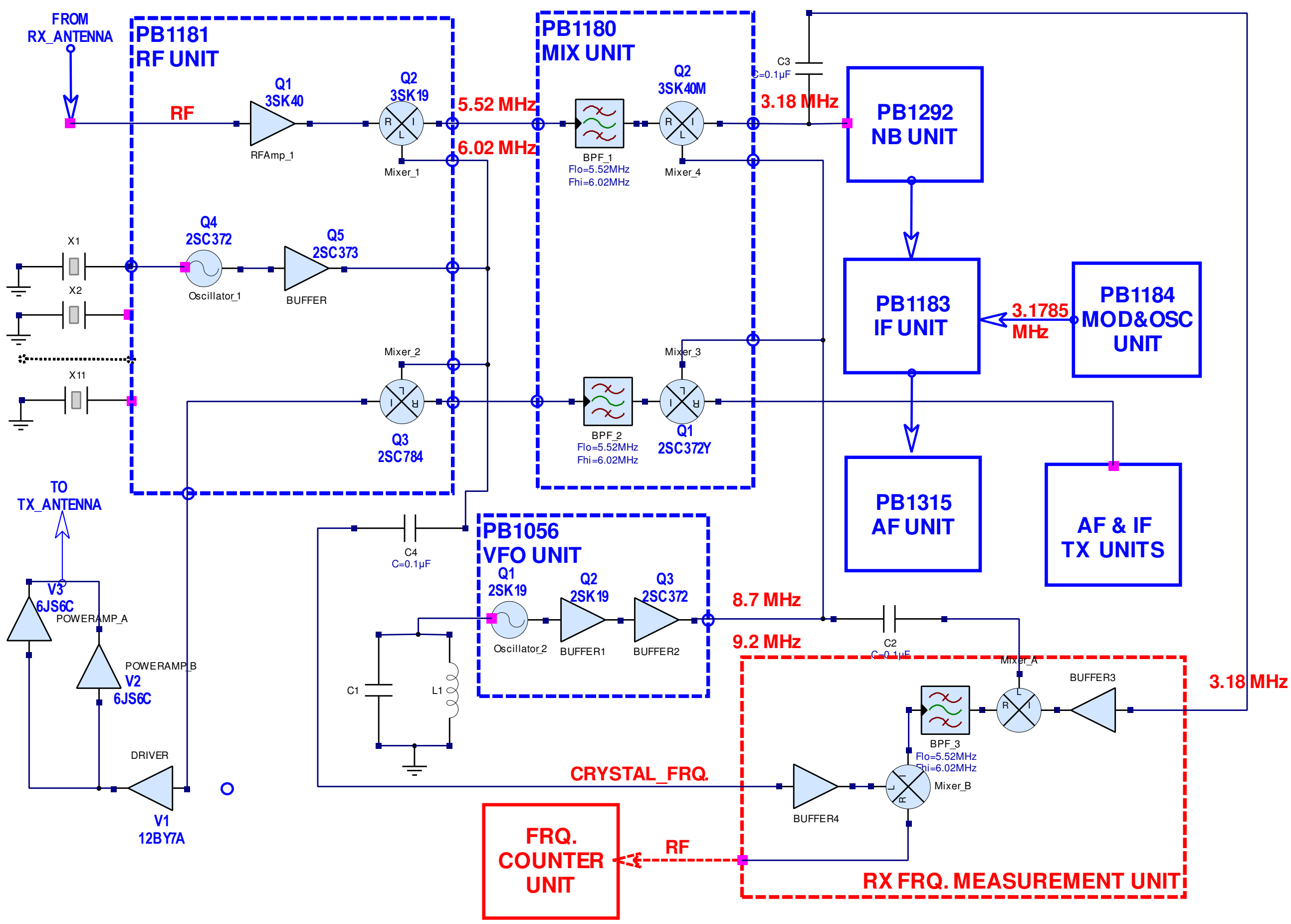


Figure 9. The adopted method to measure the receiver currently selected frequency

5. The Amplitudes of The Three Input Signals as Measured by the Owner

The project owner has measured the amplitudes of the three input signals to the new Frequency Measuring Unit as follows:

The First LO signal amplitude at the RF Oscillator output is 700 mV

The second LO signal amplitude at the VFO output is 150 mV

The received 3.18 MHz signal at the NB unit output is of the order of 20 mV

The RFMU design has been adapted to the above mentioned input signal levels.

If, at any time, the owner finds other signal levels different than those mentioned above, it is possible to adjust the system gains accordingly.

6. The Designed Hardware to Measure the Received Frequency

Two main units have been designed to measure the frequency to which the FT-101 receiver is currently tuned:

1. The Rx Frequency Measuring Unit (RFMU)
2. The Frequency Counter Unit (FCU).

6.1 The Rx Frequency Measuring Unit (RFMU)

This unit generates a radio frequency equal to that of the currently selected input sinal.

This is done at two stages:

6.1.1. The 3.18 signal is mixed with the current VFO output signal (manually tuned by the user).

6.1.2 The resulting signal is mixed with the RF output of the currently selected crystal oscillator (1 of 11 different crystals).

6.1.3. A buffer is used at each input port to guarantee unloading the oscillator from which the signal is taken in the FT-101. The buffer has very high input impedance, while its output is matched to the 50 Ohm impedance of the next mixer.

The functional diagram of the RFMU is shown in Figure 10.

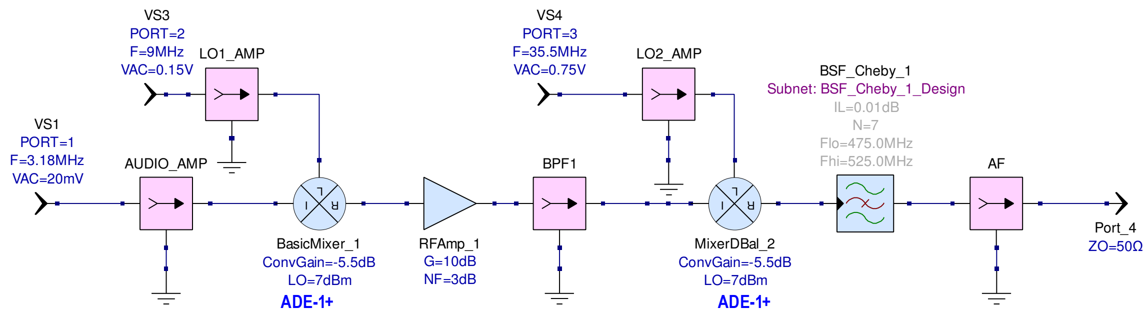


Figure 10. The RFMU

7. Verification of the output frequency bands

In the following we try to verify for the output RF frequency bands of the FT-101 at different positions of the crystal selection switch.

The following table shows the different crystal frequency values and the corresponding expected values of the RF frequencies. We have got those values by subtracting the IF from each crystal frequency.

BAND	Crystal frequency	VFO frequency	Fine IF	Total IF f_{VFO} - IF	Correct RF	Undesired spur output frequency	Required Filter
[m]	MHz	MHz	MHz	MHz	MHz	MHz	MHz
160	7.52	8.7 to 9.2	3.18	5.52 to 6.02	1.5 to 2	13.04 to 13.54	LP10
80	9.52	8.7 to 9.2	3.18	5.52 to 6.02	3.5 to 4	15.04 to 15.54	LP5
40	13.02	8.7 to 9.2	3.18	5.52 to 6.02	7 to 7.5	18.54 to 19.04	LP8
20	20.02	8.7 to 9.2	3.18	5.52 to 6.02	14 to 14.5	25.54 to 26.04	LP15
15	27.02	8.7 to 9.2	3.18	5.52 to 6.02	21 to 21.5	32.54 to 33.04	LP22
11	33.02	8.7 to 9.2	3.18	5.52 to 6.02	27 to 27.5	38.54 to 39.04	LP28
10A	34.02	8.7 to 9.2	3.18	5.52 to 6.02	28 to 28.5	39.54 to 40.04	LP30
10B	34.52	8.7 to 9.2	3.18	5.52 to 6.02	28.5 to 29	40.04 to 40.54	LP30
10C	35.02	8.7 to 9.2	3.18	5.52 to 6.02	29 to 29.5	40.54 to 41.04	LP30
10D	35.52	8.7 to 9.2	3.18	5.52 to 6.02	29.5 to 30	41.04 to 41.54	LP30

8. Detailed Design of the RFMU

In the following sections we shall describe the different blocks of the RFMU shown in Figure 10 above. We start by the three input signal buffer amplifiers.

8.1. Signal Buffer Amplifiers

It is an important design criterion that the new RFMU should not load any signal source and should not affect its performance.

Therefore, the following precautions have been followed:

The input impedance of each buffer amplifier should be much higher than the source output impedance.

A capacitance is inserted between each signal source and the buffer amplifier input to guarantee no mutual effect between the output DC level of the signal source and the input DC level of the buffer amplifier. The value of this capacitance should be big enough not to degrade the system gain at the frequency band of the input signal.

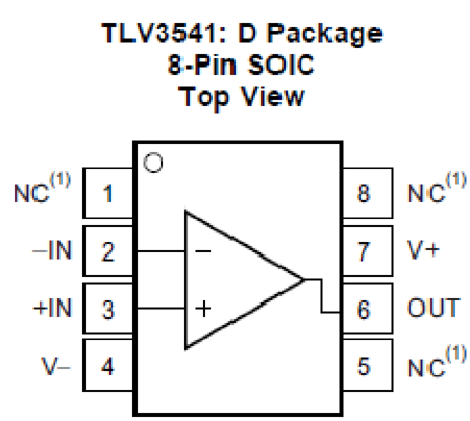
The buffer amplifier's gain should be adjusted to guarantee the overall system gain required to raise the input signal to the operational required level.

The output impedance of the buffer amplifier is optimized for maximum power transfer to next stages. This is achieved when the real part of the buffer output impedance is 50 [Ω] and the output return loss is maximized at the frequency band of interest (3.18 MHz for the audio signal input, 8.7 to 9.2 MHz for the first LO input and 7.5 to 35.5 MHz for the second LO input).

The following paragraphs will show how these criteria have been fulfilled and how the three buffer amplifiers have been optimized for best performance.

A very good OPAMP has been selected for all the three buffer amplifiers. It is the Texas Instruments' **TLV3541** with the following characteristics:

- *Unity-Gain Bandwidth: 200 MHz*
- *High Slew Rate: 150 V/μs*
- *Low Noise: 7.5 nV/√Hz*
- *High Output Current: > 100 mA*
- *Excellent Video Performance:*
    - *Diff Gain: 0.02%, Diff Phase: 0.09°*
    - *0.1-dB Gain Flatness: 40 MHz*
- *Low Input Bias Current: 3 pA*
- *Quiescent Current: 5.2 mA*



- *Thermal Shutdown*
- *Supply Range: 2.5 V to 5.5 V*
- *Open loop gain 100 dB*

- *Input impedance 10^{13}Ohms*
- *Output resistance 35 Ohm.*

8.1.1. Audio Buffer Amplifier

Figure 11 shows the schematic diagram of the Audio Buffer Amplifier.

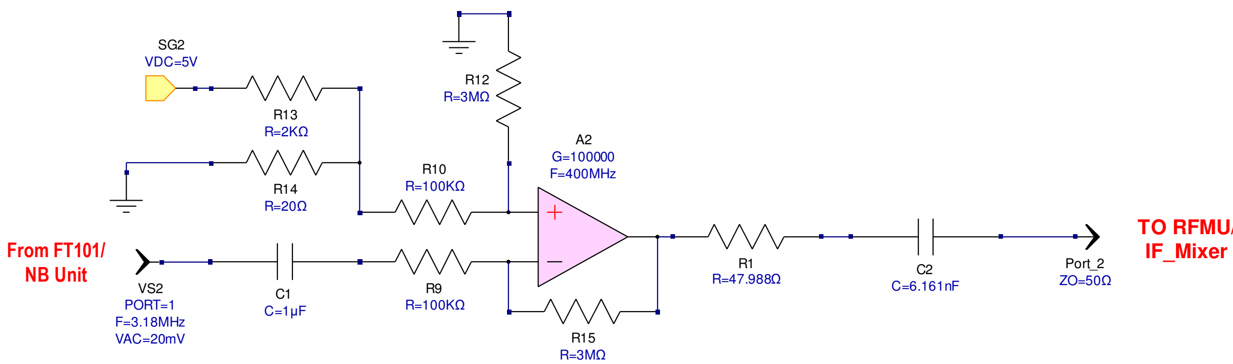


Figure 11. The audio signal buffer amplifier schematic

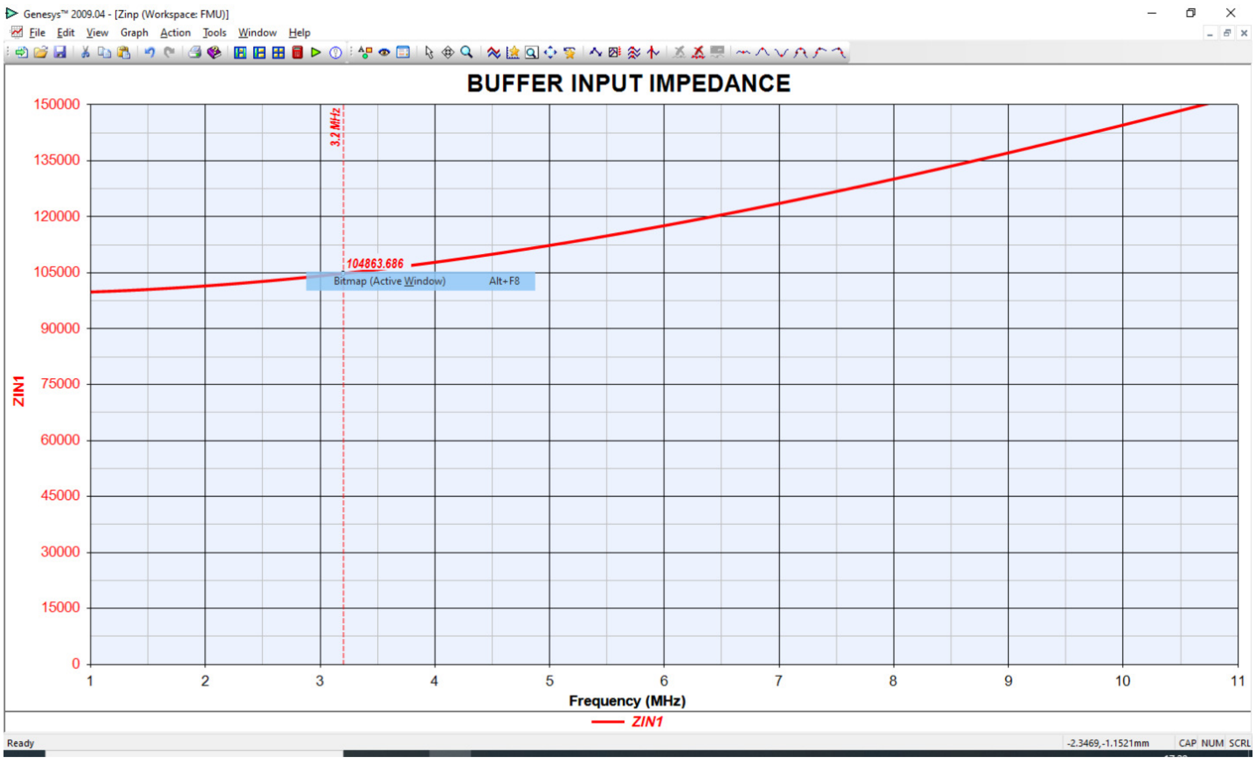


Figure 12. the Buffer Input impedance

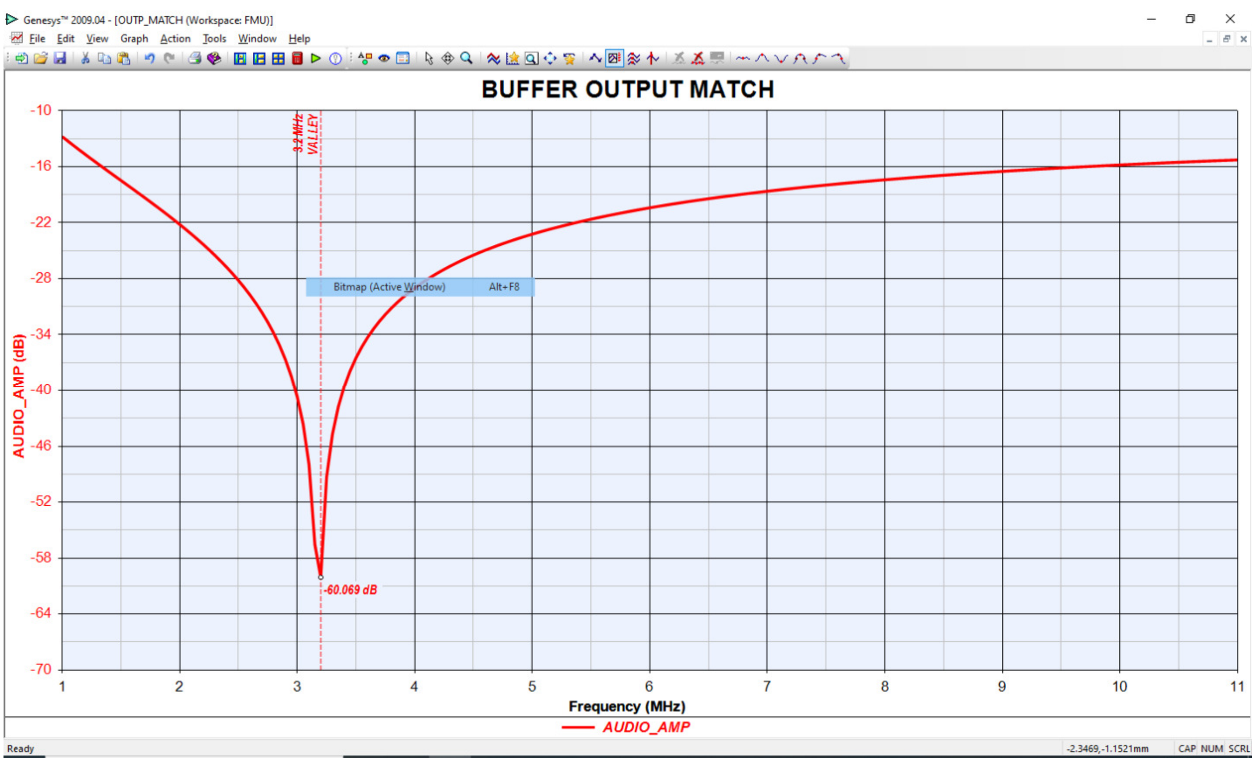


Figure 13. Audio buffer amplifier output return loss optimized at 3.18 MHz

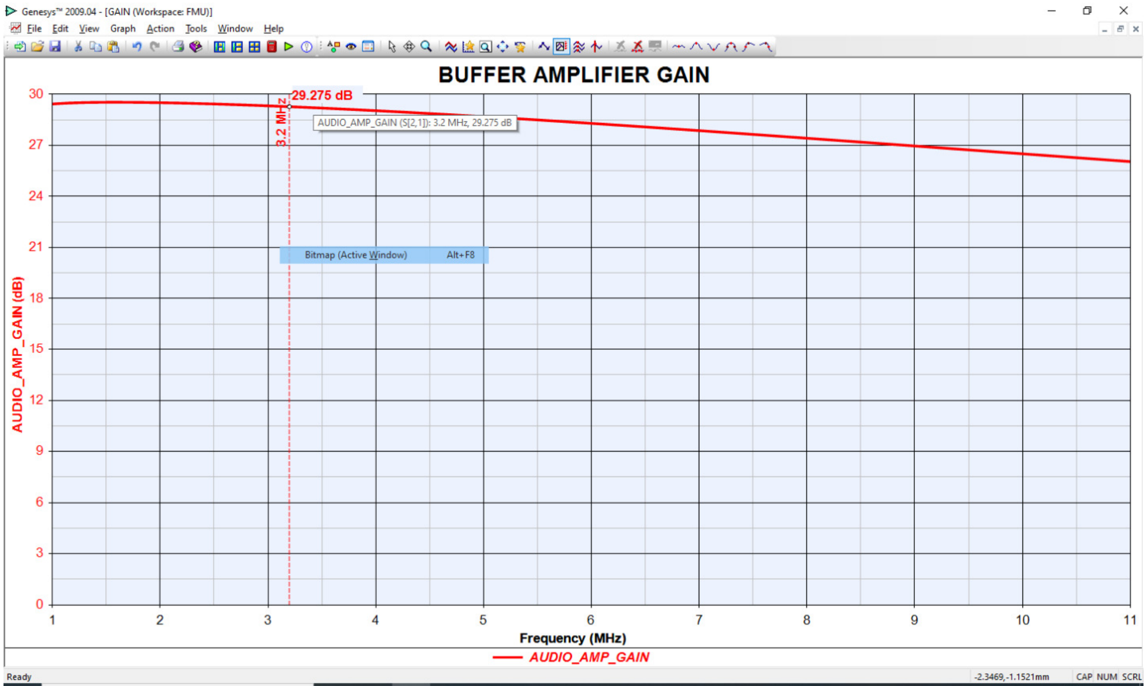


Figure 14. The Audio Buffer Amplifier Gain

It can be clearly seen from the above three figures that the audio signal buffer amplifier at 3.18 MHz has:

A 104 kOhm input impedance

A 60 dB output return loss with 50 Ohm load

A 29.27 dB gain

8.1.2. LO1 Buffer Amplifier

Figure 15 shows the schematic diagram of the LO1 Buffer Amplifier.

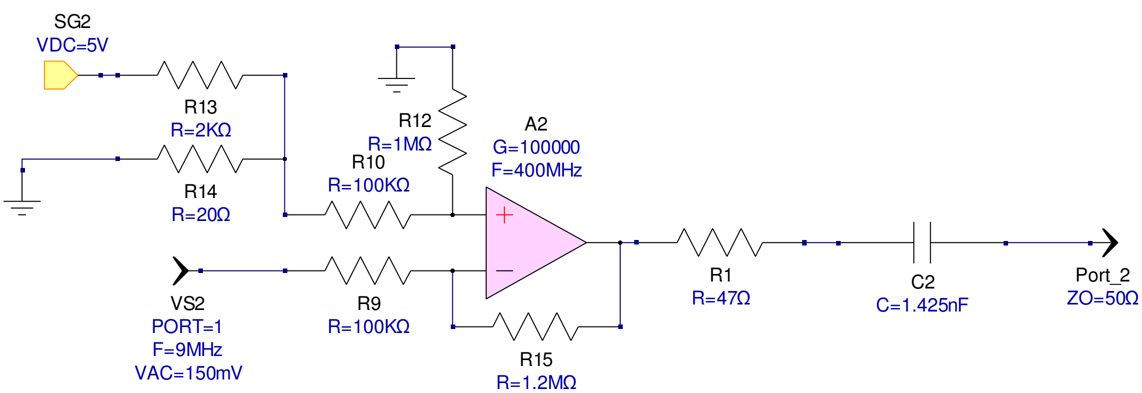


Figure 15. The LO1 signal buffer amplifier schematic

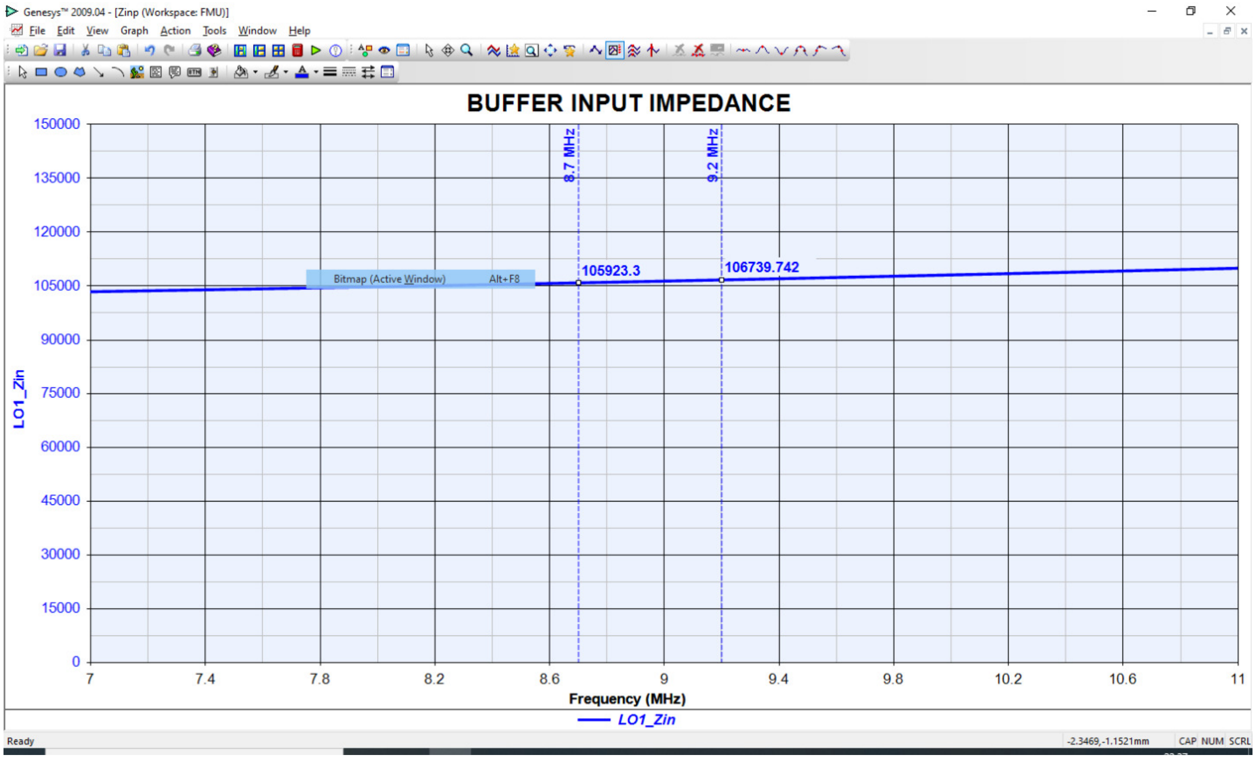


Figure 16. The LO1 Buffer Input impedance

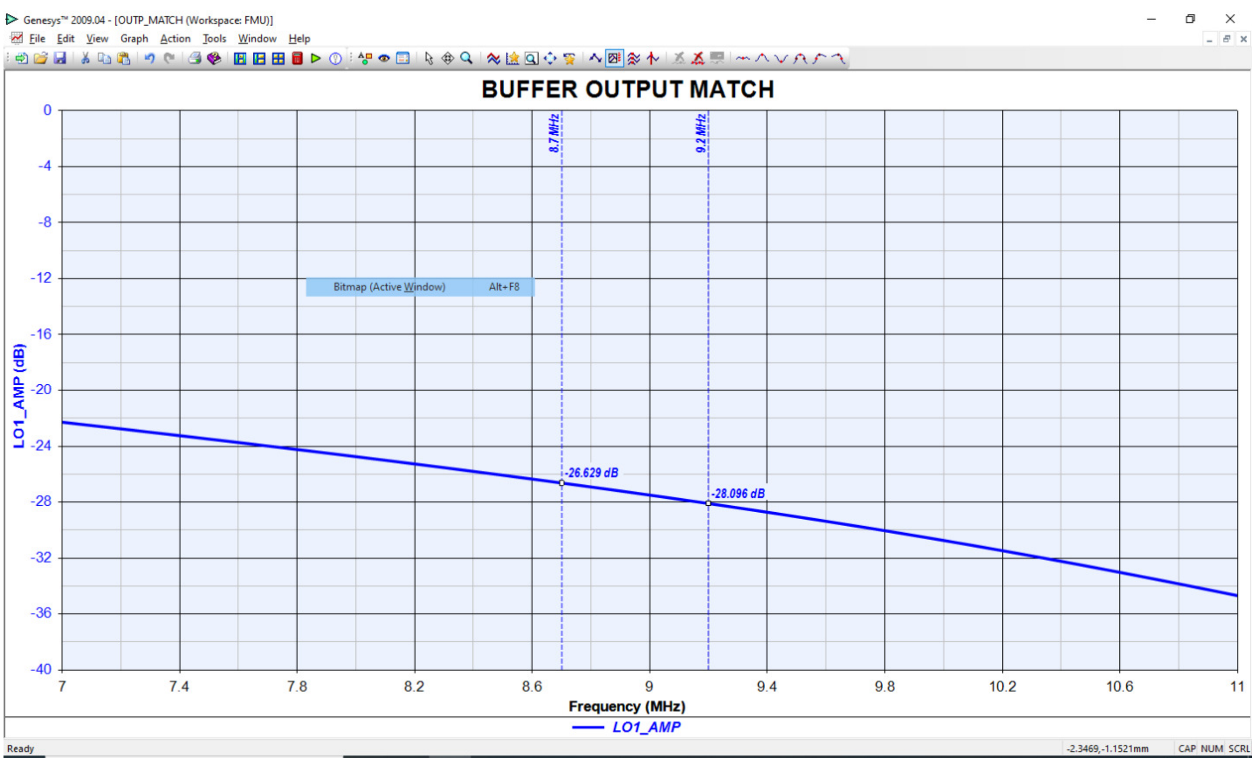


Figure 17. LO1 buffer amplifier output return loss

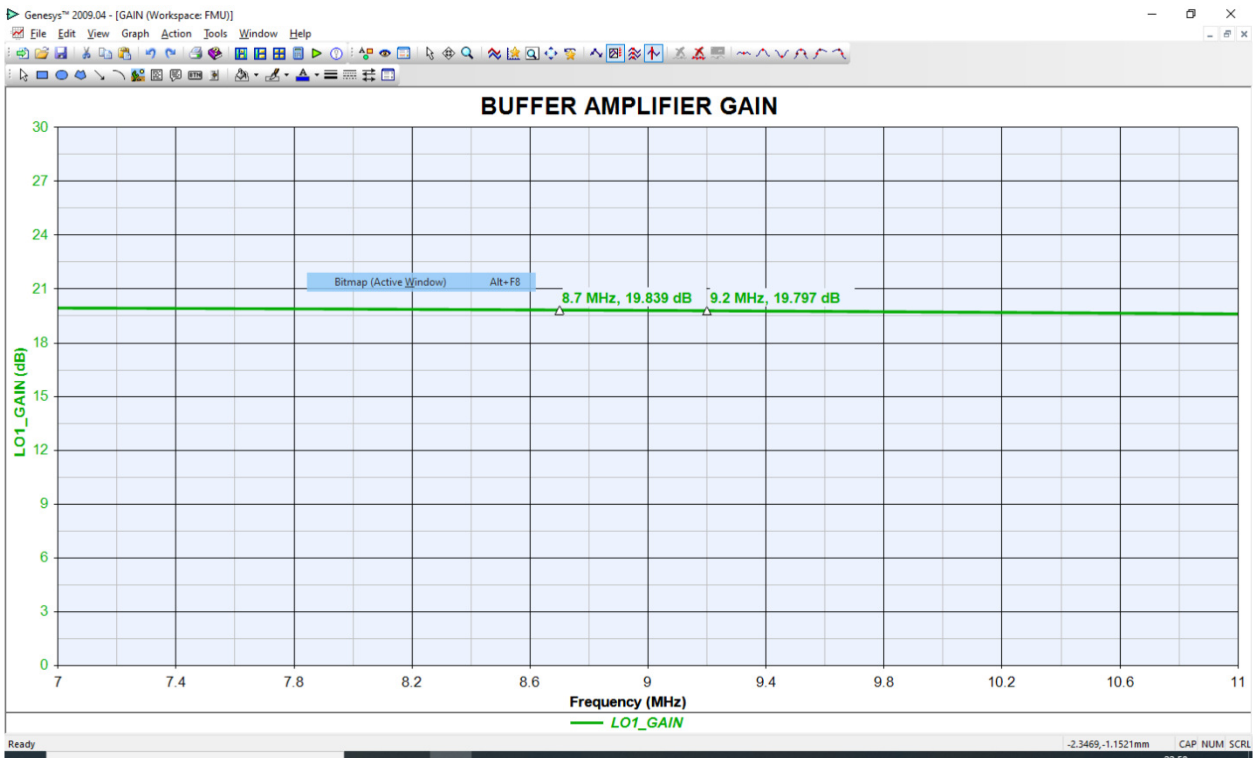


Figure 18. The LO1 Buffer Amplifier Gain

It can be clearly seen from the above three figures that the LO1 signal buffer amplifier in the frequency range 8.7 MHz to 9.2 MHz MHz has:

An input impedance > 106 kOhm

An output return loss with 50 Ohm load > 26.6 dB

An RF gain > 8.7 dB. This gain has been adjusted and optimized to raise the 150 mV input LO1 signal to the required +7dBm level for driving the ADE-1+ mixer, shown in Figure 19. This mixer has been selected as the best mixer for the RFMU after a thorough research detailed comparisons. The LO signal at the mixer input is shown in Figure 20.

Figure 19. the ADE-1+ Mixer

The IDE-1+ mixer has the following characteristics:

- *low conversion loss, 5.0 dB typ.*
- *excellent L-R isolation, 55 dB typ.*
- *excellent IP3, 15 dBm typ.*
- *low profile package*
- *aqueous washable*

These performance parameters have been substituted in the system simulator.

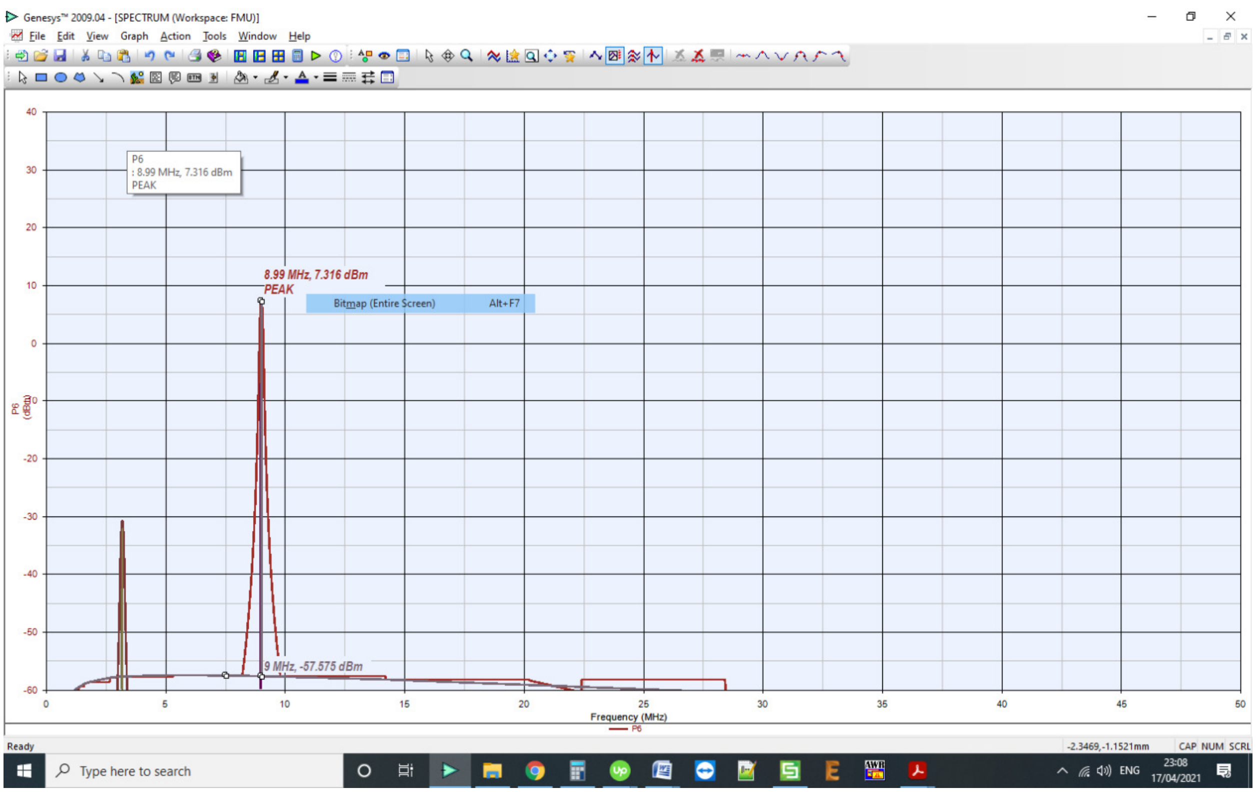


Figure 20. The LO spectrum at the mixer input

8.1.3. LO2 Buffer Amplifier

Figure 20 shows the schematic diagram of the LO2 Buffer Amplifier.

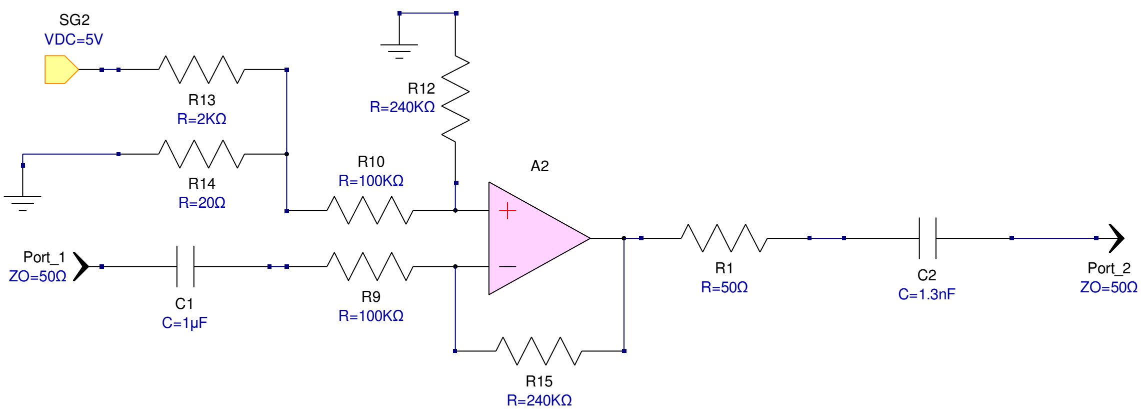


Figure 20. The LO2 signal buffer amplifier schematic

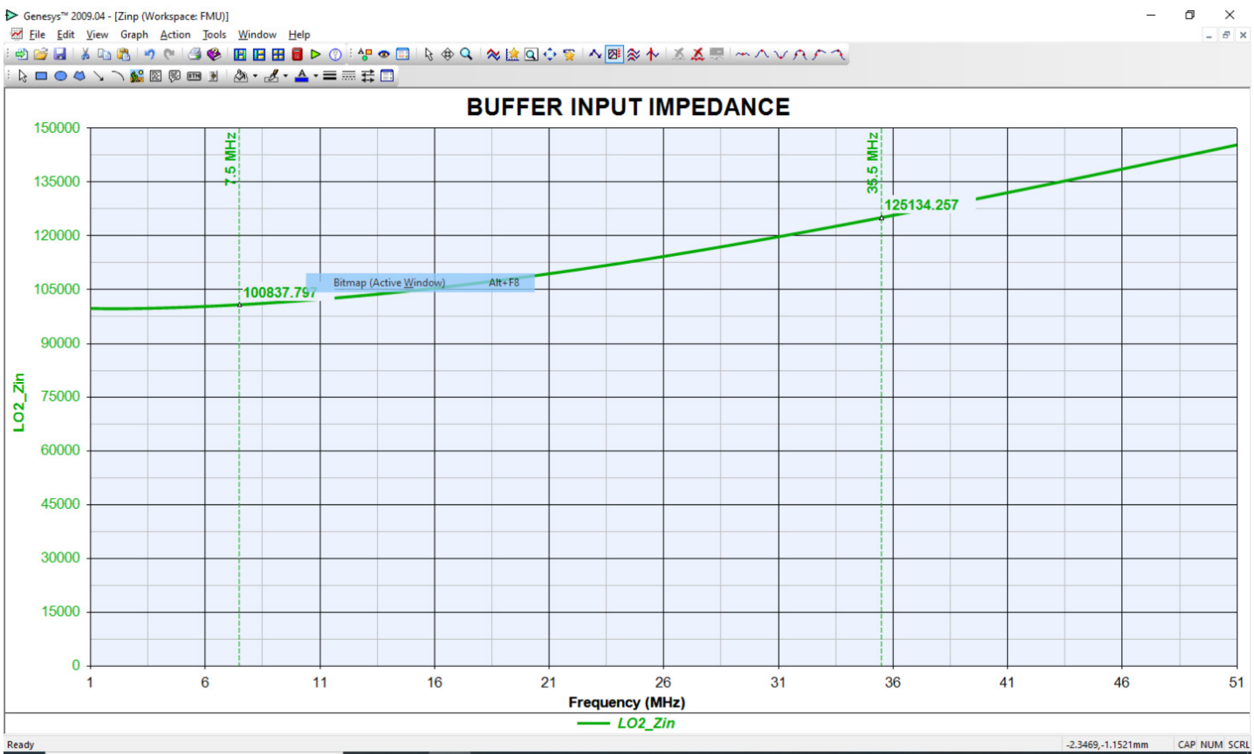


Figure 21. The LO2 Buffer Input impedance

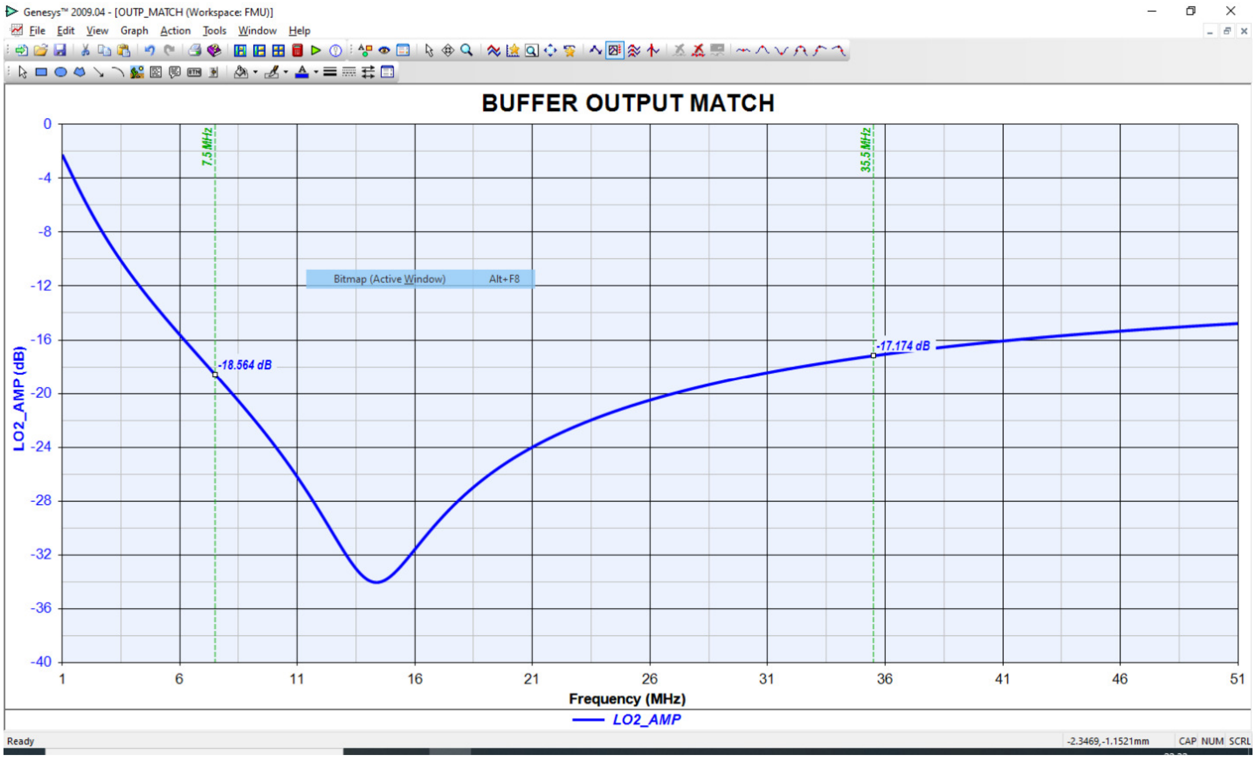


Figure 22. LO2 buffer amplifier output return loss

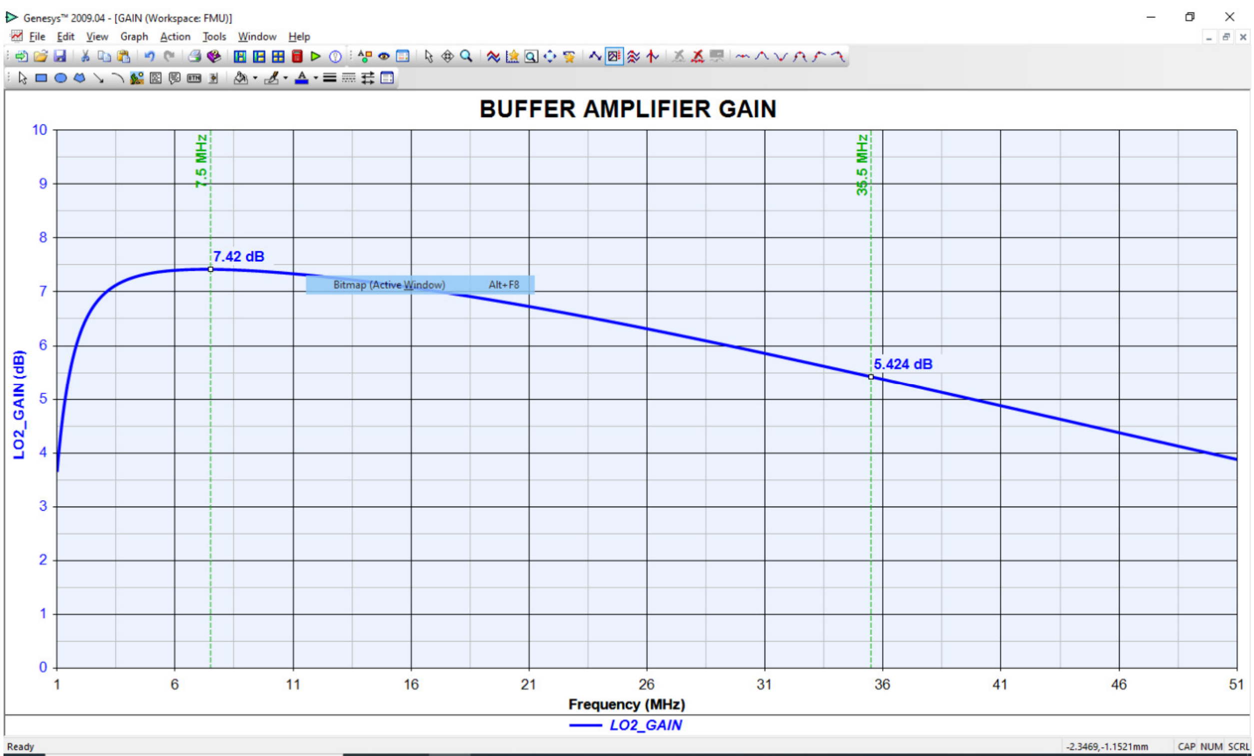


Figure 23. The LO2 Buffer Amplifier Gain

It can be clearly seen from Figures 21 TO 23 that the LO2 signal buffer amplifier in the frequency range 7.5 MHz to 35.5 MHz MHz has:

An input impedance > 100 kOhm

An output return loss with 50 Ohm load > 17.1 dB

An RF gain between 5.42 dB and 7.42 dB along the frequency range 7.5 to 35.5 MHz. This gain has been adjusted and optimized to raise the 700 mV input LO2 signal to the required +7dBm level for driving the ADE-1+ mixer for the ten frequency bands of the LO2 starting from 7.5 MHz up to 35.5 MHz. The LO2 spectrum at the mixer input at the two extremes of its frequency values is shown in Figure 24.

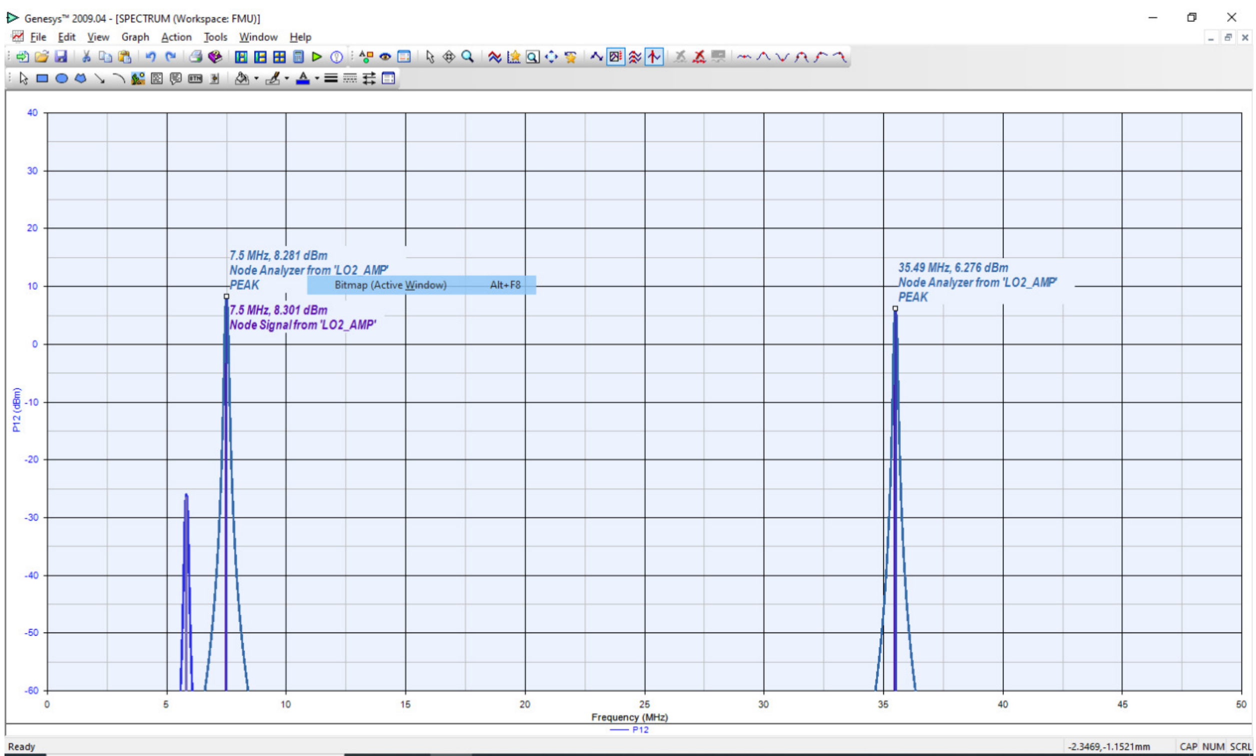


Figure 24. LO2 spectrum at the mixer input for different frequencies.

8.2. First Mixer Output

The first mixer mixes the 3.18 MHz received signal with the LO1 signal. The resulting spectrum is shown in Figure 25.

In Figure 25 we can see two mixer outputs with (f_L - f_A) and (f_L + f_A), where f_L is the LO1 frequency, which is controlled by fine tuning between 8.7 and 9.2 MHz and f_A is the receiver output signal frequency as taken from the NB Unit. The two output signals (5.81 MHz and 12.15

MHz) have nearly equal power levels (-6.88 and -7.44 dBm respectively), while a residual from the LO1 signal appears at the mixer output with reduced power (-22.7 dBm).

For proper operation, we need only the (f_L - f_A) component. Therefore, an IF (5.52 to 6.02 MHz) BPF is used after the first mixer to select the difference component.

In order to adjust the overall system gain, a 10 dB RF amplifier is inserted between the mixer output and the filter input as shown in the block diagram of Figure 10, repeated for convenience in the next figure.

A Mini Circuit's MAR-3SM+ has been selected for this function.

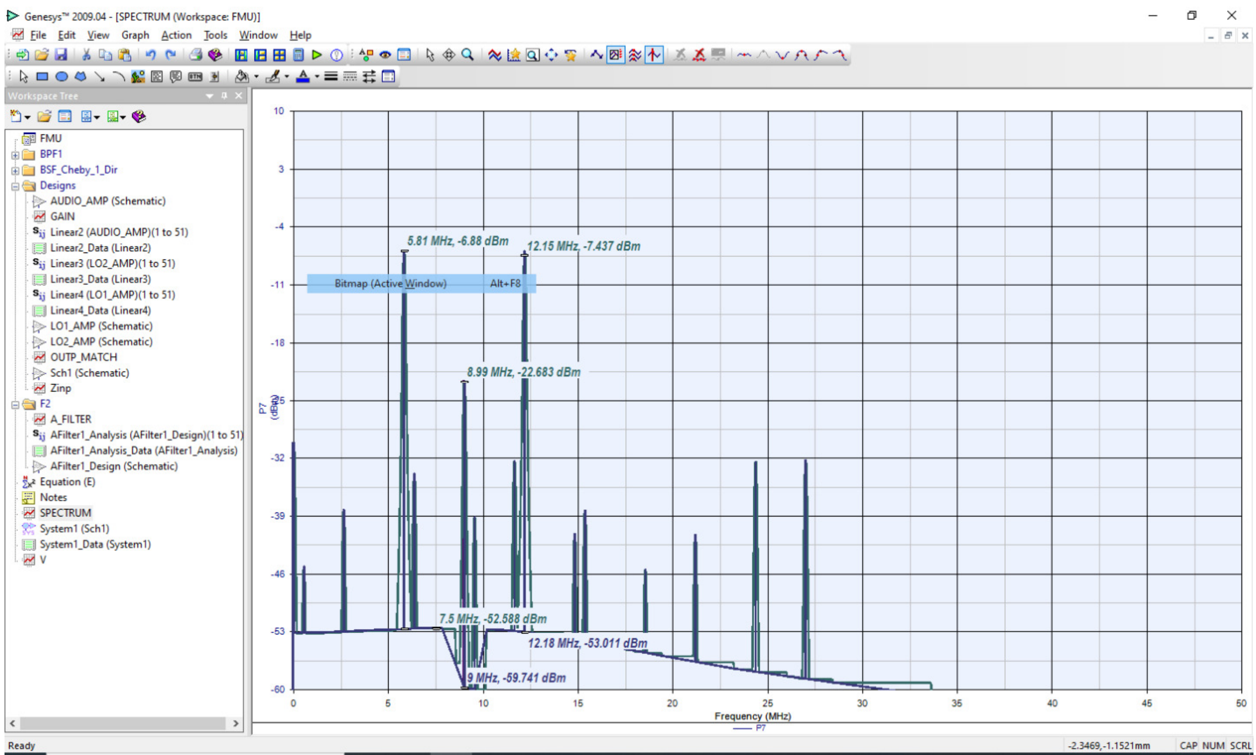


Figure 25. First Mixer Output Spectrum

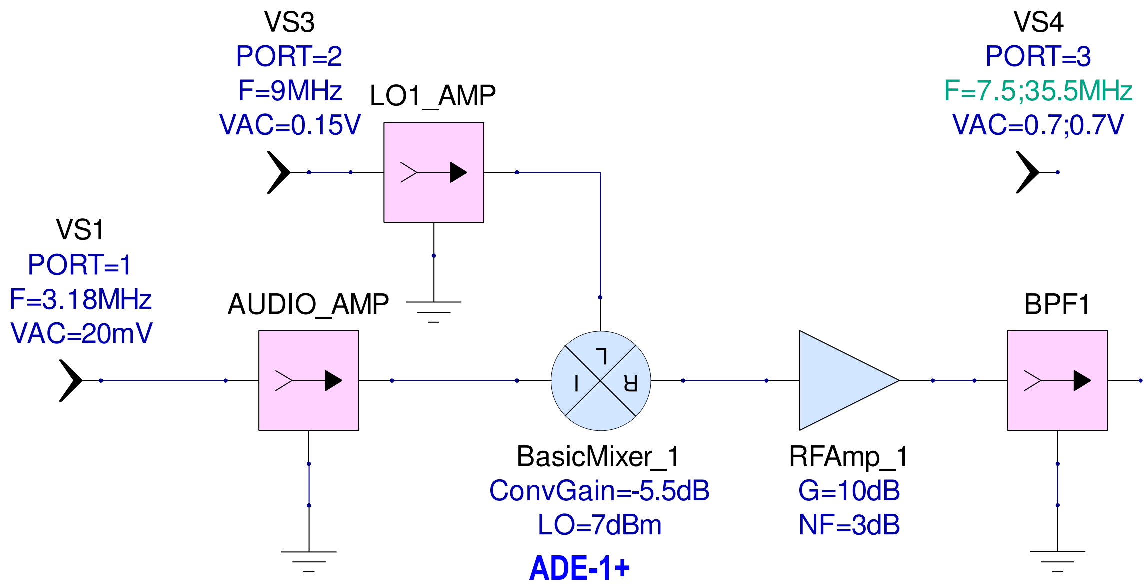


Figure 26. First part of the RFMU schematic

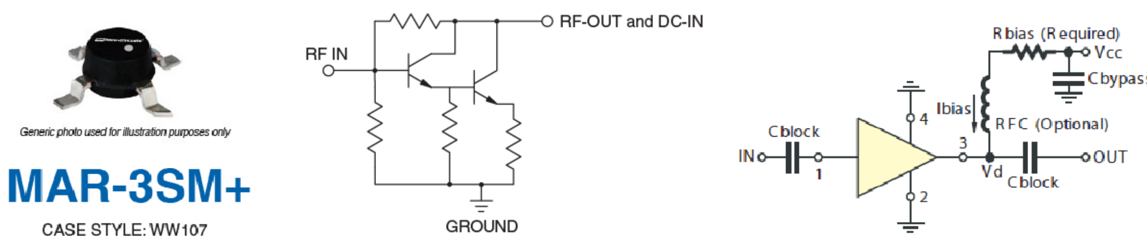


Figure 27. Thr MAR-3SM+ Amplifier.

As the Vd is 5V and our supply is +5V, we don't use a bias resistor.

Since the desired operation frequency is very small, we don't need any bias choke. The amplifier is directly connected to the +5V power supply. Only the input and output blocking capacitors are used. A big value (1 µF) has been selected for the DC blocking capacitances to minimize its effect on signal levels. The impedance of a 1 µF at 5 MHz is of the order of 32 [mΩ]. The layout of this part of the RFMU is shown in Figure 28.

In this figure we can see the two buffer amplifiers for the 3.18 audio signal and for the LO1. We can see the first ADE-1 mixer and the MAR3SM+ amplifier. The first mixer output goes to an edge smb connector, while the LO1 input comes through another edge smb connector and the 3.18 MHz signal via a two-pin connector.

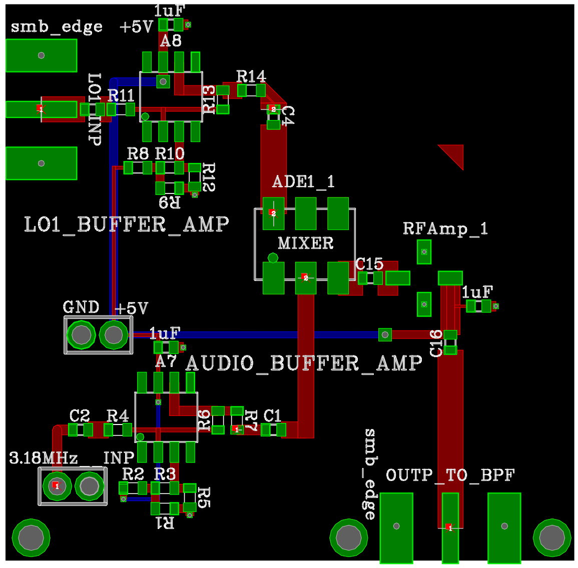


Figure 28. Layout of the first part of the RFMU.

The MAR-3SM+ has a high gain at this low frequency band, of the order of 13 dB. This additional gain enhances the system performance at higher output frequencies where the overall gain decreases. The MAR-3SM+ gain vs. frequency characteristic is shown in Figure 29.

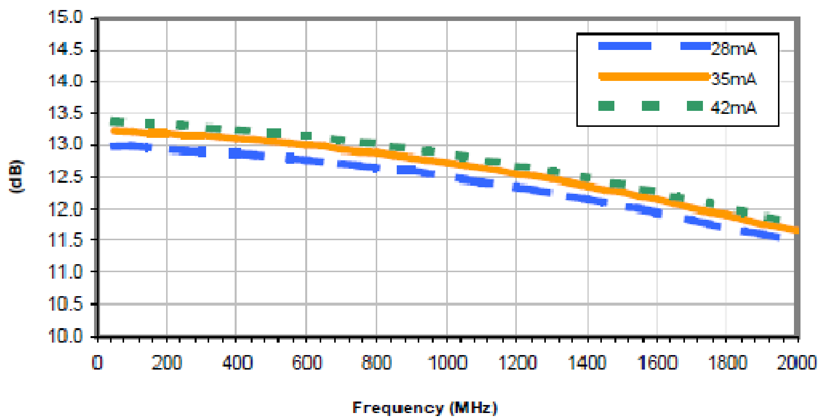


Figure 29. The gain frequency characteristics of the MAR3SM+ amplifier

The amplifier performance parameters have been substituted in the system simulator.

The simulated spectrum at the amplifier output is shown in Figure 30.

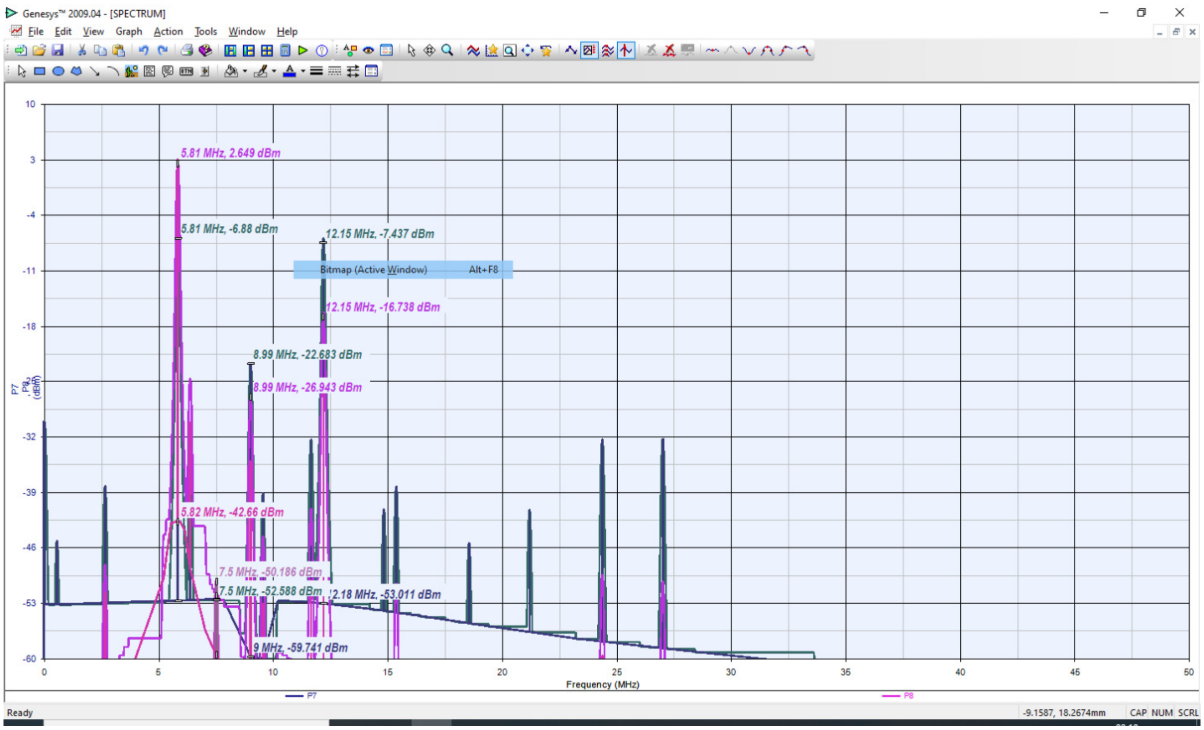


Figure 30. the amplifier output spectrum

8.3. The IF Bandpass Filter

This BPF is intended to select the lower side band of the mixer output and reject the upper side band. It should pass the (f_L - f_A) component and reject the (f_L + f_A) component of the mixer output. Since the LO frequency varies between 8.7 and 9.2 MHz and f_A = 3.18 MHz; then the desired component lies in the range:

$$5.52 \text{ MHz} < (f_L - f_A) < 6.02 \text{ MHz}$$

The filter has been designed to satisfy these requirements.

Figure 32 a and b show the frequency response of the filter. While Figure 32a shows how the filter suppresses any higher frequency in the frequency range of the system, Figure 32b shows a detailed view of the filter passband.

The in-band insertion loss is about 4.2 dB and the return loss is better than 14 dB. This has been achieved by using high Q inductors of Coilcraft's square air core inductors with Q values > 30 in the frequency band of interest.

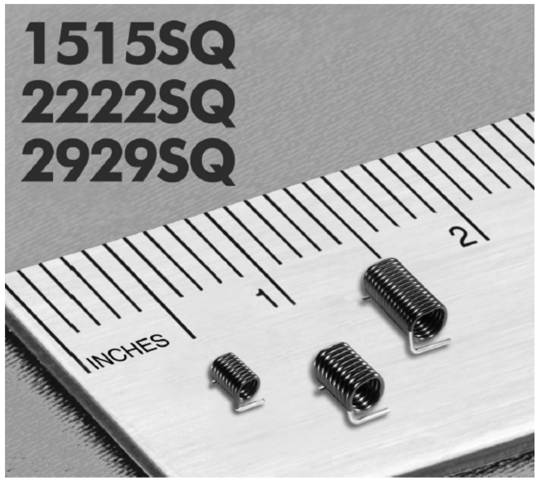


Figure 31. Square Air Core Inductors

If other inductors were used, the filter selectivity, insertion loss and return loss would have been worse.

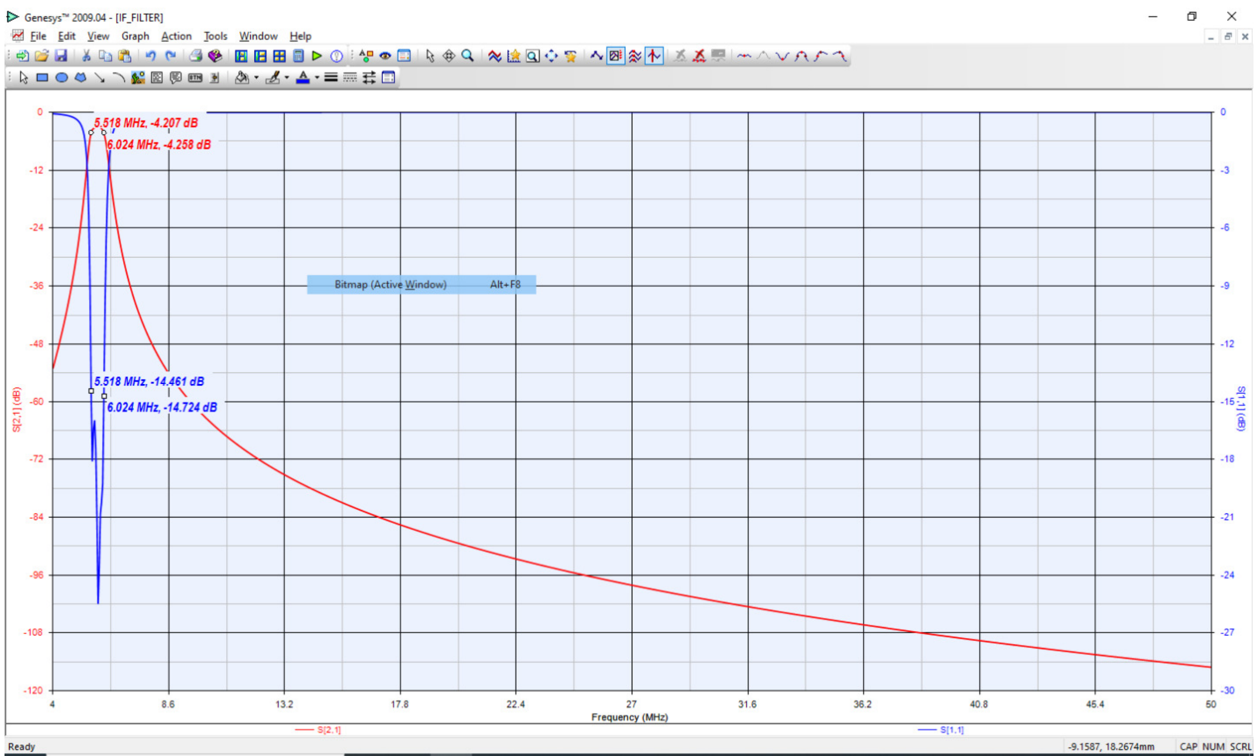


Figure 32.a

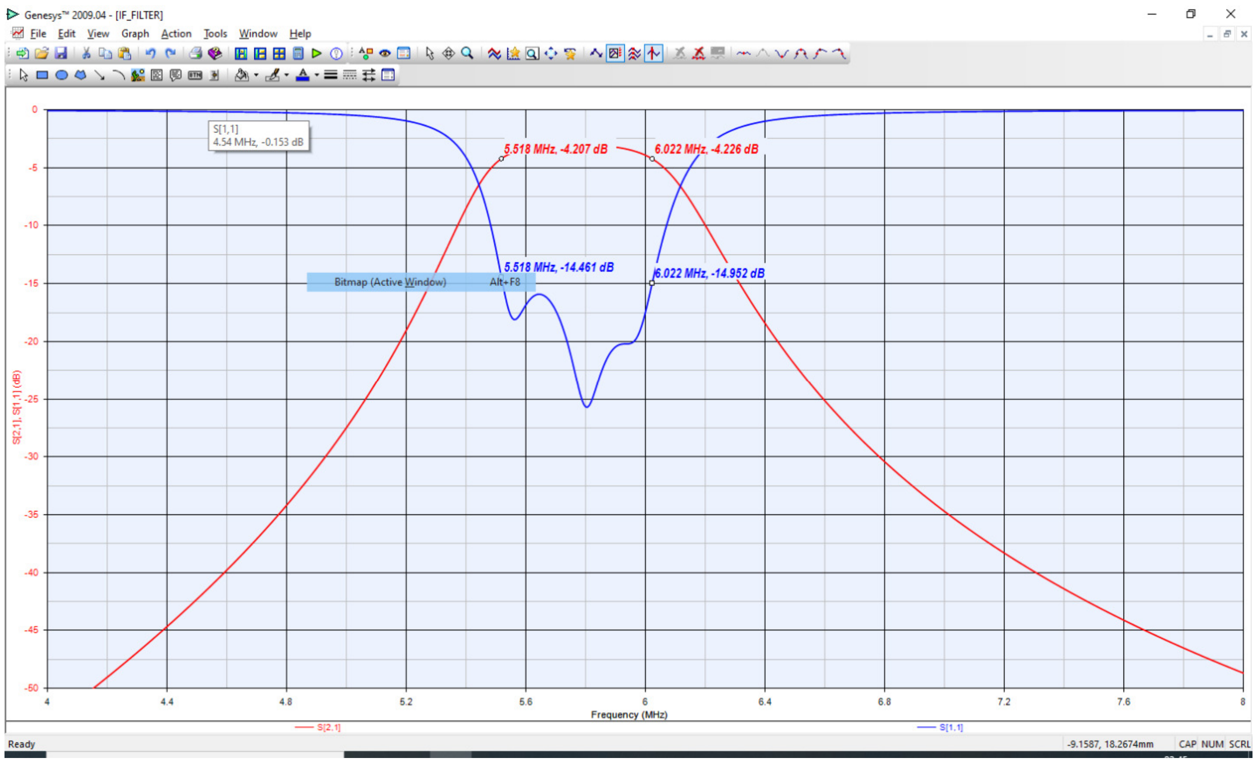


Figure 32.b. The BPF Frequency Response

Figure 33 shows the filter schematic diagram, while Figure 34 shows its layout drawing with the selected inductors.

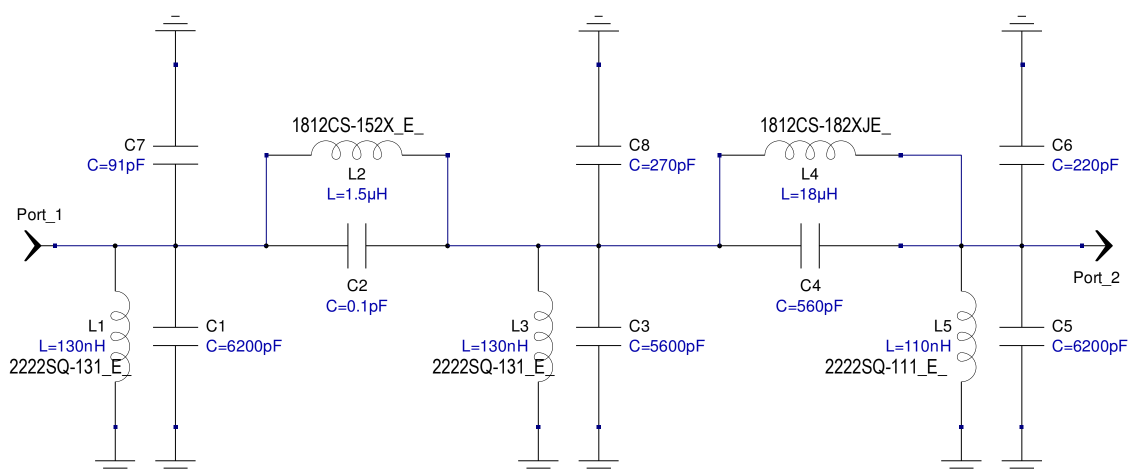


Figure 33. The BPF Schematic

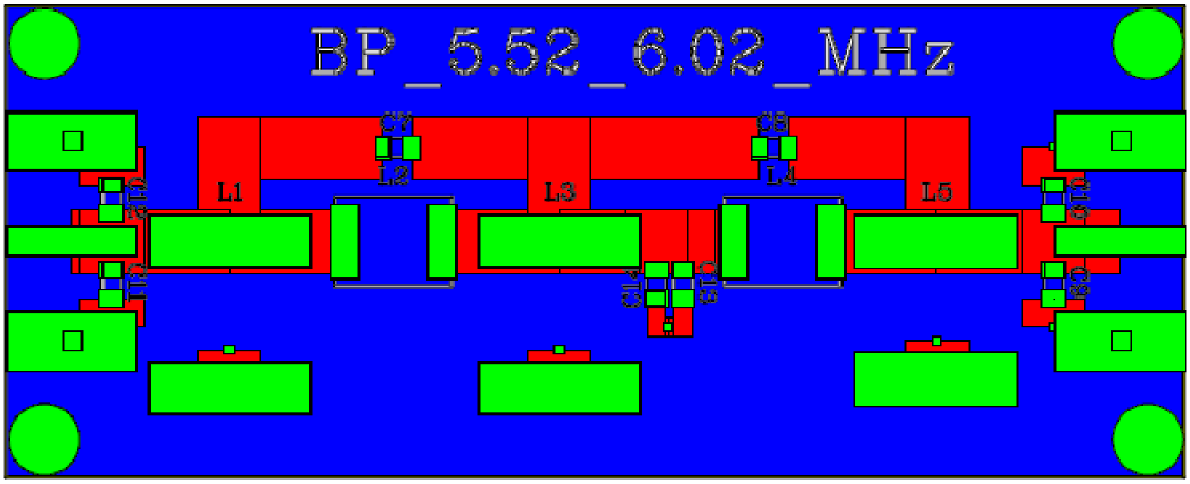


Figure 34. The BPF Layout

Signal spectra before and after the BPF are shown in Figure 35 a and b respectively.

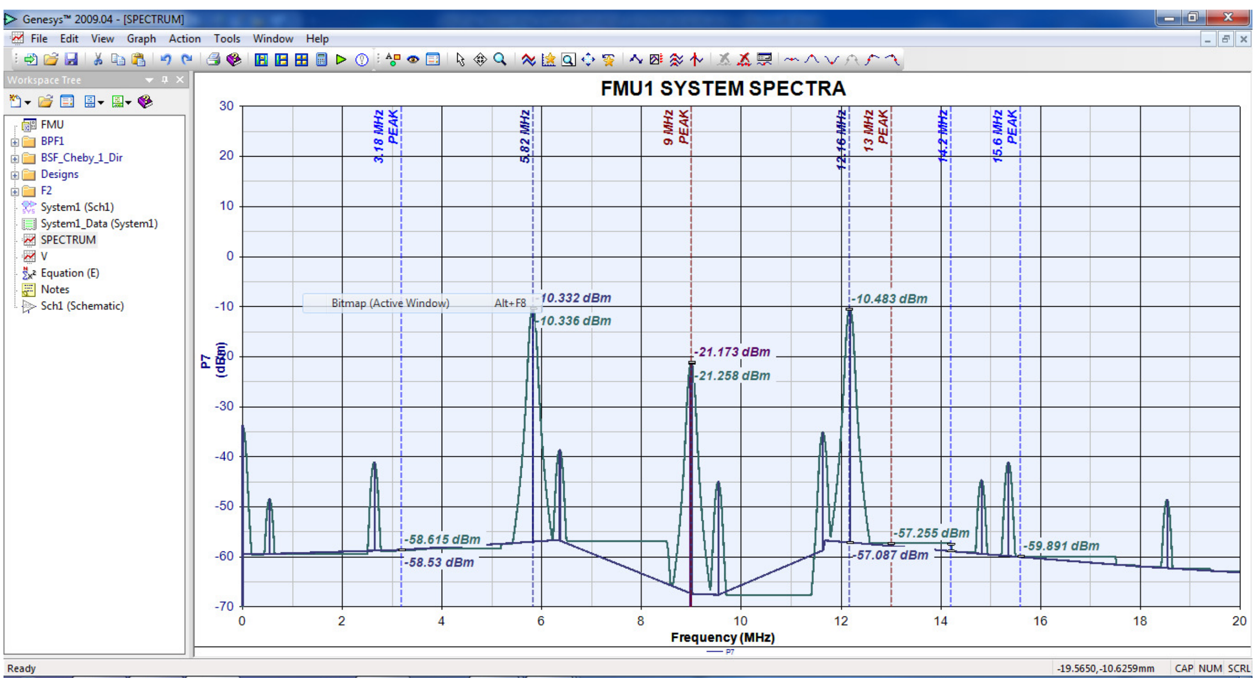


Figure 35a. BPF Input Spectrum

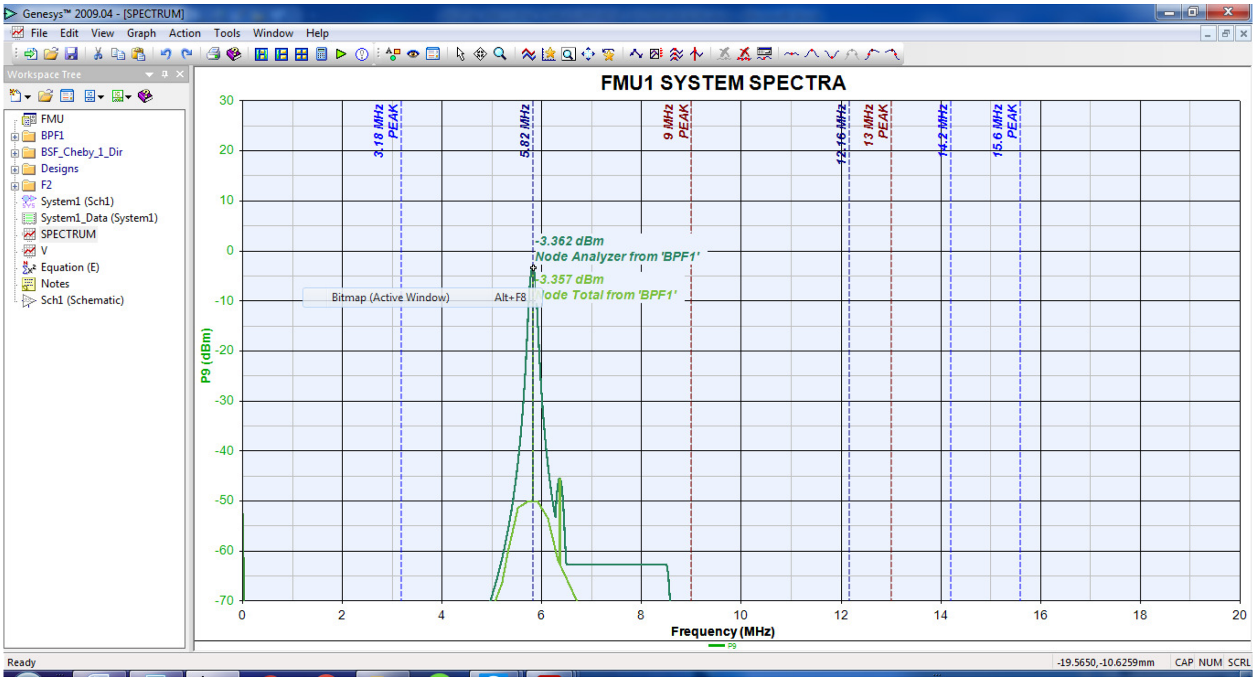


Figure 35a. BPF Output (second mixer input) Spectrum

8.4. The Second Mixer

1. The simulated signal spectrum at the two inputs and at the output of the second mixer are shown in Figure 36 (a and b) for LO2 frequency = 7.5 MHz (the 160m band).

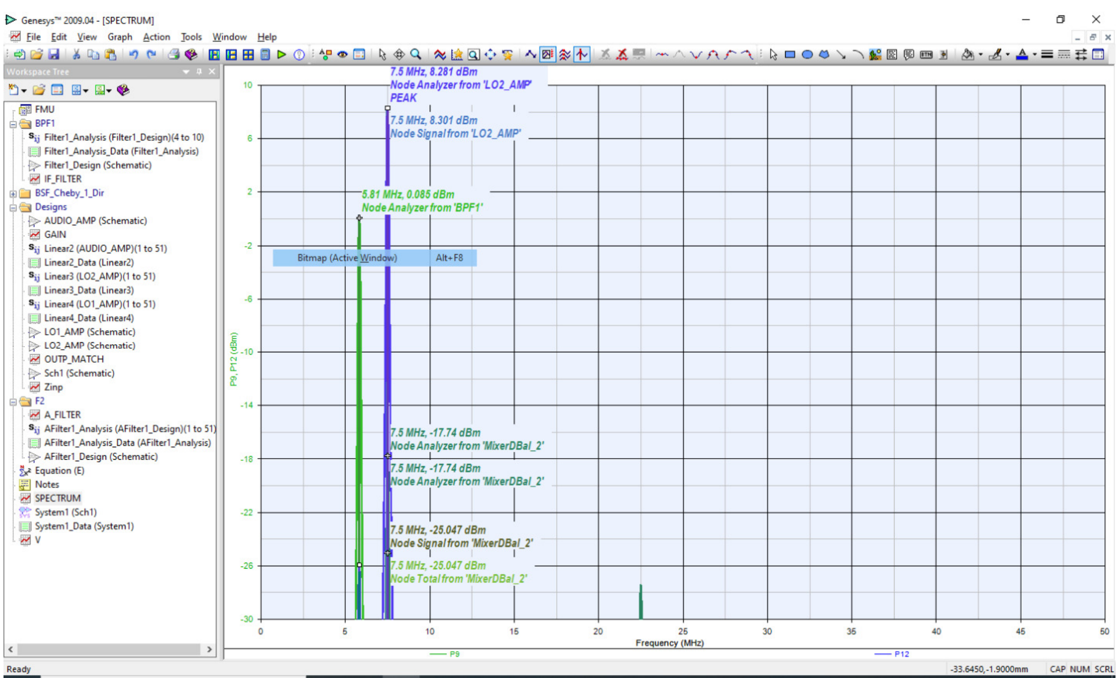


Figure 36a. The 2nd mixer input for the first frequency band (LO2 = 7.5 MHz)

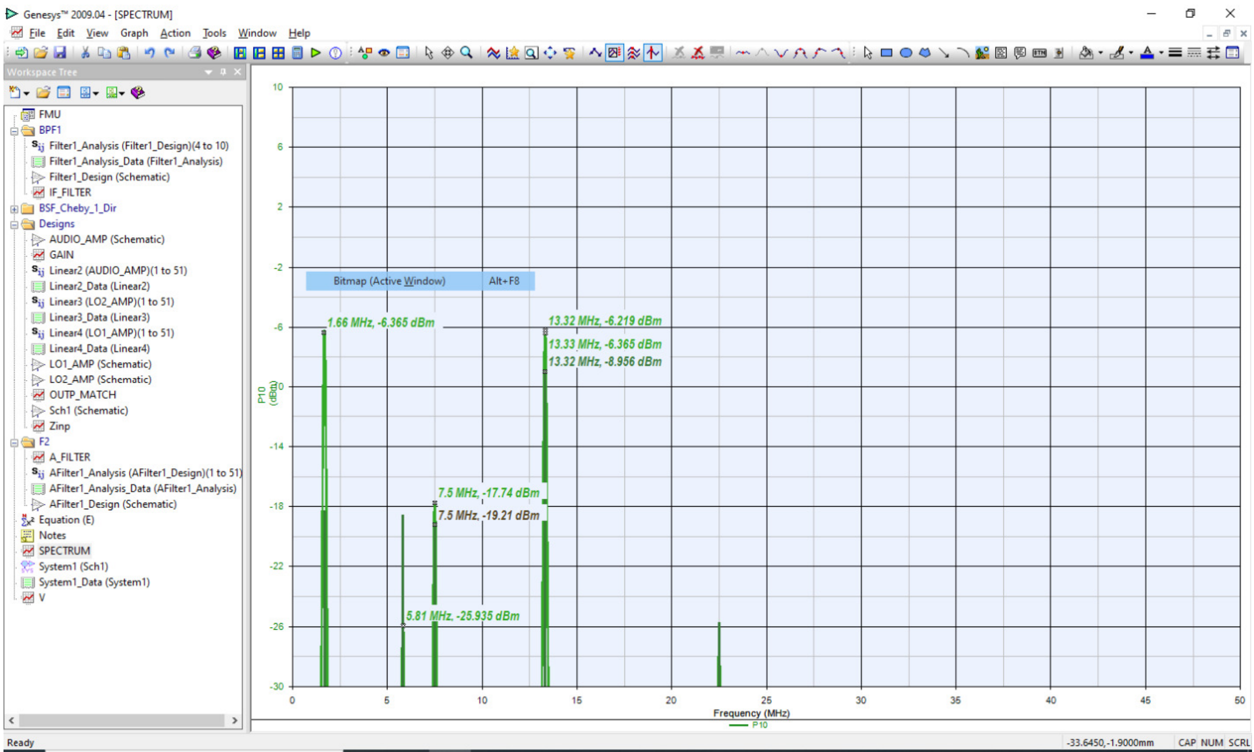


Figure 36b. The 2nd mixer output for the first frequency band (LO2 = 7.5 MHz)

We can notice the following in Figure 36:

- The LO2 drive signal level is +8.28 dBm, which is a little more than the driving level of the ADE-1+ mixer.
- The IF input signal has a 5.81 MHz frequency and a 0.085 dBm power.
- The mixer outputs two signals of nearly equal powers at frequencies $f_L - f_I =$ 1.66 MHz and $f_L + f_I =$ 13.32 MHz.
- The power level of the mixer outputs is lower than its IF input by about 6 dB. It means a conversion loss of the order of 6 dB.
- A residual LO output signal with -17.74 dBm power level appears at the mixer output; which means a good LO-RF isolation of the order of 26 dB.

2. The simulated signal spectrum at the two inputs and at the output of the second mixer are shown in Figure 37 (a and b) for LO2 frequency = 20MHz (the 20m band).

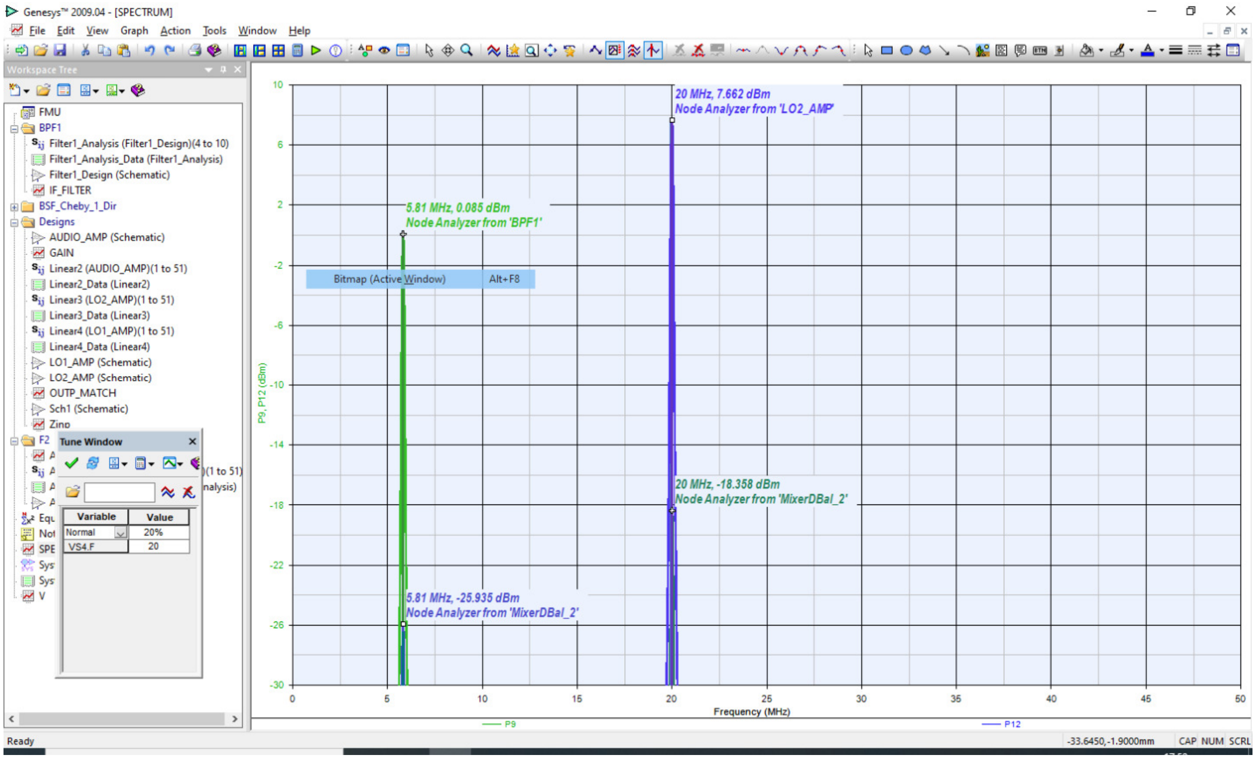


Figure 37a. The 2nd mixer input for the first frequency band (LO2 = 20 MHz)

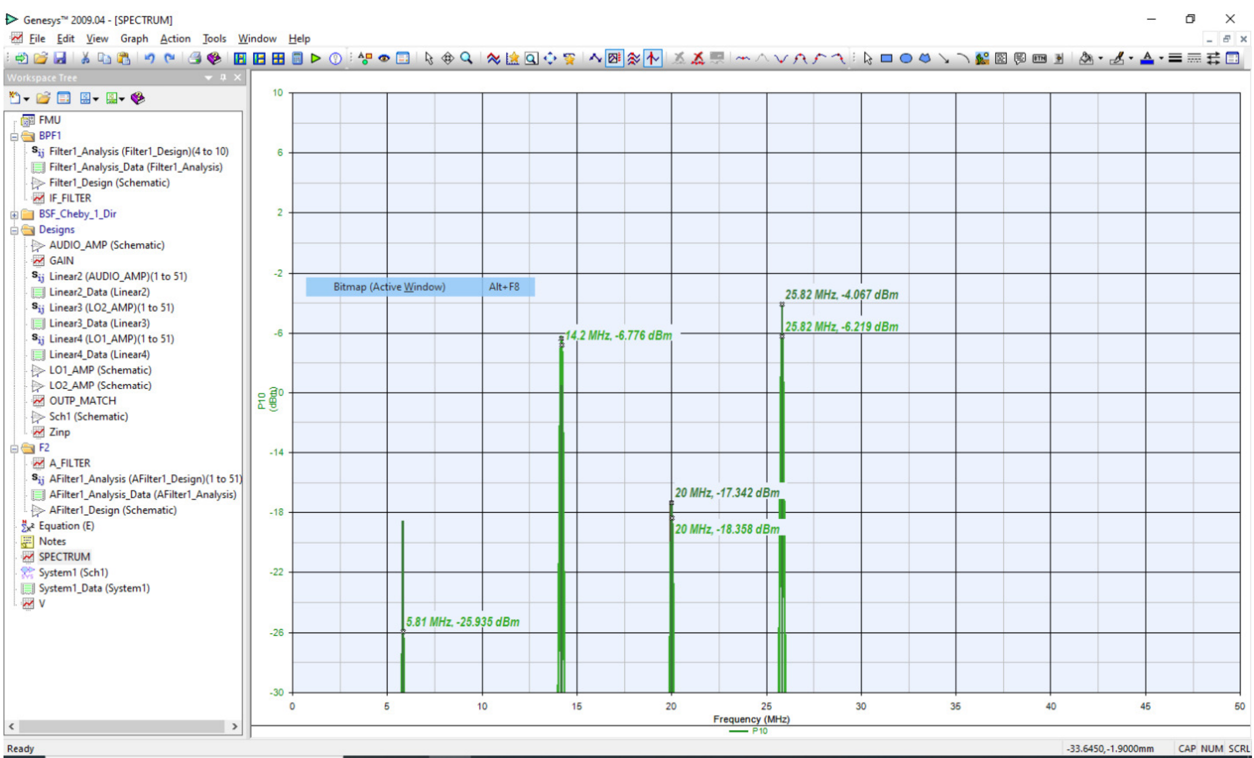


Figure 37b. The 2nd mixer output for the first frequency band (LO2 = 20 MHz)

We can notice the following in Figure 37:

- The LO2 drive signal level is +7.662 dBm, which is slightly higher than the driving level of the ADE-1+ mixer.
- The IF input signal has a 5.81 MHz frequency and a 0.085 dBm power.
- The mixer outputs two signals of nearly equal powers at frequencies $f_L - f_I =$ 14.2 MHz and $f_L + f_I =$ 25.82 MHz.
- The power level of the mixer outputs is lower than its IF input by about 6.5 dB. It means a conversion loss of the order of 6.5 dB.
- A residual LO output signal with -18.35 dBm power level appears at the mixer output; which means a good LO-RF isolation of the order of 26 dB.

3. The simulated signal spectrum at the two inputs and at the output of the second mixer are shown in Figure 38 (a and b) for LO2 frequency = 35.5MHz (the 10D band).

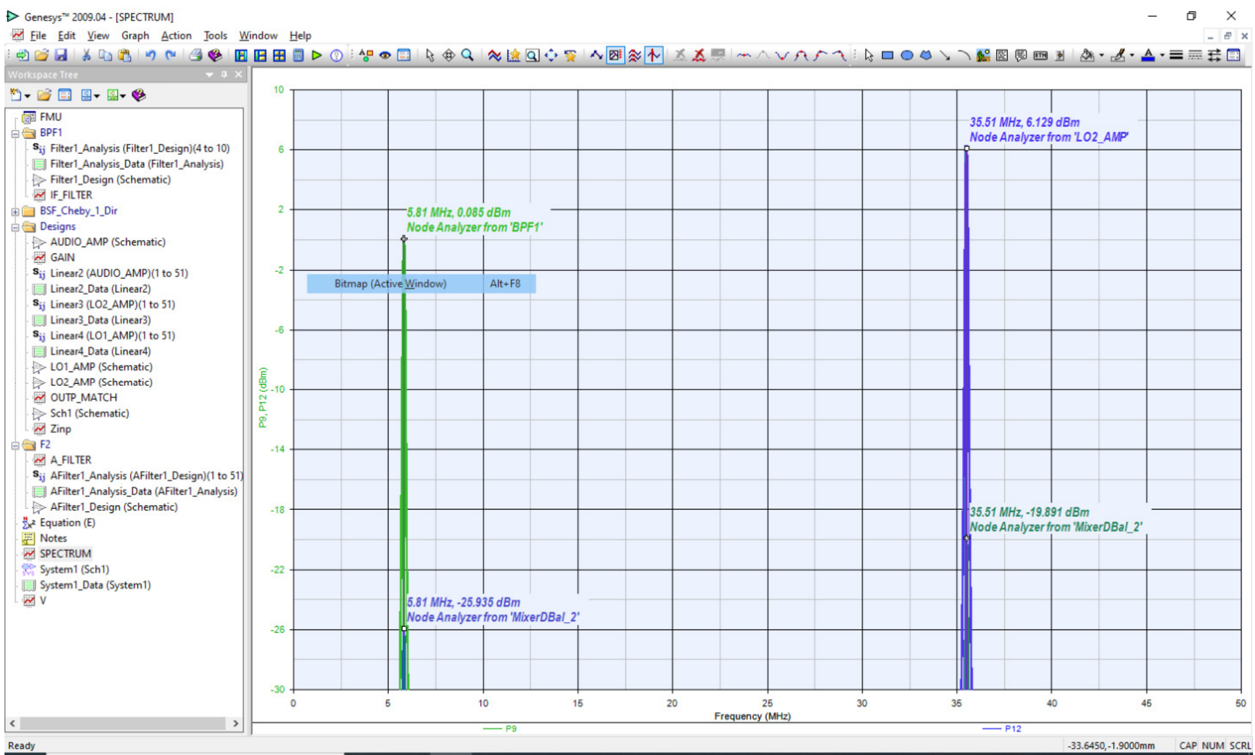


Figure 38a. The 2nd mixer input for the first frequency band (LO2 = 35.5 MHz)

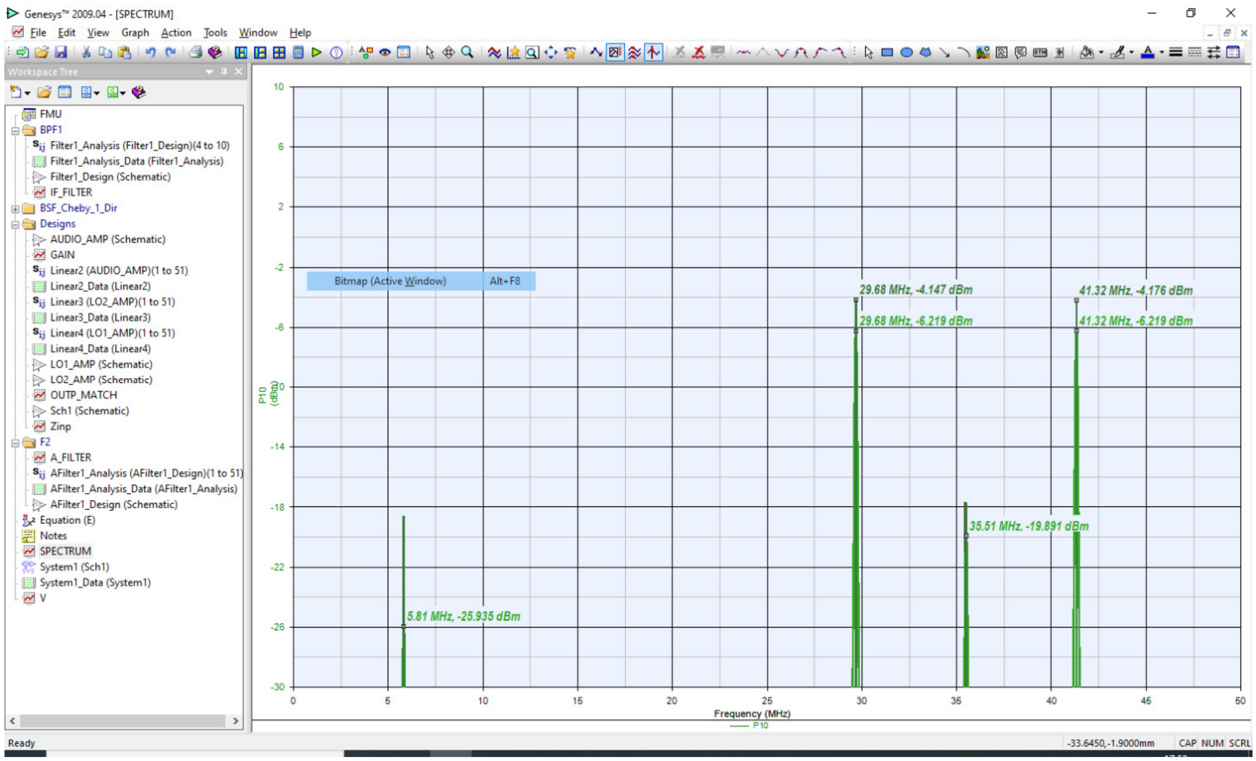


Figure 38b. The 2nd mixer output for the first frequency band (LO2 = 35.5 MHz)

We can notice the following in Figure 38:

- The LO2 drive signal level is +6.129 dBm, which is slightly lower than the driving level of the ADE-1+ mixer.
- The IF input signal has a 5.81 MHz frequency and a 0.085 dBm power.
- The mixer outputs two signals of nearly equal powers at frequencies $f_L - f_I =$ 29.68 MHz and $f_L + f_I =$ 41.32 MHz.
- The power level of the mixer outputs is lower than its IF input by about 6dB. It means a conversion loss of the order of 6 dB.
- A residual LO output signal with about -20 dBm power level appears at the mixer output; which means a good LO-RF isolation of the order of 27 dB.

8.5. Double Side-band Detection Problem

As described above, at each of the ten LO2 frequencies, we get two frequency components ($f_L - f_I$) and ($f_L + f_I$) at the second mixer output with nearly equal powers.

Let us study the behaviour of a zero crossing detection comparator when it gets such two signals with different frequencies and equal amplitudes at its input.

The zero crossing detector is shown schematically in Figure 39. A time domain simulation has done for the zero crossing detector with the same input signal of Figure 38b (with 29.68 MHz frequency and -6 dBm level). The input and output waveforms are shown in Figure 40.

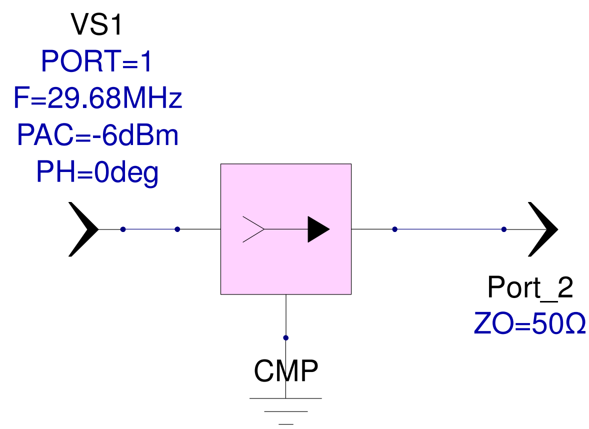


Figure 39. A Zero Crossing Detector with a single input tone

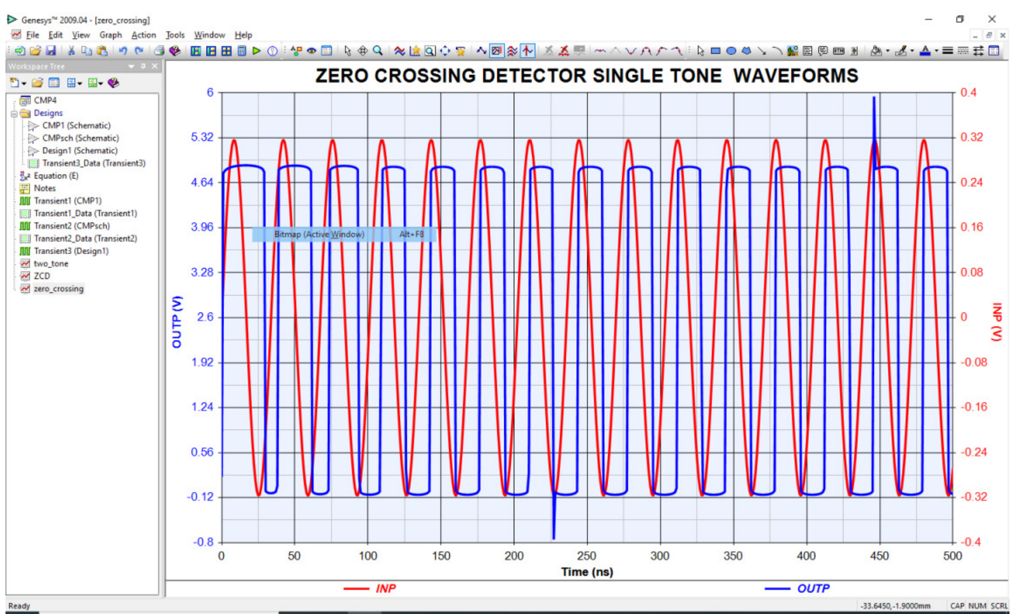


Figure 40. Input and output waveforms with a 29.68 MHz -6dBm input

We can count 15 output rectangular wave during the 500 ns time window. It means that the rectangular wave output of the comparator will be given to the counter to count correctly 29.68 cycles each millisecond.

Let us now activate the sane zero crossing detector with the two mixer outputs of Figure 38b (the 29.68 MHz and the 41.32 MHz), each with the same -6 dBm power level, as shown in Figure 41.

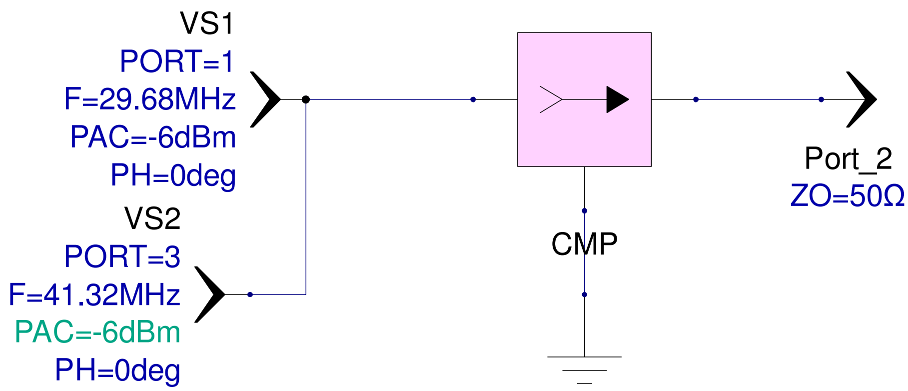


Figure 41. The zero crossing detector with two tones inputs with equal levels

The resulting input and output waveforms are shown in Figure 42.

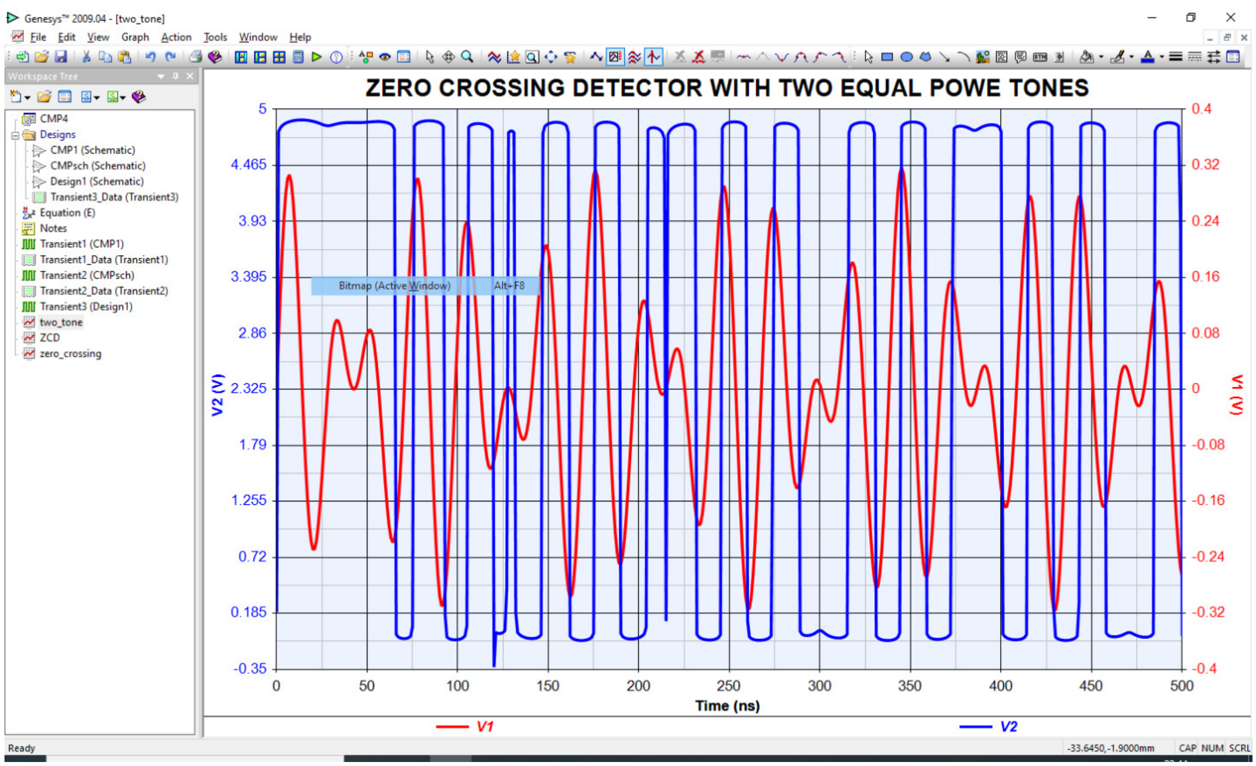


Figure 42. The zero crossing detector waveforms with two tones inputs with equal levels

A confusion is evident in the output waveform that will affect the correct counter operation.

Let us decrease the power level of the spurious input signal (the sum signal) by 10 dB and see the result. The same detector is shown in Figure 43 when the SUM component is attenuated by 10 dB. The resulting input and output waveforms are shown in Figure 44.

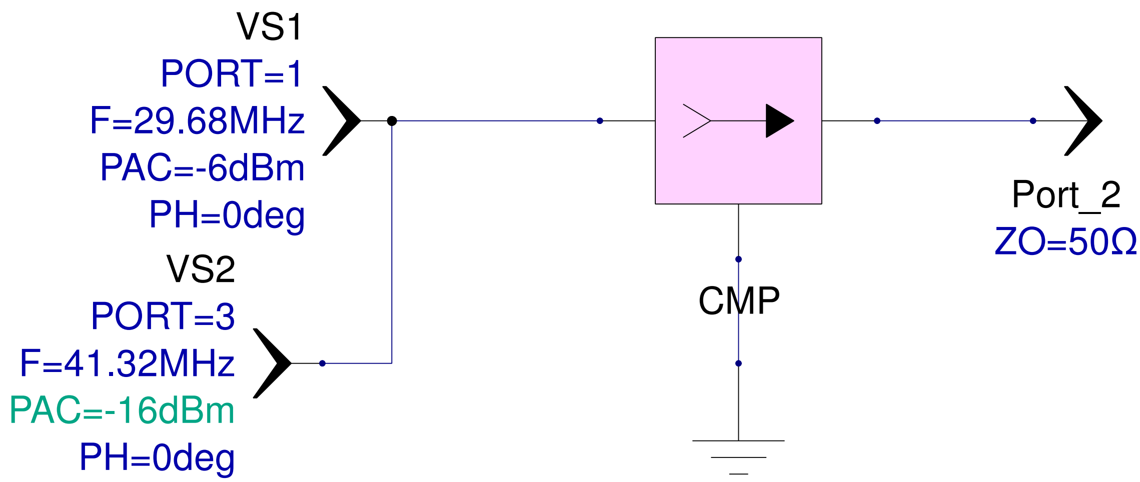


Figure 43. The zero crossing detector with two tones inputs with unequal levels

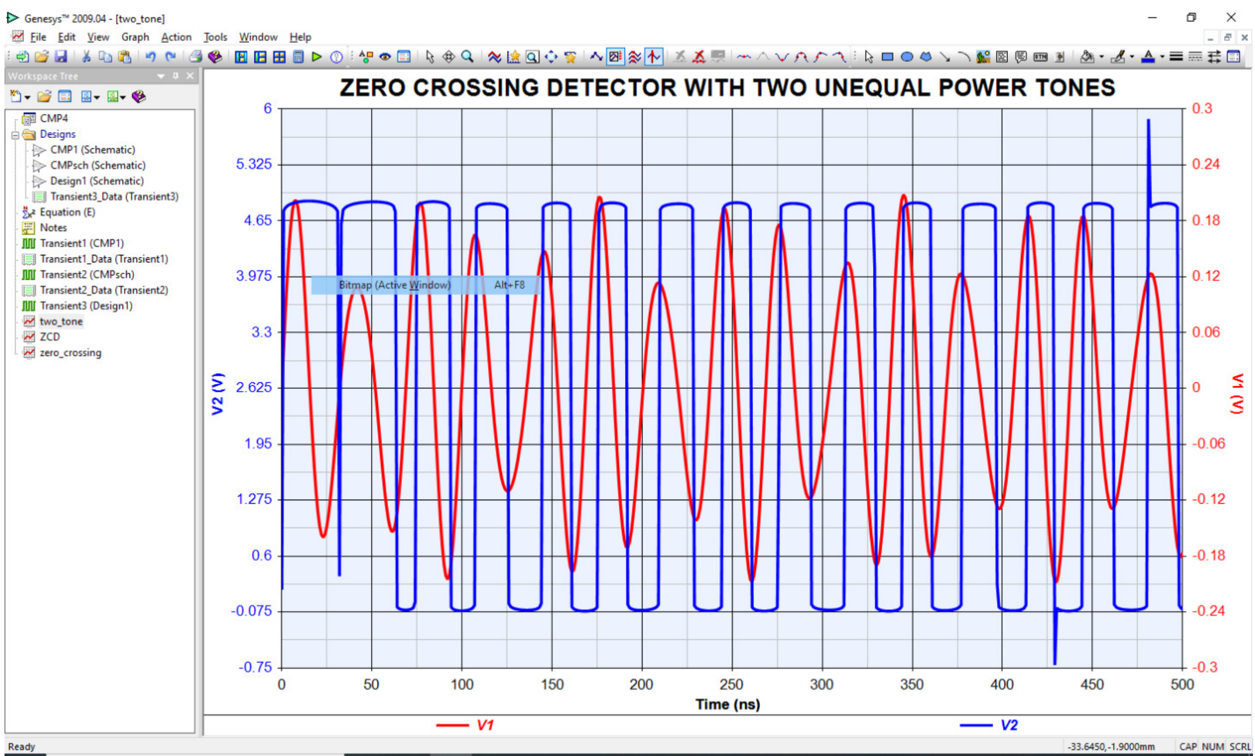


Figure 44. The zero crossing detector waveforms with two tones inputs with unequal levels

It can be seen in Figure 44 that both the input and output waveforms became nearer to thos of Figure 40 and the counter can correctly count the desired signal frequency.

If we simulate the zero crossing detector operation with the 160 m signal frequencies (1.68 and 13.32 MHz) and even with the 20 m signal frequencies (14.2 and 25.82 MHz) we get better results as shown in the following figures, even with equal input signal levels.

The following figure shows the input and output waveforms with the frequencies (1.68 and 13.32 MHz) inputs of the 160m band with equal input levels.

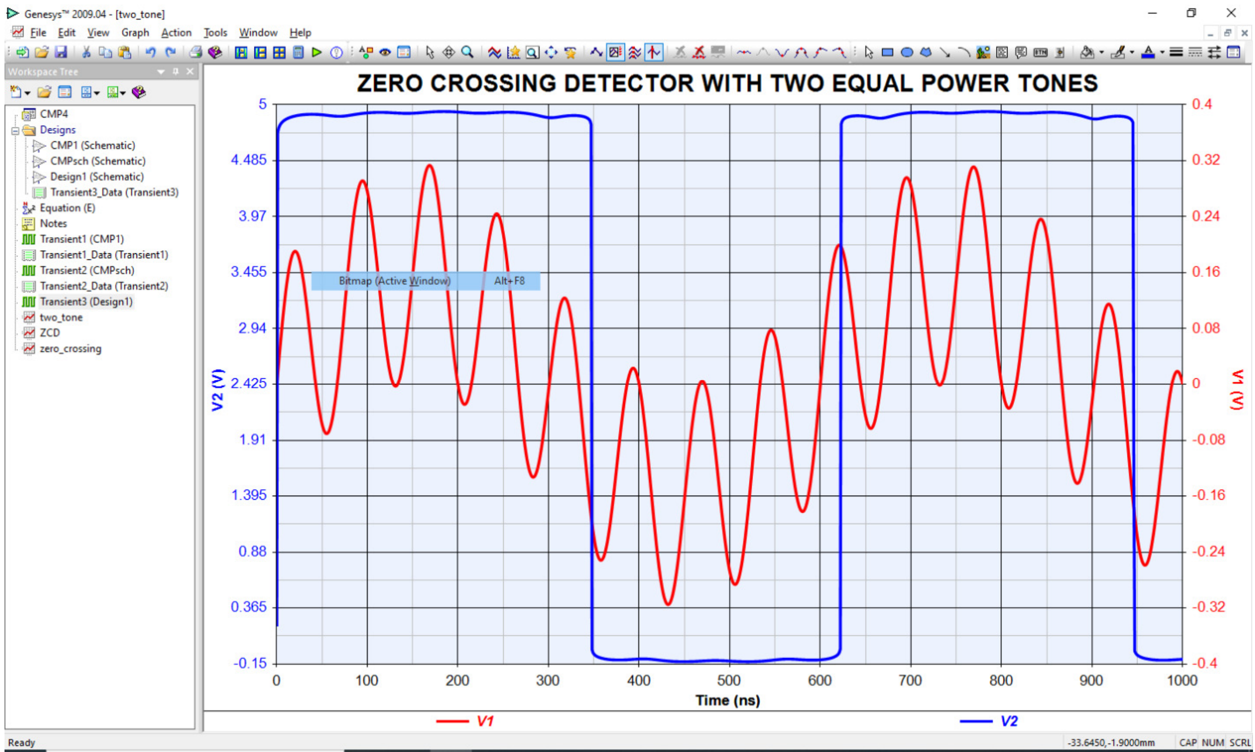


Figure 45. The detector waveforms with two equal 160m band input signals

The following figure shows the input and output waveforms with the frequencies (14.2 and 25.82 MHz) inputs of the 160m band with equal input levels.

When the upper band signal is attenuated by 10 dB, the result is even better as shown in Figure 47.

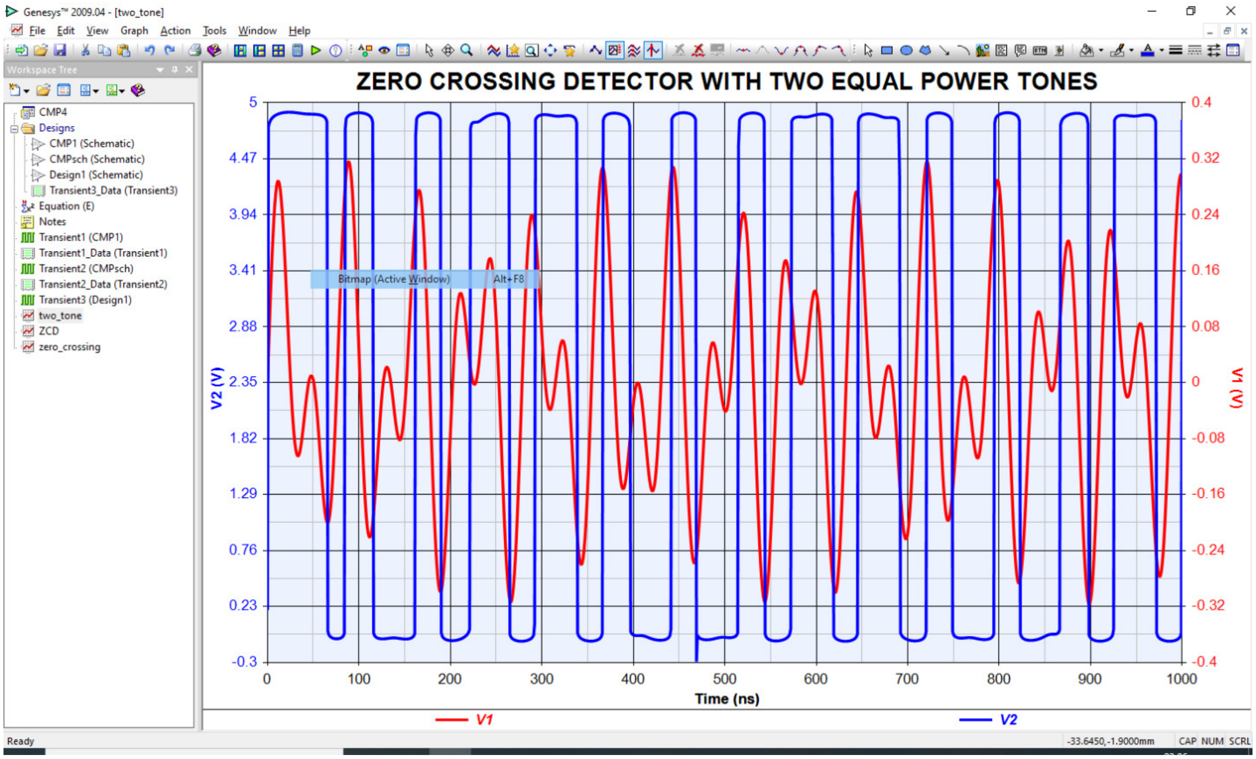


Figure 46. The detector waveforms with two equal 20m band input signals

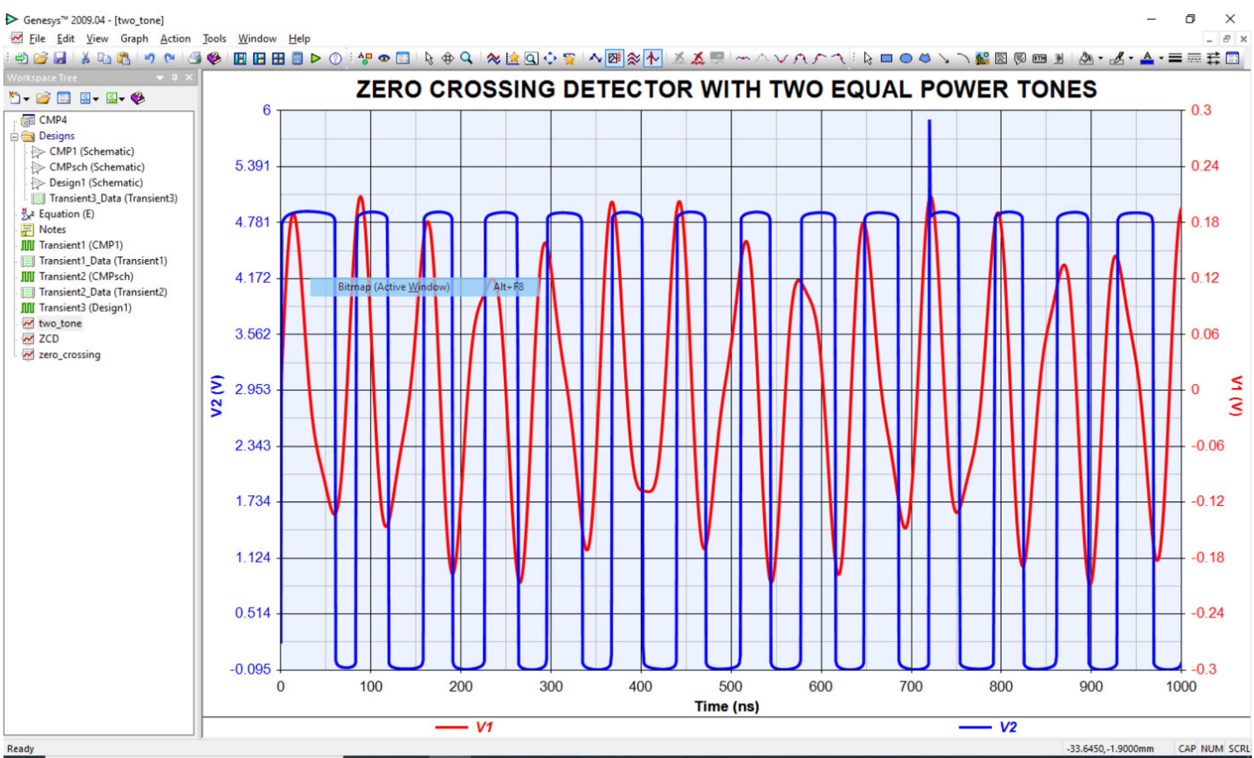


Figure 47. The detector waveforms with two unequal 20m band input signals

Conclusion

The counter operation can be secured if the upper sideband signal of the mixer output is attenuated by more than 10 dB with respect to the desired lower sideband signal.

8.6. Output Filter Design

An active filter has been designed and optimized such that each frequency in the 6th column of Table 3 is suppressed by more than 10 dB than the corresponding frequency of column 5. Table 3 shows for every frequency band of the FT-101 the following:

1. The band number
2. The band name
3. The band crystal frequency
4. The required Lower Side Band (LSB) frequency
5. The undesired Upper Side Band (USB) spur frequency
6. The actual USB suppression in dB as read from the actual frequency response of the filter

TABLE 3

1	**2**	**3**	**4**		**5**		**6**
BAND	**Band Name**	**Crystal Freq.**	**Correct LSB RF**		**Undesired USB Spur**		**Actual USB Suppression** *from design*
			from	**to**	**from**	**to**	
	[m]	**MHz**	**MHz**	**MHz**	**MHz**	**MHz**	**dB**
1	**160**	7.52	1.5	2.0	13.04	13.54	**32**
2	**80**	9.52	3.5	4.0	15.04	15.54	**30**
3	**40**	13.03	7.0	7.5	18.54	19.04	**39.66**
4	**20**	20.02	14	14.5	25.54	26.04	**25.9**
5	**15**	27.02	21	21.5	32.54	33.04	**23.5**
6	**11**	33.02	27	27.5	38.54	39.04	**15.8**
7	**10A**	34.02	28	28.5	39.54	40.04	**15**
8	**10B**	34.52	28.5	29	40.04	40.54	**14.79**
9	**10C**	35.02	29	29.5	40.54	41.04	**14.28**
10	**10D**	35.52	29.5	30	41.04	41.54	**14.17**

The frequency response of the active filter is shown in Figure 48 below.

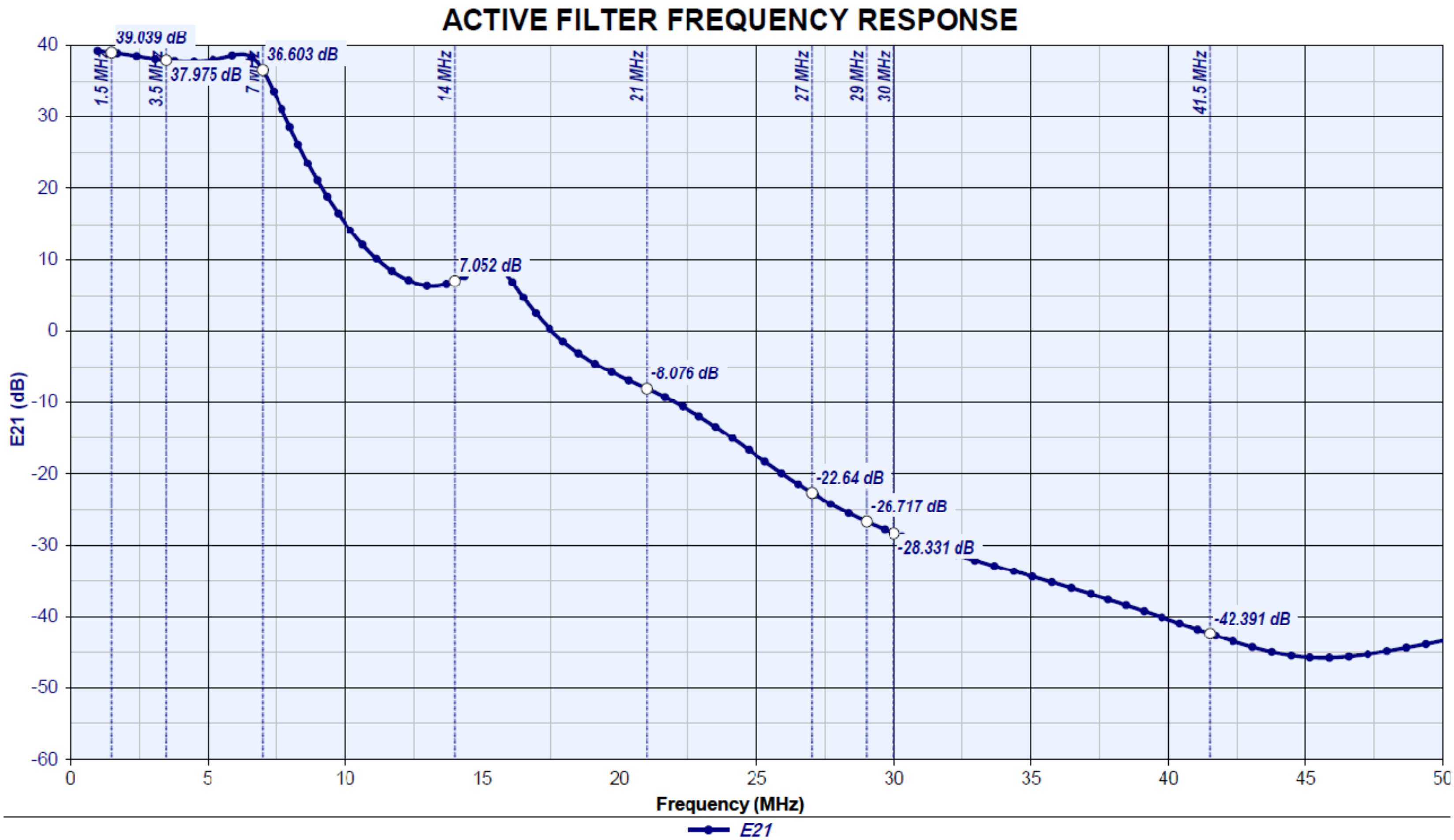


Figure 48. The active filter frequency response

- Since the LPF suppresses higher frequencies; a gain stage has been added at the filter output to raise the signal level for higher frequencies.

- The gain has been adjusted such that the output signal amplitude at the highest desired frequency (30 MHz) is of the order of 5 mV.
- A special high resolution comparator (**LMV761**) has been selected such that it responds safely to a 4 mV signal.
- At lower frequencies, the filter output signal amplitude increases with decreasing frequency. The maximum output signal amplitude should be of the order of 15V for the first 1.5 MHz frequency band. But it will be limited by the supply voltage of the OPAMP.
- A 100 [Ω] resistor is inserted in series with the power supply pin of the TLV3544 and of the TLV3542 OPAMP ICs; in order to limit the supply voltage of each to about 4.5V instead of 5V. This is intended to limit the output signal amplitude to 4.5V such that it may not damage the comparator. The comparator is supplied by 5V for its security.

Figure 49 shows the simulated output voltage signal amplitudes at the lowest and the highest frequency bands of the FT-101.

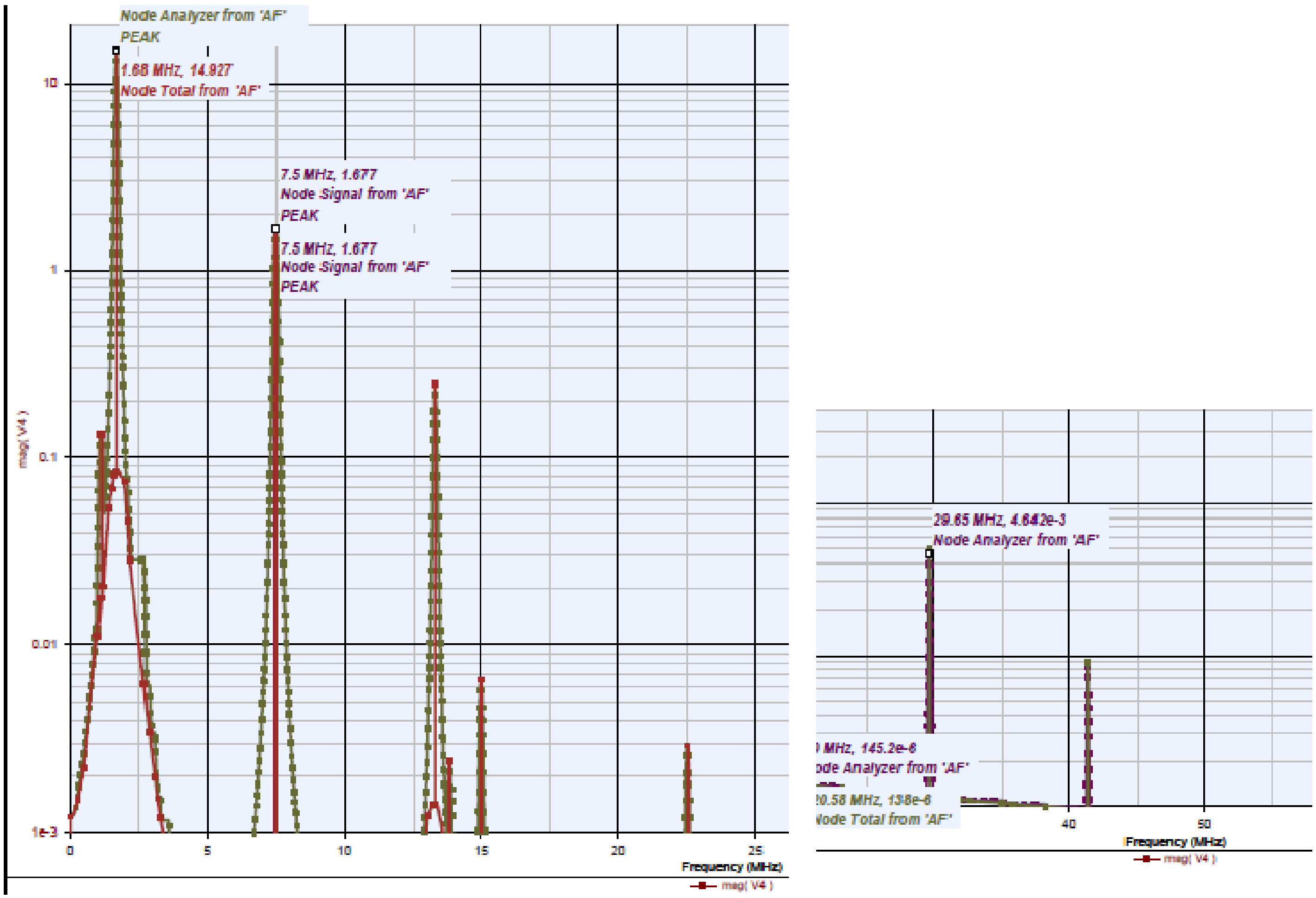


Figure 49. Output signal amplitude at lowest and highest frequencies

Figure 50 shows the active filter schematic design. The TLV3544 QUAD_OPAMP has been used for the first stages of the filter, while a TLV3542 DUAL_OPAMP is used for the last two stages.

Figure 51 shows the layout drawing of the active filter.

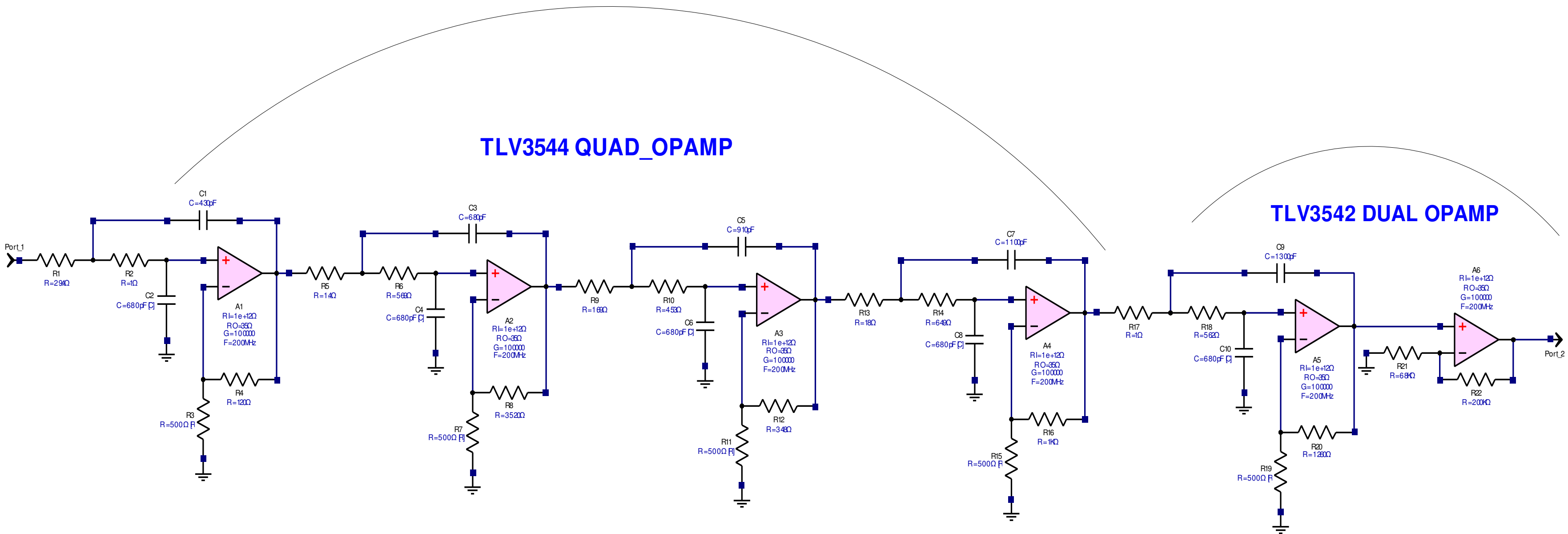


Figure 50. The Active Filter Schematic Drawing

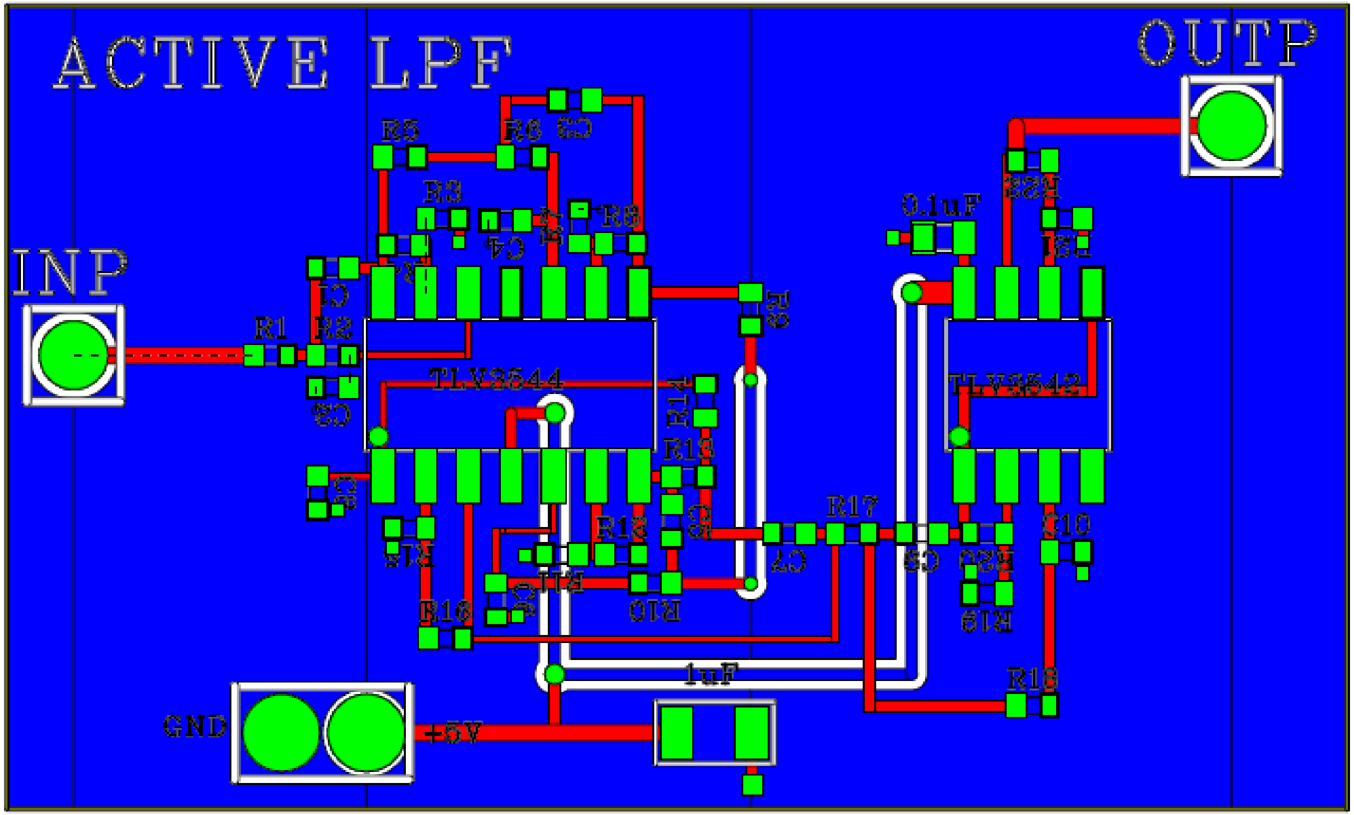


Figure 51. The Active Filter Layout Drawing

8.7. RFMU System Simulation Analysis

Figure 52 shows the complete functional diagram of the RFMU1 unit.

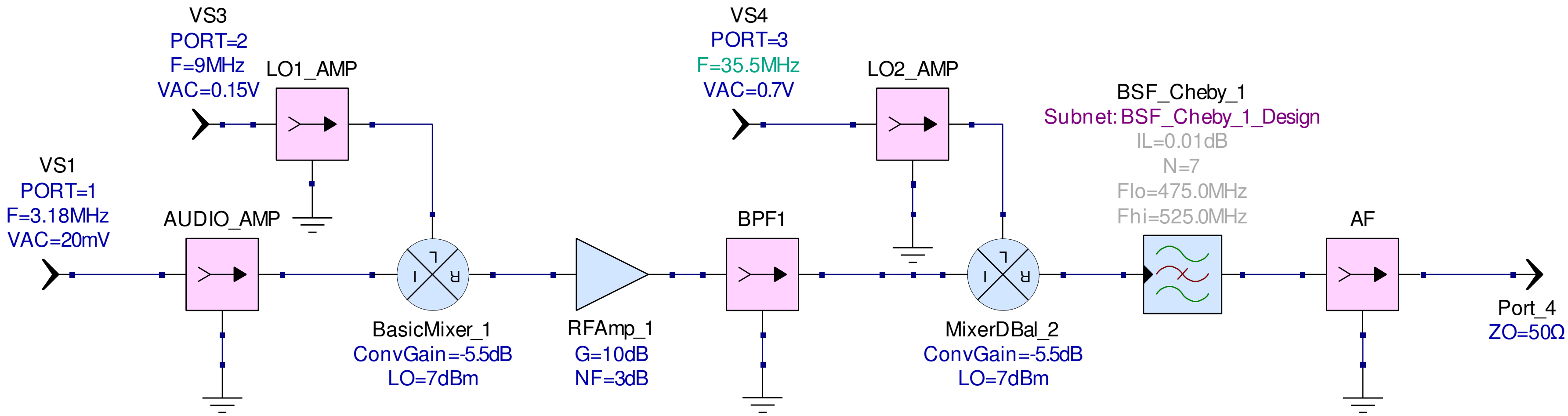


Figure 52. The complete functional diagram of the RFMU1 unit.

A complete system simulation has been done with GENESYS to see the signal spectrum at each node of the system and a thorough analysis has been done at the ten system frequency bands.

The following figures show samples of the signal spectra at different system nodes for three sample frequency bands:

1. The 160m band with 7.5 MHz crystal frequency
2. The 20m band with 20 MHz crystal frequency
3. The 10D band with 35.5 MHz crystal frequency.

8.7.3. Second Mixer Output Spectrum

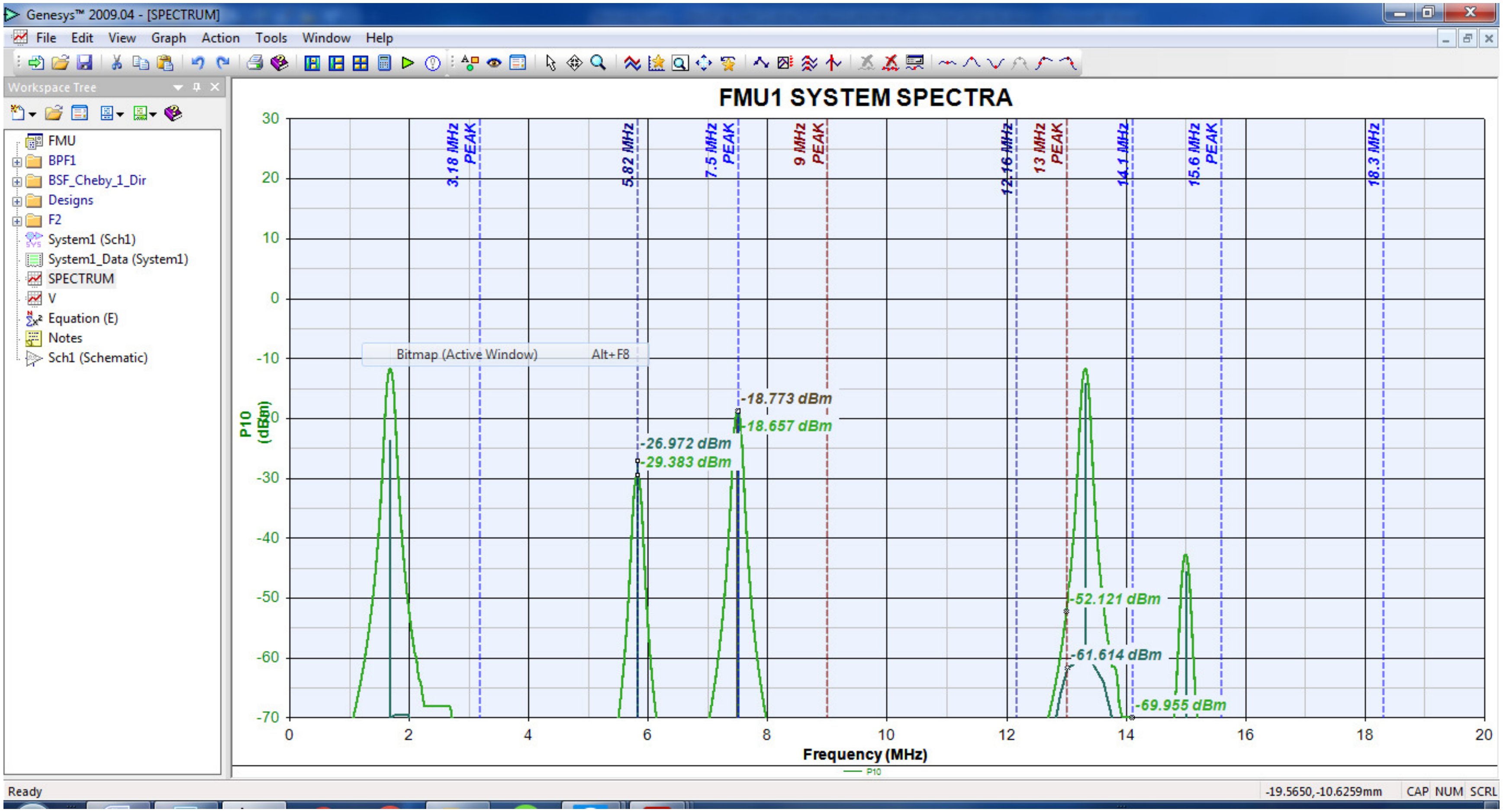


Figure 53a. Second mixer output spectrum in the 160m band

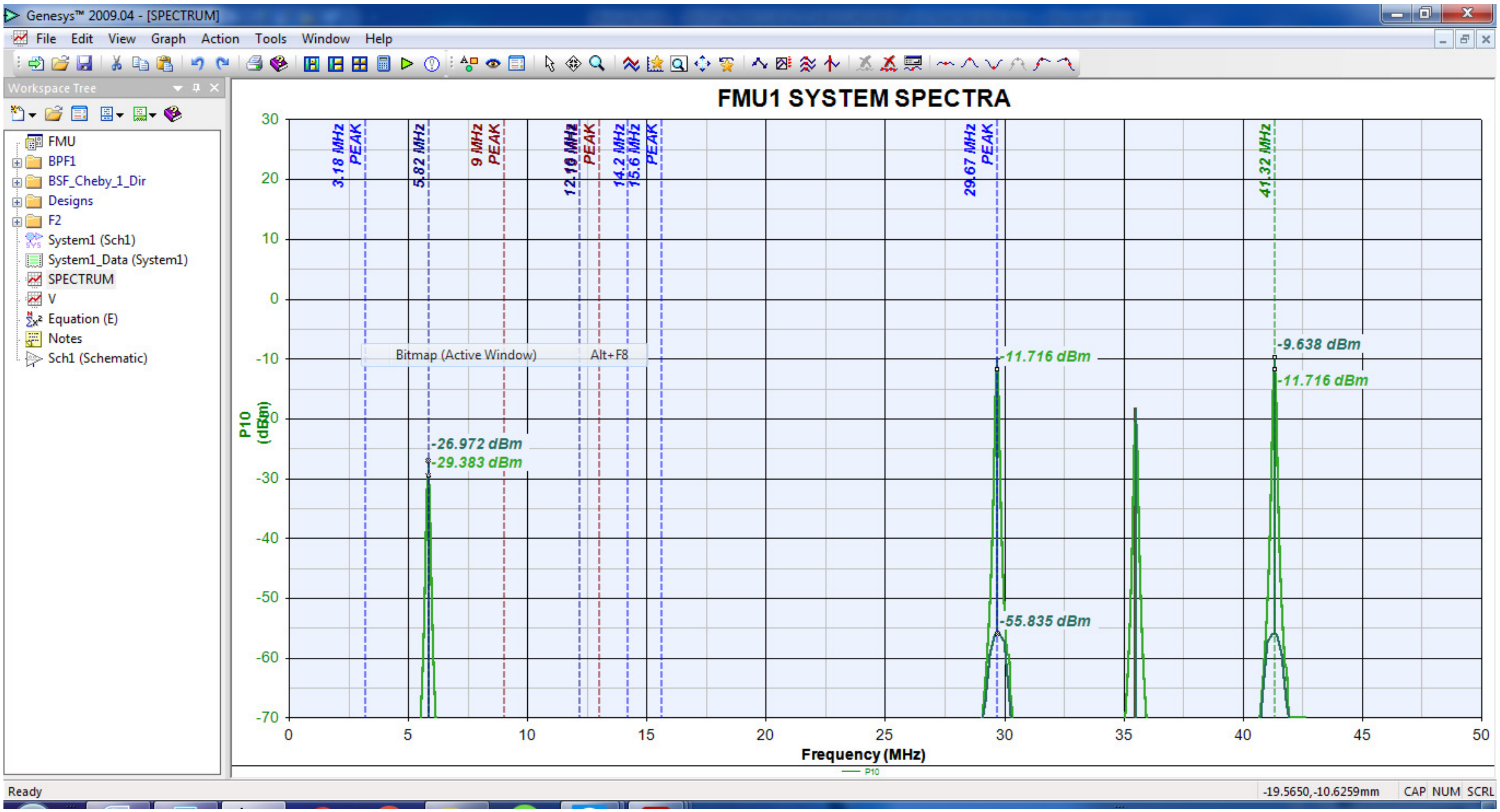


Figure 53b. Second mixer output spectrum in the 20m band

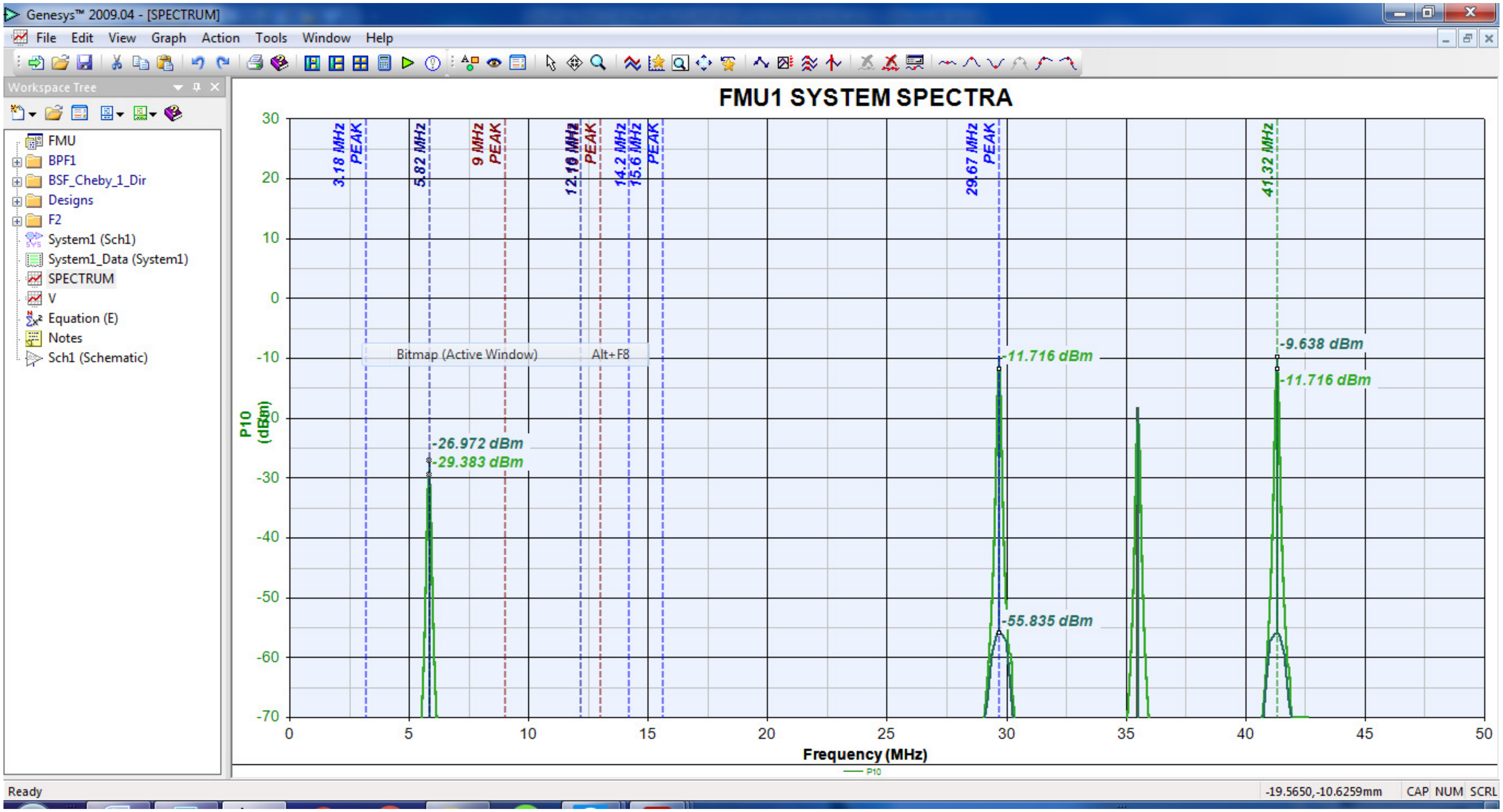


Figure 53c. Second mixer output spectrum in the 10D band

8.7.3. The IF Band Stop Filter

In the second mixer output spectrum we can note that a residual of the first IF signal exists at about -27 dBm level. It would appear in the output of the system; since it will be amplified by the active LPF of the next stage.

Therefore, a special band stop filter has been designed to suppress this spurious signal. This BSF has bee inserted after the second mixer and its output is shown in the following figure.

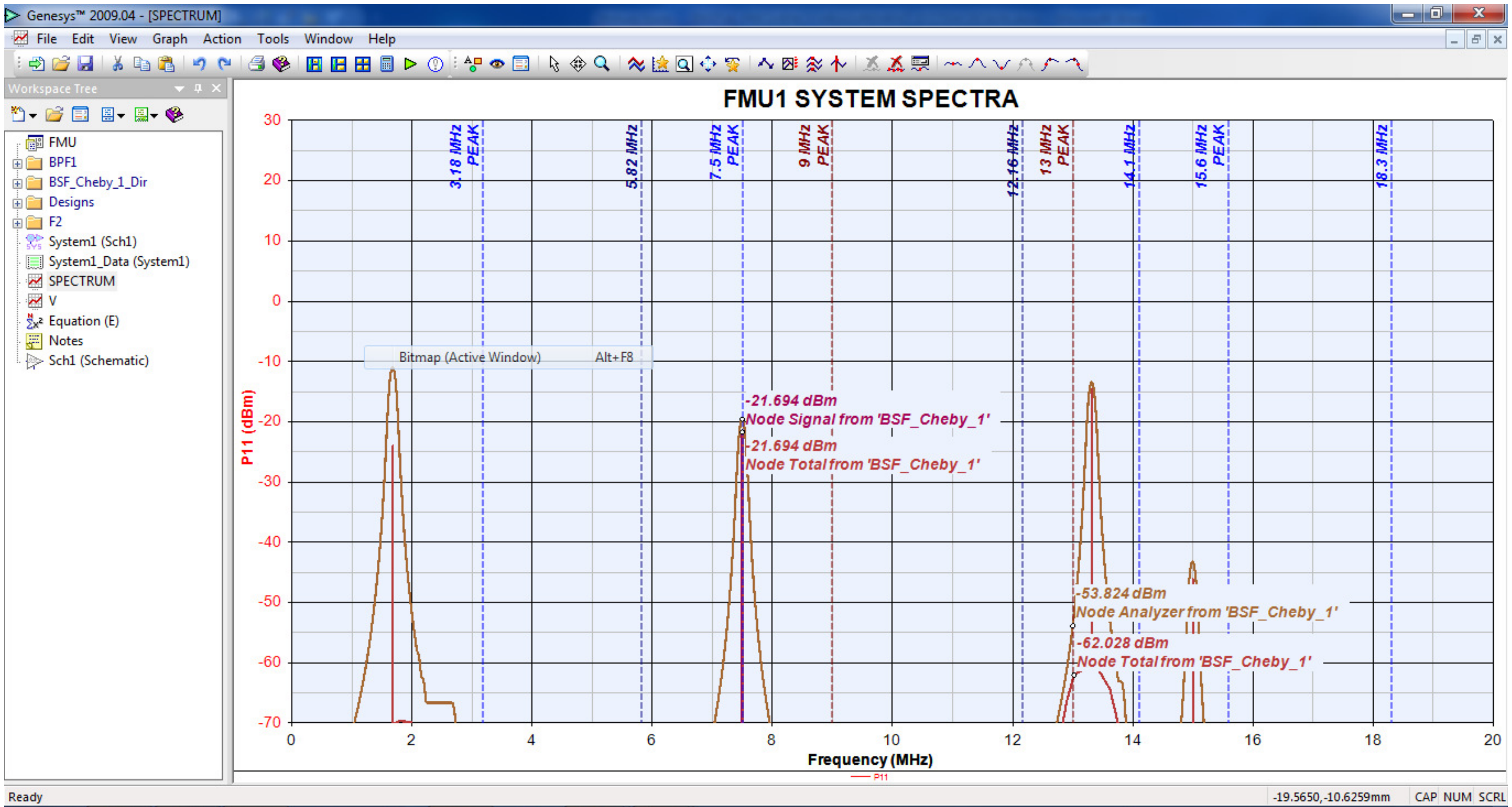


Figure 54a. BSF output spectrum in the 160m band

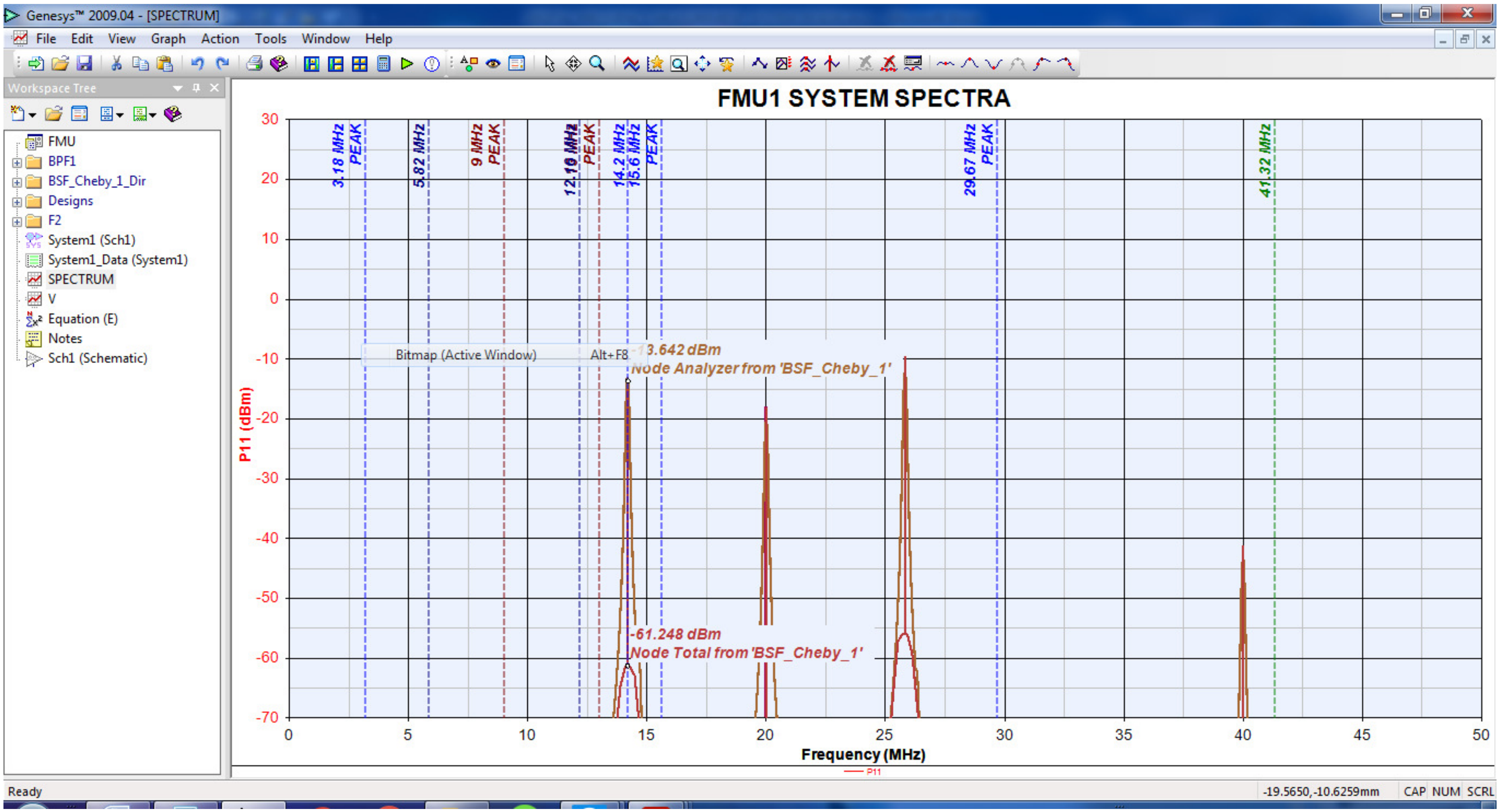


Figure 54b. BSF output spectrum in the 20m band

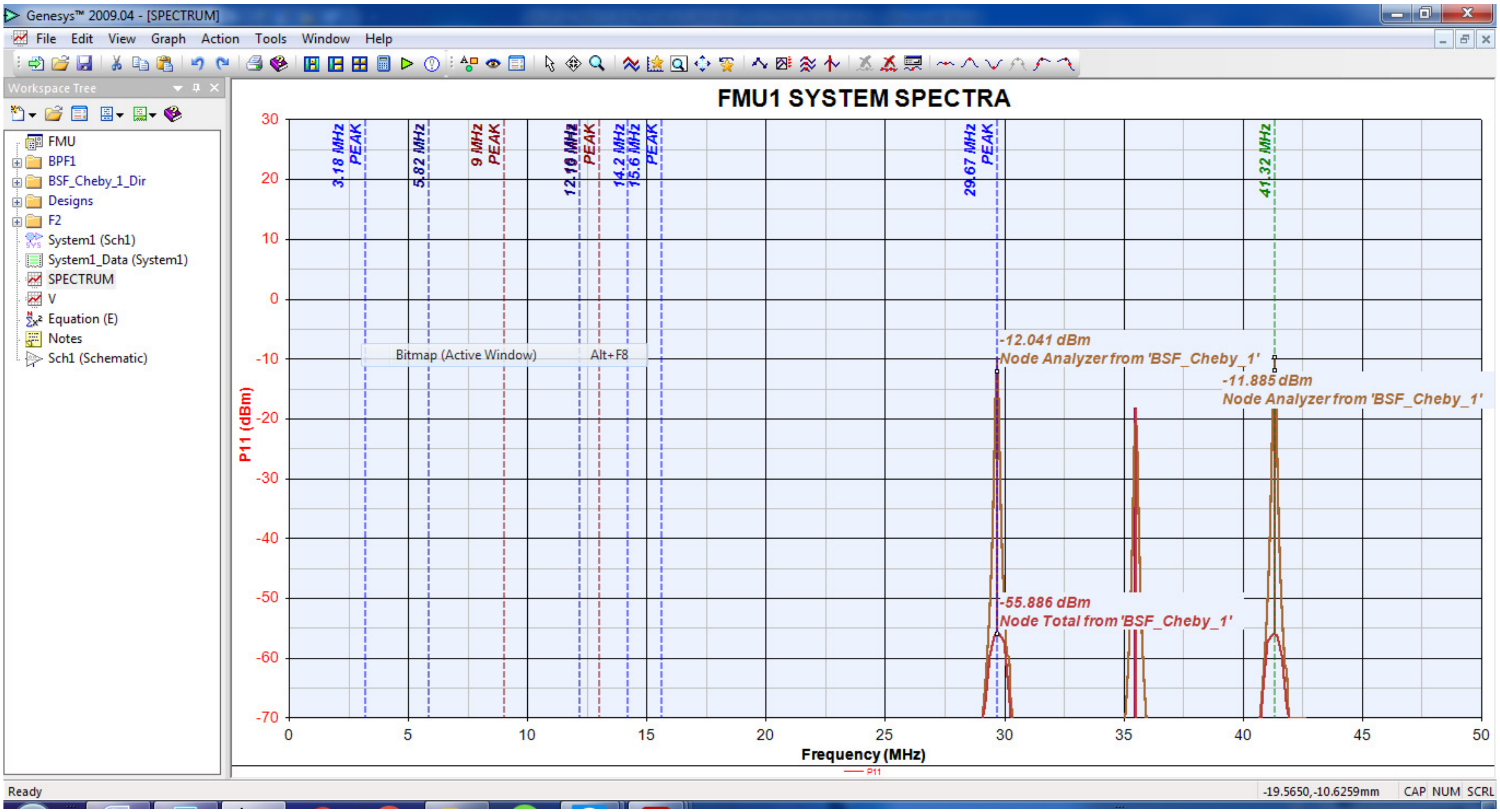


Figure 54c. BSF output spectrum in the 10D band

The BSF frequency response is shown in Figure 55, while its schematic and layout drawings are shown in Figure 56.

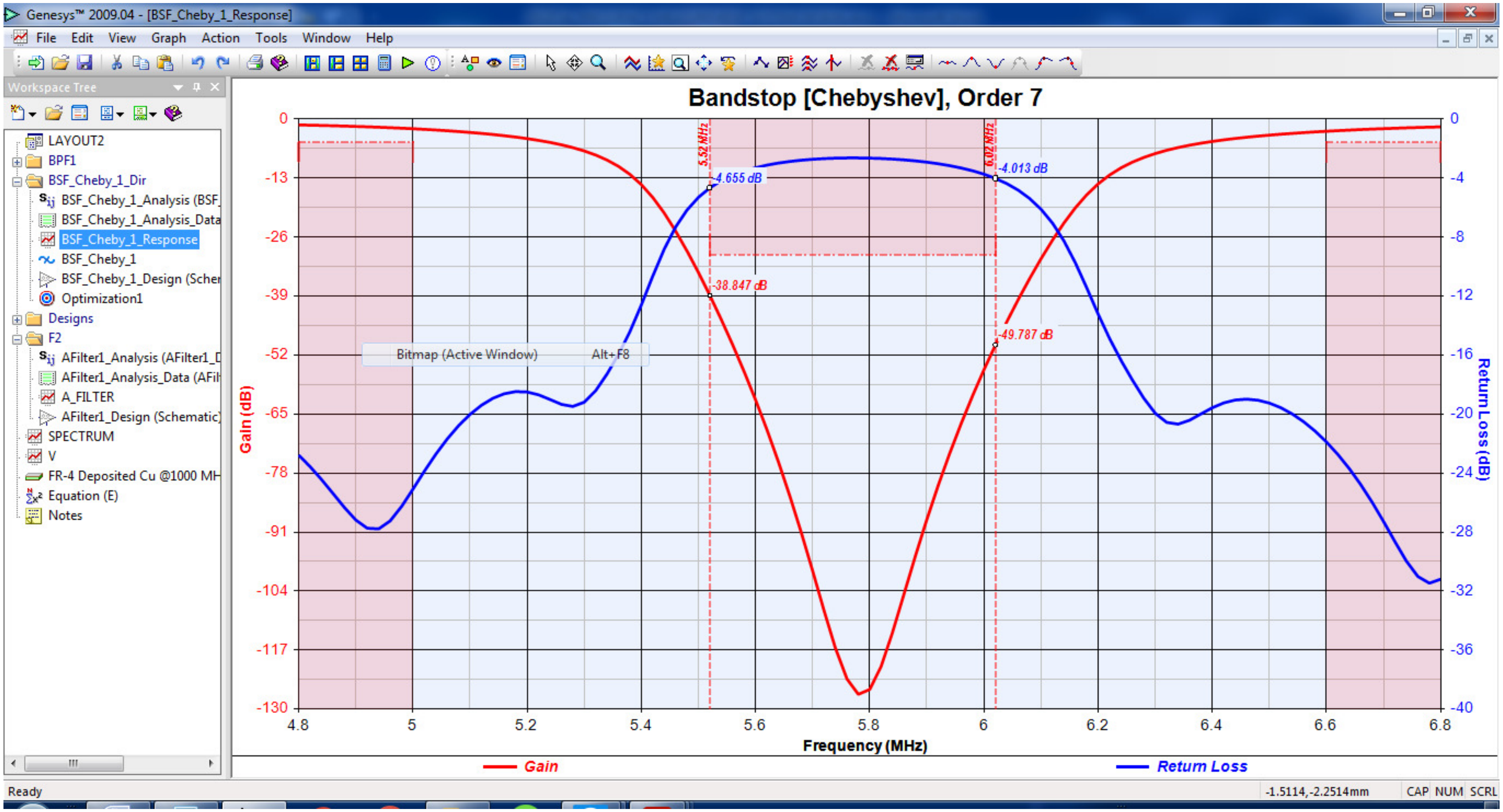


Figure 55. The BSF Frequency Response

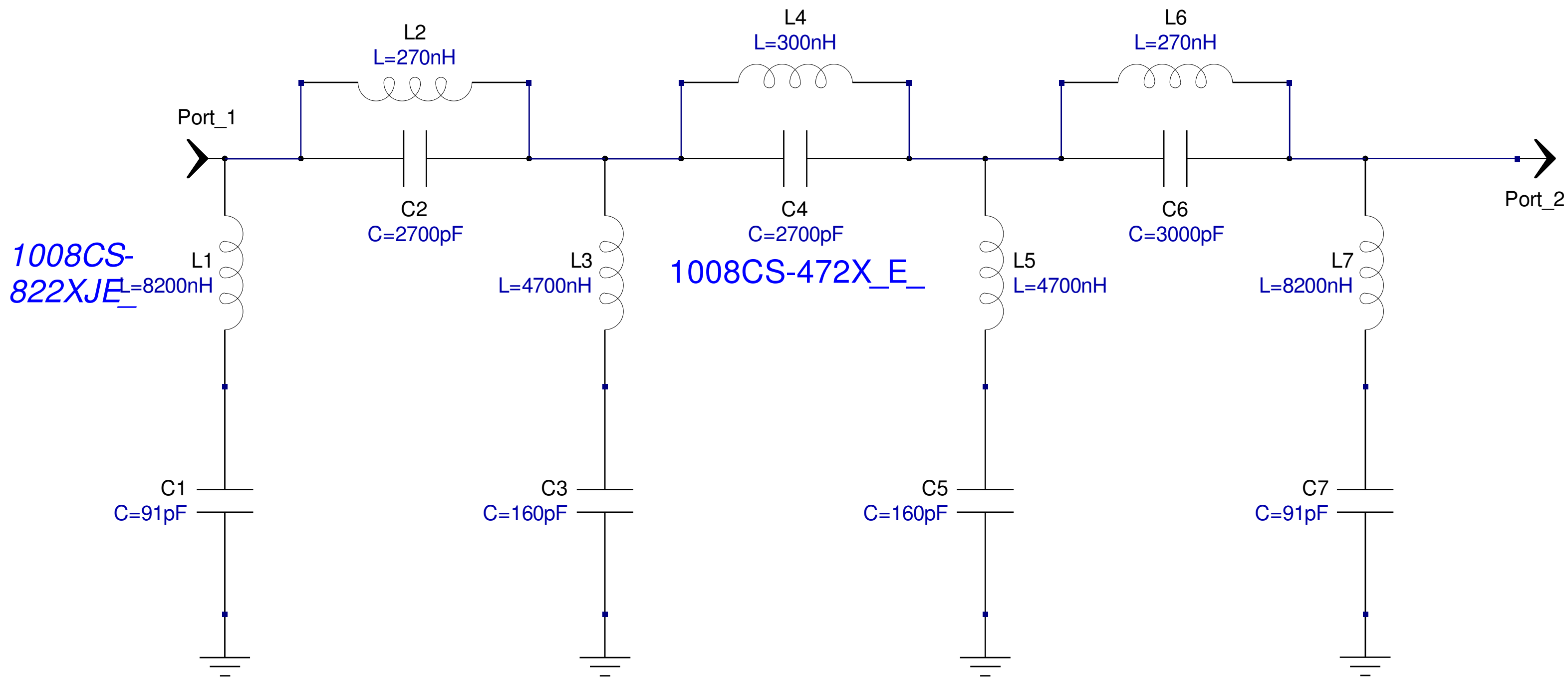


Figure 56a. The BSF Schematic Design

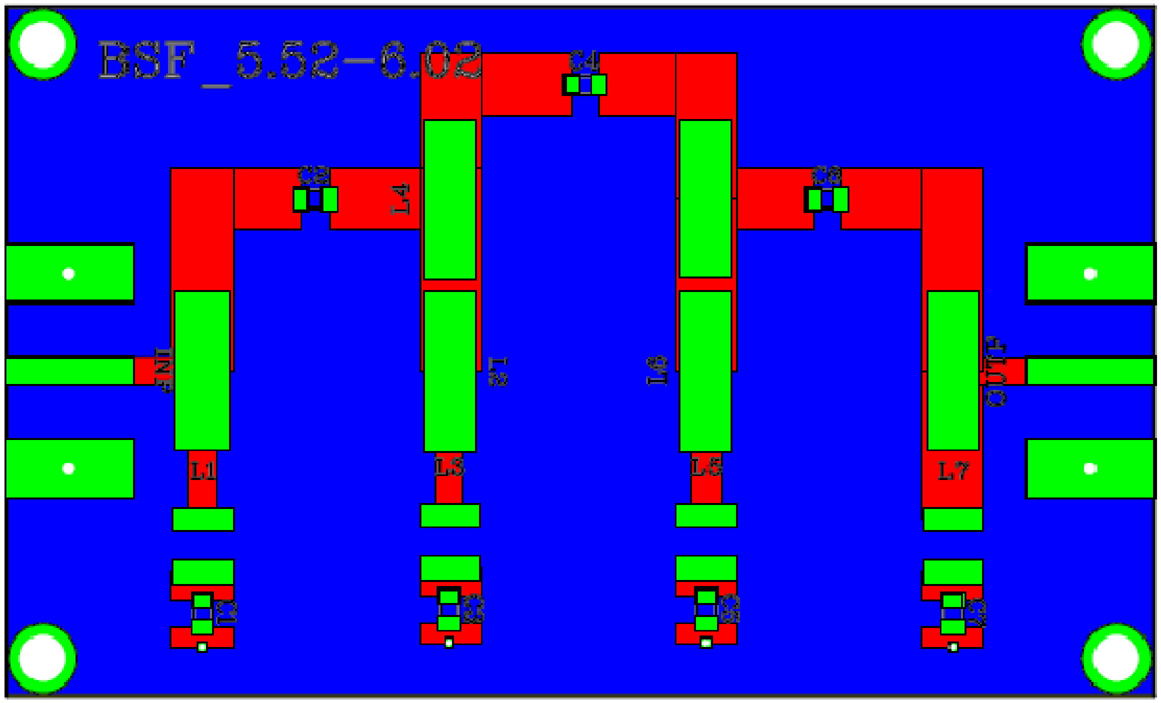


Figure 56b. The BSF Layout Drawing

8.7.4. Output Spectrum

Figure 57 (a, band c) shows the output power spectra of the RFMU in the first, the middle and the last frequency bands respectively.

In each band, the difference between the desired signal and the spur signals is more than 10 dB.

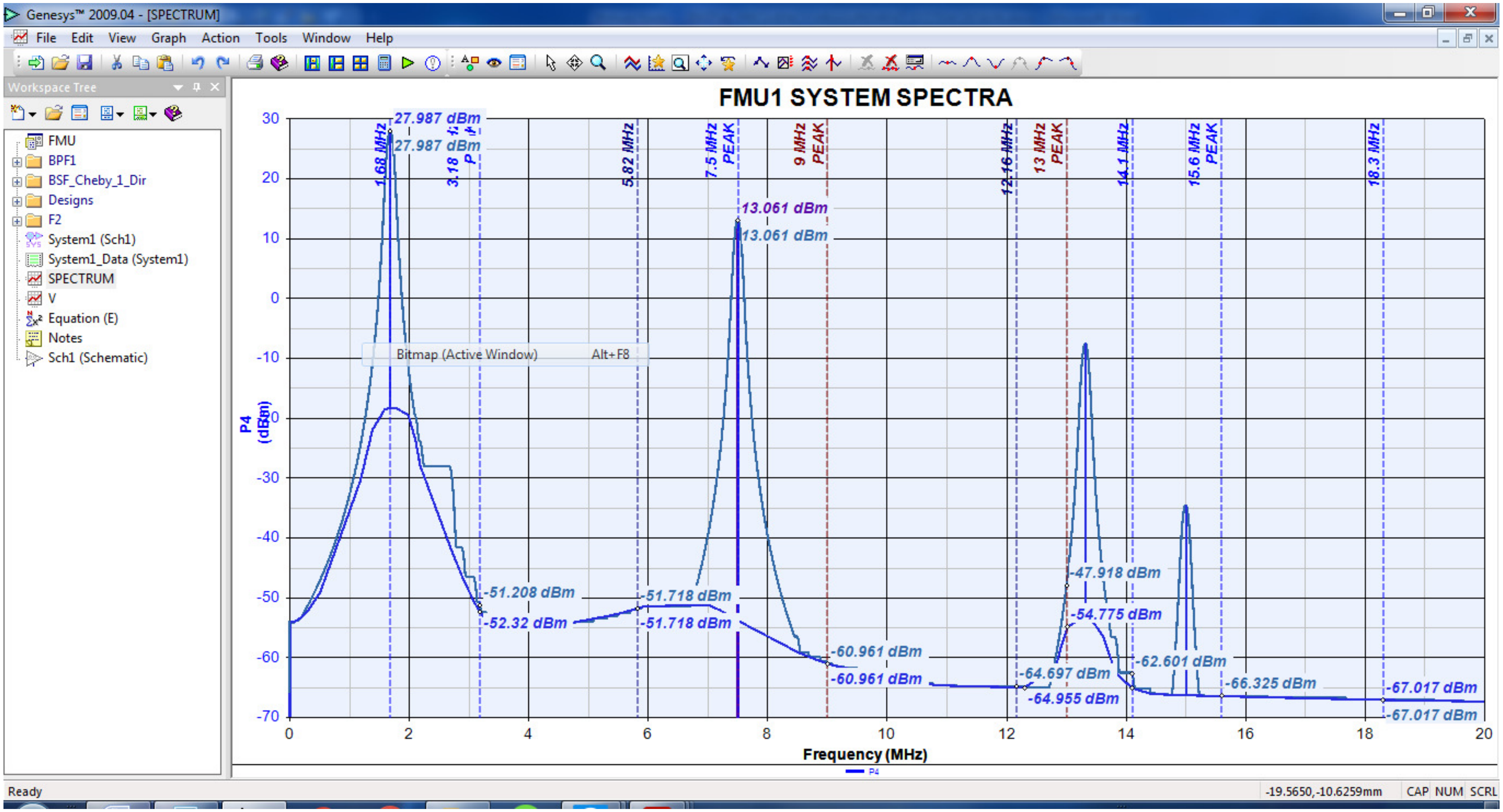


Figure 57a. RFMU Output spectrum in the 160m band

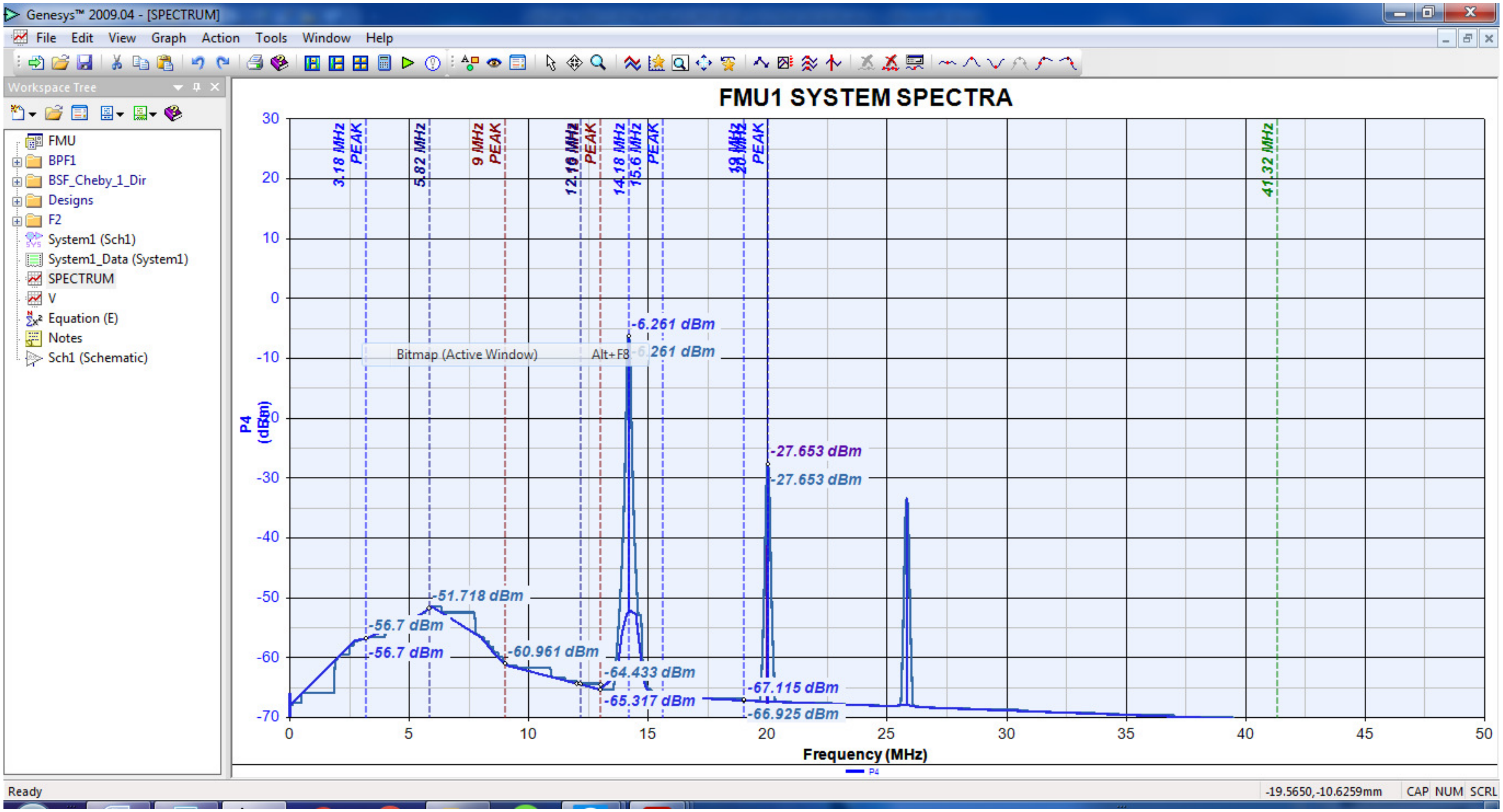


Figure 57b. RFMU Output spectrum in the 20m band

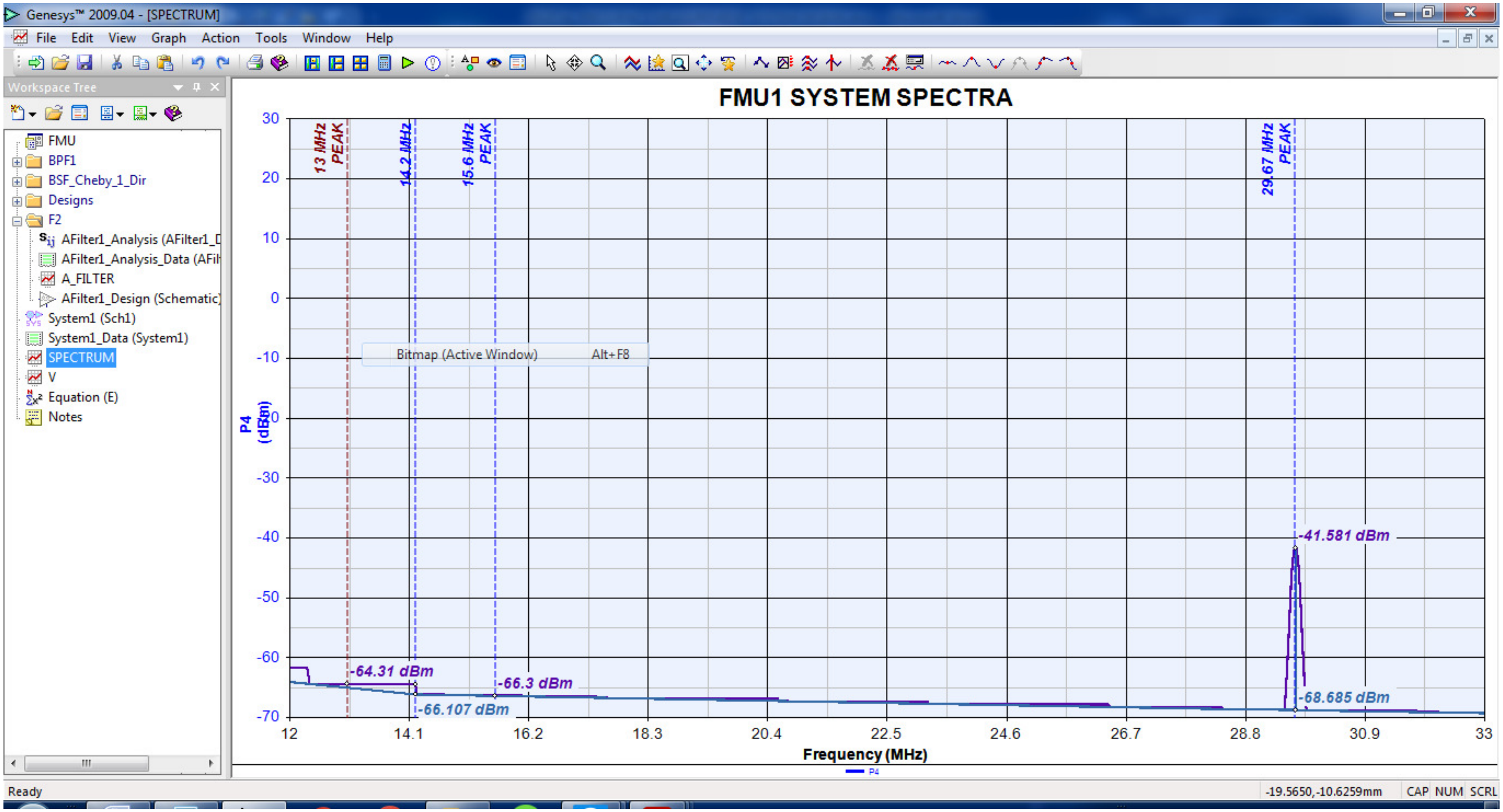


Figure 57c. RFMU Output spectrum in the 10D band

8.8. Evaluation of This Solution

1. The output signal amplitude changes in a large dynamic range with frequency variations; starting at 15V in the 160m band, down to 4.7mV in the 10D band.
2. A high resolution precision comparator (LMV761) has been selected at the RFMU output that can detect input signal amplitudes as low as a few milli volts with Input Offset Voltage 0.2 mV and Input Offset current of 0.2 pA. with such a high sensitivity and resolution, this comparator can generate a rectangular output waveform with a very high slew rate when its input just crosses the zero voltage level.
3. Adding the comparator to the output active filter, its schematic drawing becomes as shown in Figure 57. Its layout drawing becomes as shown in figure 56.

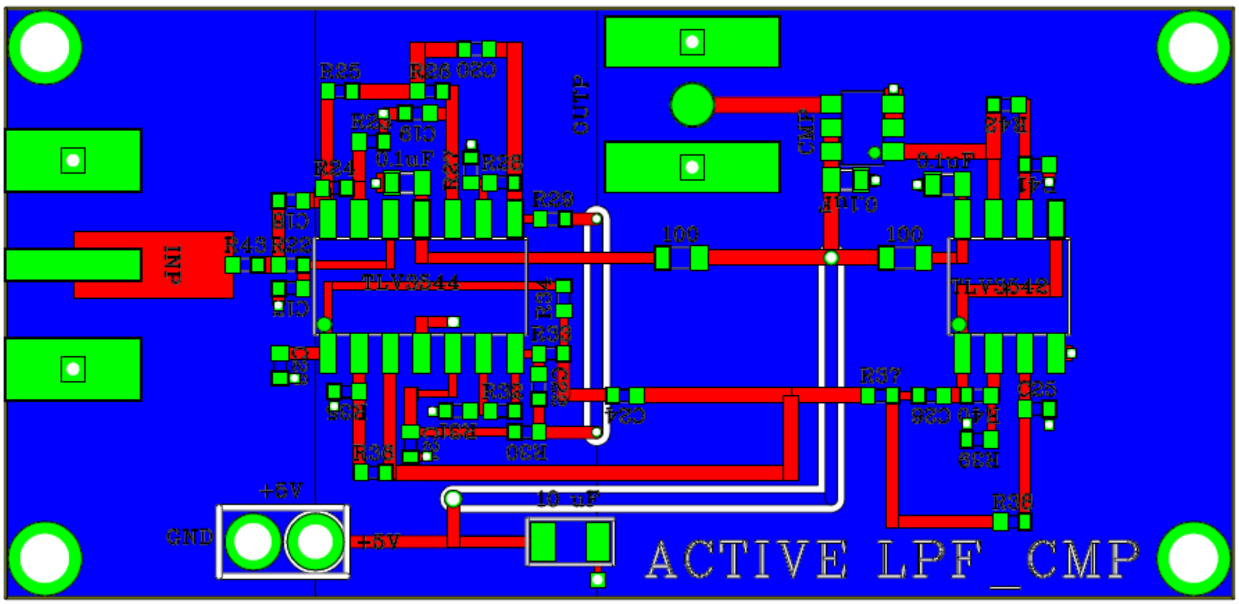


Figure 58.layout of the Active LPF + the Comparator

4. As it can be seen in the layout, a 100 [W] resistor is inserted in series with each of the two OPAMP ICs to limit its supply voltage to +4.5V, while the comparator is supplied by +5V for its security.
5. Another solution was studied and fully designed. The other solution would give the same output signal level in all frequency bands. But it was more complex; since it divides the frequency channels into three groups. For each group, a dedicated filter was designed to suppress the USB output frequency. The selection of the filter was done by sensing the band selection switch position and automatically switching the BPF.
6. Although the other solution was more efficient and gives a constant output signal level in all the ten frequency bands, it was excluded due to its complexity.
7. The second solution is explained in the appendix.

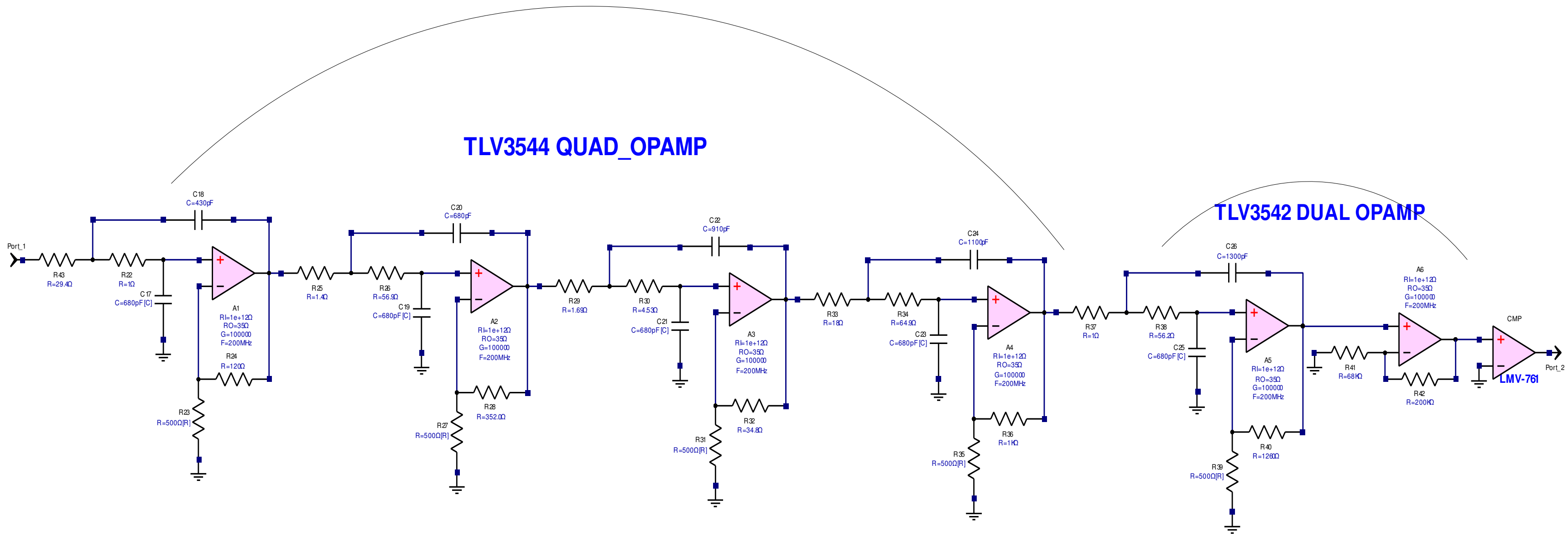


Figure 59. The Active LPF + the Comparator

8.9. FMU1 Layout

In order to minimize PCB area and apply modularity principle, the RFMU has been subdivided into the following modules:

1. The FMU1 Module, which is the main frequency measurement unit, responsible for generating a sinusoidal signal with frequency equal to that being currently received by the FT-100. This generation is done by mixing three signals:
    a. The 3.18 MHz signal taken from the FT-100 receiver output.
    b. The IF local oscillator signal generated by the VFO Unit.
    c. The RF local oscillator signal generated by the RF Unit.

   This module contains the two mixers, the three input signal buffer amplifiers and the main connections.

2. The main connections of the FMU1 module are the following:
    a. The 3.18 MHz input signal coming via a two-pin connector by a simple twisted pair cable from the NB Module of the FT-100.
    b. The LO1 output signal coming from the VFO Unit of the FT-100 via a coaxial cable and an edge smb connector.
    c. The LO2 signal coming from the RF Unit of the FT-100 via a coaxial cable and an edge sma connector.
    d. The first mixer output going the BPF via an edge smb connector and a short coaxial cable.
    e. The BPF output coming via a short coaxial cable and an edge smb connector.
    f. The second mixer output going to the BSF via an edge smb connector and a short coaxial cable.

Those connections are summarized in Table 4.

TABLE 4

FMU1 MODULE CONNECTIONS

Connection	I/O	FROM	TO	SIGNAL	CONNECTOR	CABLE
A	I	FT-100 NB Unit		3.18 MHz received signal	Two-pin	Twisted pair
B	I	FT-100 VFO Unit		5.52 TO 6.02 MHz LO1 signal	Edge smb	coaxial
C	I	FT-100 RF Unit		7.5 to 35.5 MHz LO2 signal	Edge sma	coaxial
D	O		BPF Module	First mixer output	Edge smb	coaxial
E	I	BPF Module		BPF output signal	Edge emb	coaxial
F	O		BSF input	Second mixer output	Edge smb	coaxial

Figure 60 shows the FMU1 PCB layout where all these connections can be seen. 16 (ϕ2 mm) holes are located at their properly calculated places for mechanical fixation of the four modules. The inter-module connections can be understood by looking at Figure 61.

3. The IF Band Pass Filter (BPF) with passband from 5.52 to 6.02 MHz. It is built on a separate PCB that gets its input from the first mixer output of the FMU1 and delivers its output to the second mixer input in the same module. Two short coaxial cables with smb connectors should be used for this purpose.

4. The IF Band Stop Filter (BSF) with passband from 5.52 to 6.02 MHz. It is built on a separate PCB that gets its input from the second mixer output of the FMU1 and delivers its output to the Active Filter Module input.

5. The Active Filter Module fully described and characterized above. It is an independent module responsible for suppressing the USB output signals of the second mixer. The same module is responsible for adjusting the overall gain of the RFMU. At its output there is a zero crossing detector to give a TTL rectangular waveform with the same frequency of the received RF signal.

6. The output of the AF Unit is delivered to the Counter Unit to count and display the RF frequency.

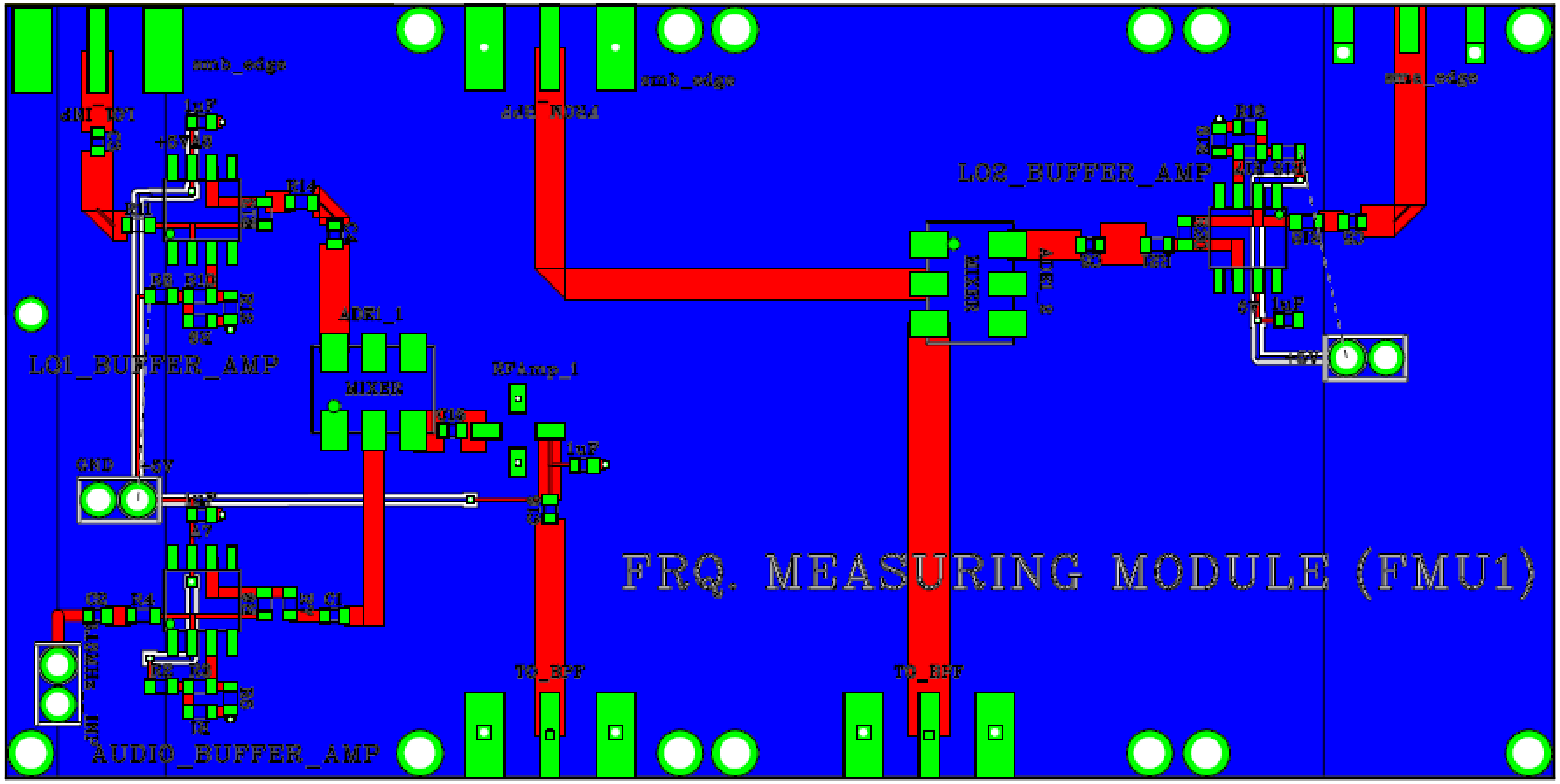


Figure 60. The FMU1 Module Layout and connections

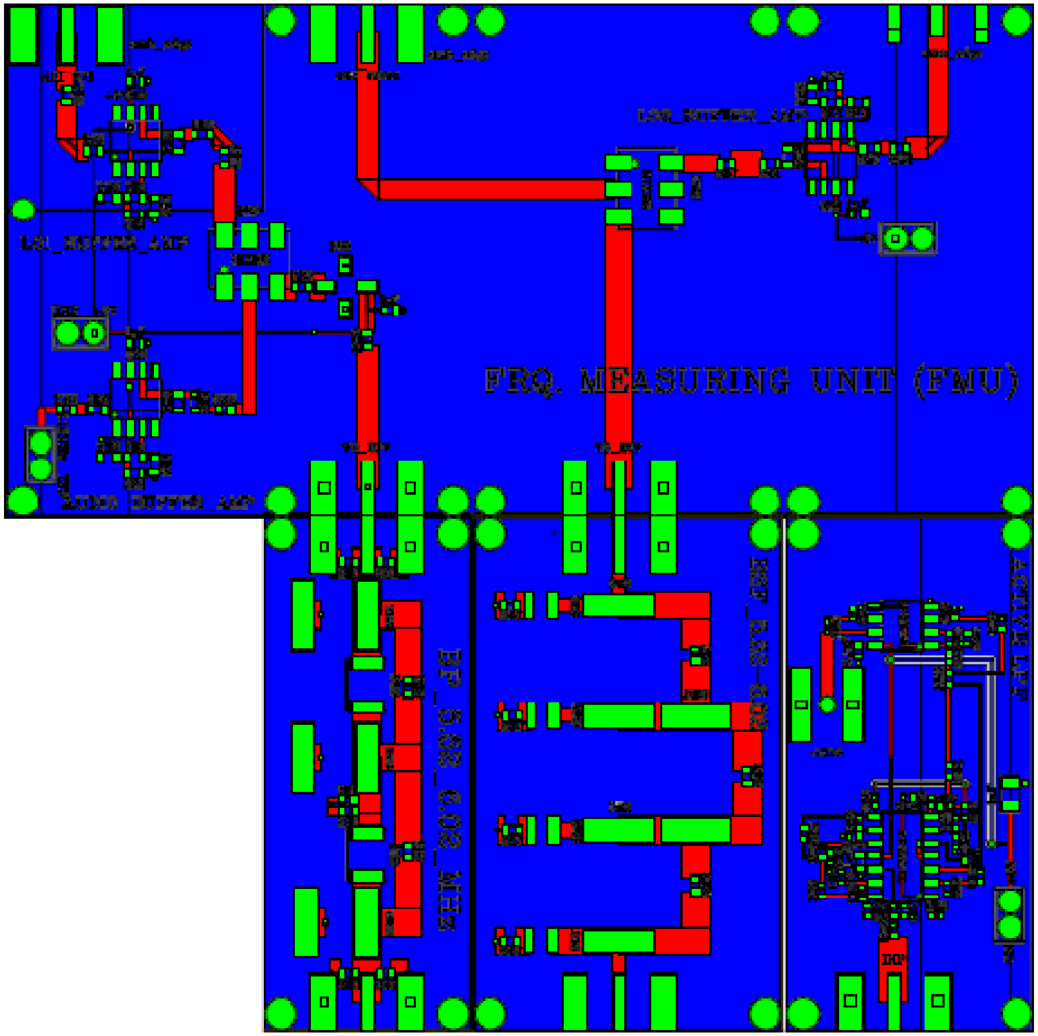


Figure 61. Inter-module connection of the RFMU Unit

8.10. Mechanical Layout of the RFMU

Figure 62 shows the mechanical layout outlines of the RFMU. The three daughter PCBs are fixed to the FMU1 mother board by screws and spacers. Coaxial cables should be used for interconnections between the PCBs.

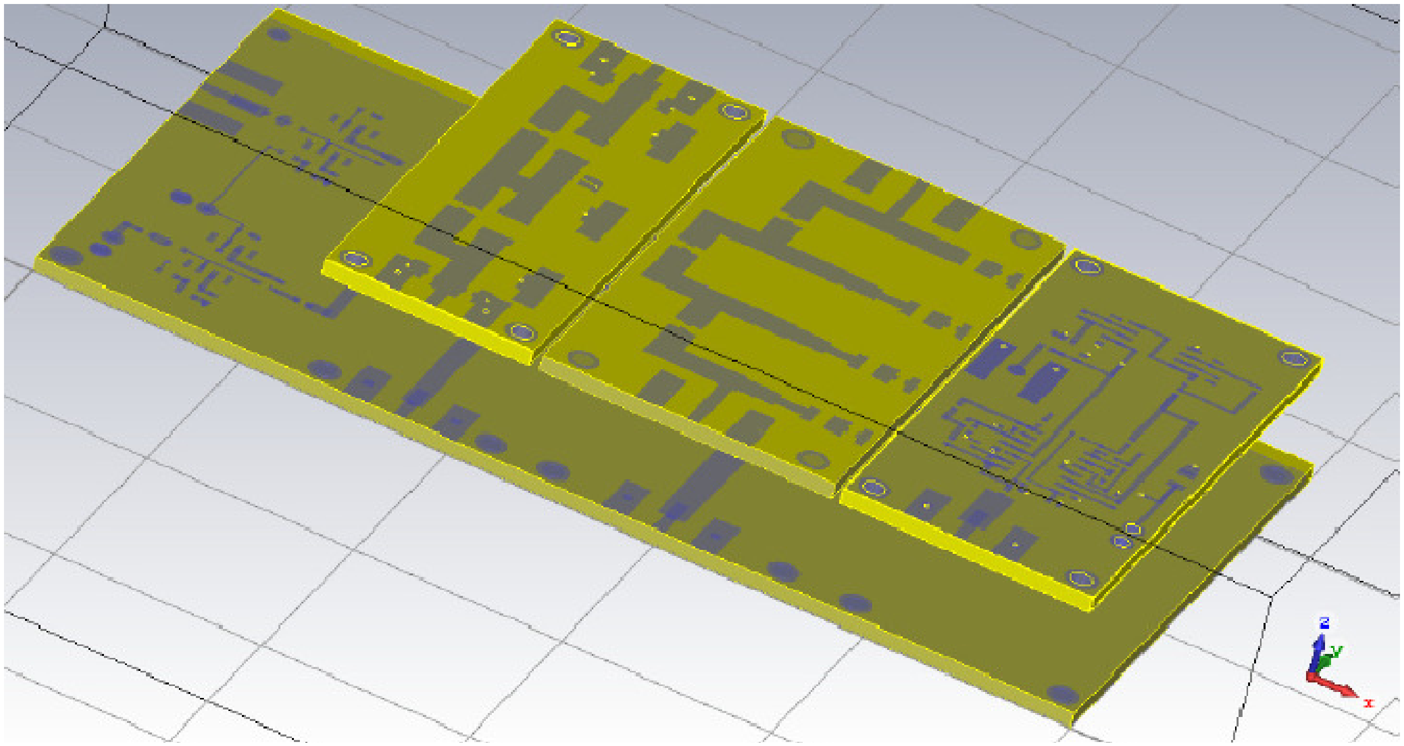


Figure 62a. Mechanical Layout of the RFMU Unit; the FMU1 as a mother board

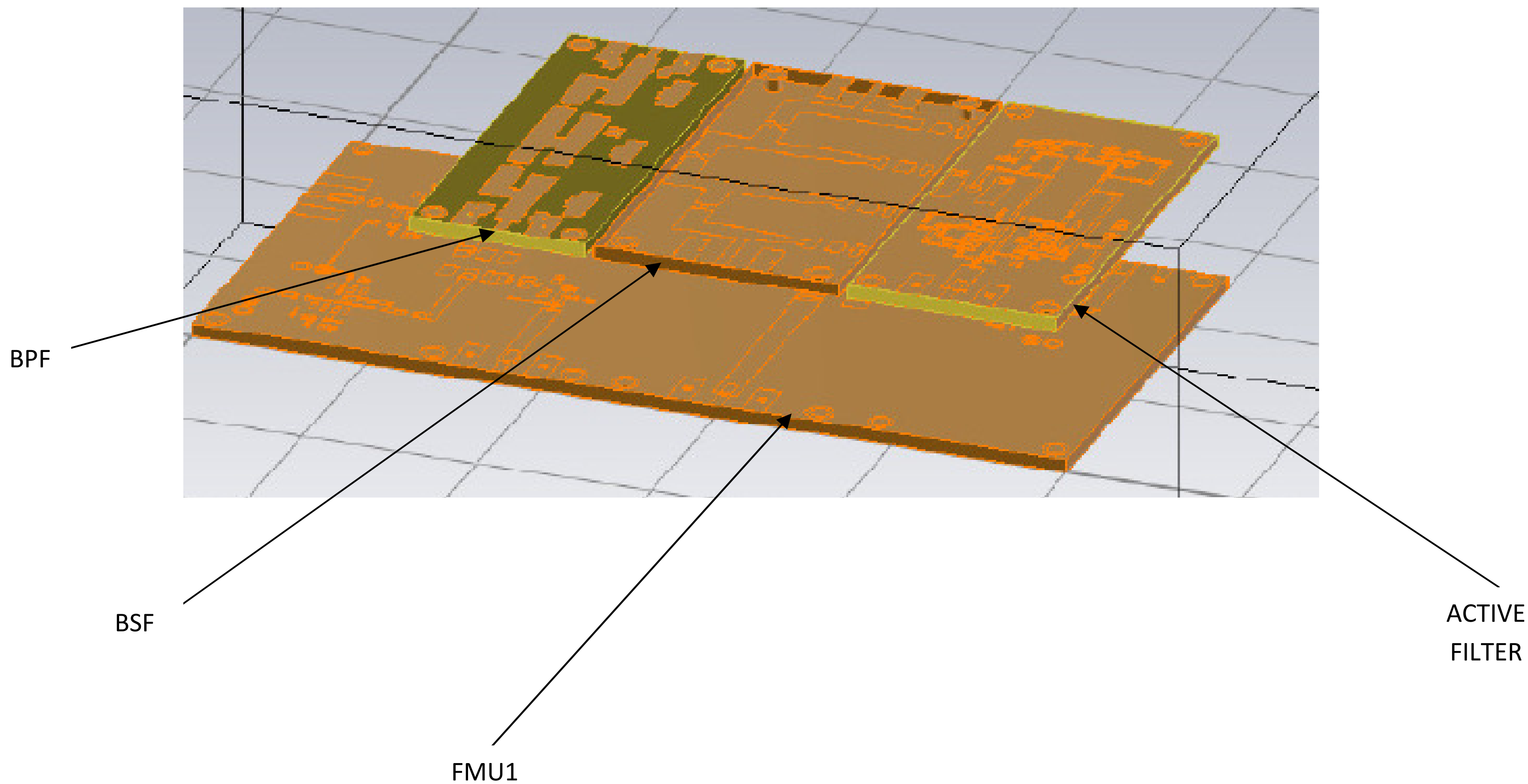


Figure 62b. Mechanical Layout of the RFMU Unit; the FMU1 as a mother board

9. The Counter Unit Design

A full hardware approach has been followed to design the Counter Unit. The following are the main design features:

1. The comparator output of the RFMU unit is a train of pulses with the exact frequency (f) being received by the FT-100. It is taken via an smb connector to the first two cascaded decade counters to get a train of pulses with frequency f/100.

2. A 1Hz stable oscillator (Y1) is used with a simple D-type flip flop divider (IC12A) to generate a 1 sec time gate every two seconds (the Q and Q* outputs of IC12A). The IC10 comparator is used to get a TTL waveform from the initial LVCMOS output of the 1Hz clock generator. It is compared with 1V to get the TTL_1Hz waveform. The TTL_1Hz wavefprm is used as a clock for the D-type flip flop to generate the 0.5 Hz TTL waveform at the IC12A output (Q and Q*). See Figure 63 below.

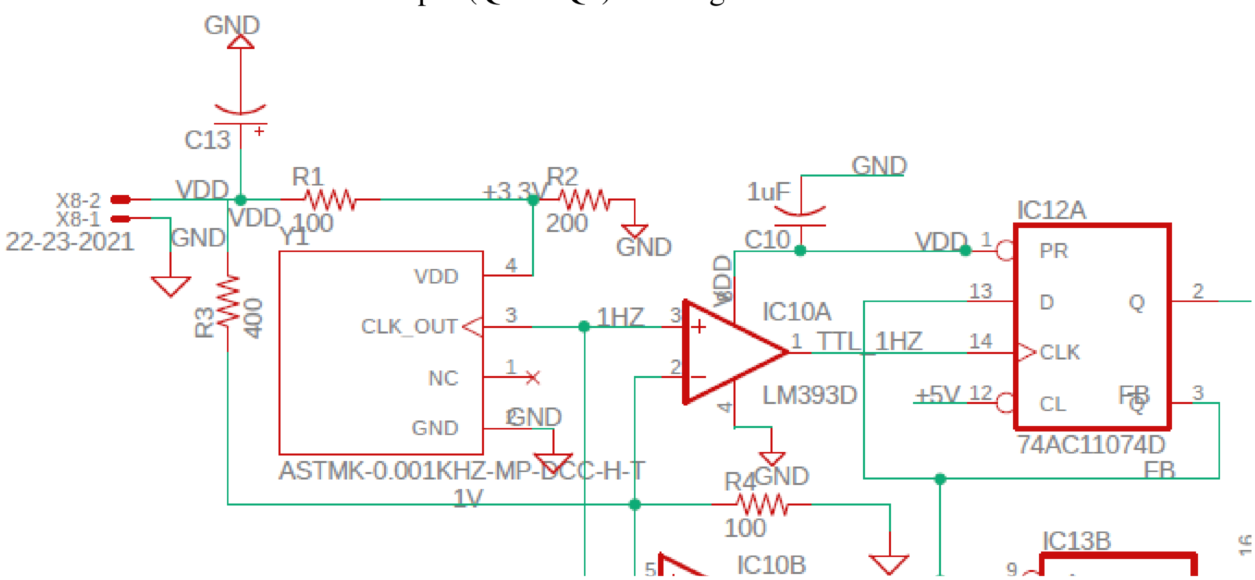


Fig. 63. Counting gate generation in the Counter1 PCB

3. The counting is enabled while Q is LOW, as it can be seen in the logic diagram of the first decade counter 74HC4017 shown in the following figure:

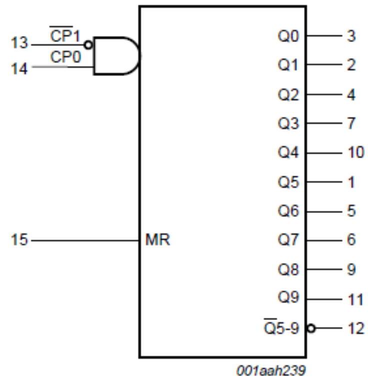


Figure 64. Logic diagram of the first 74HC4017 decade counter.

The connections of the two decade counter stages are shown in the following figure, where the 0.5 Hz Q enables the input clock (X7) for 1 second every two seconds as said above.

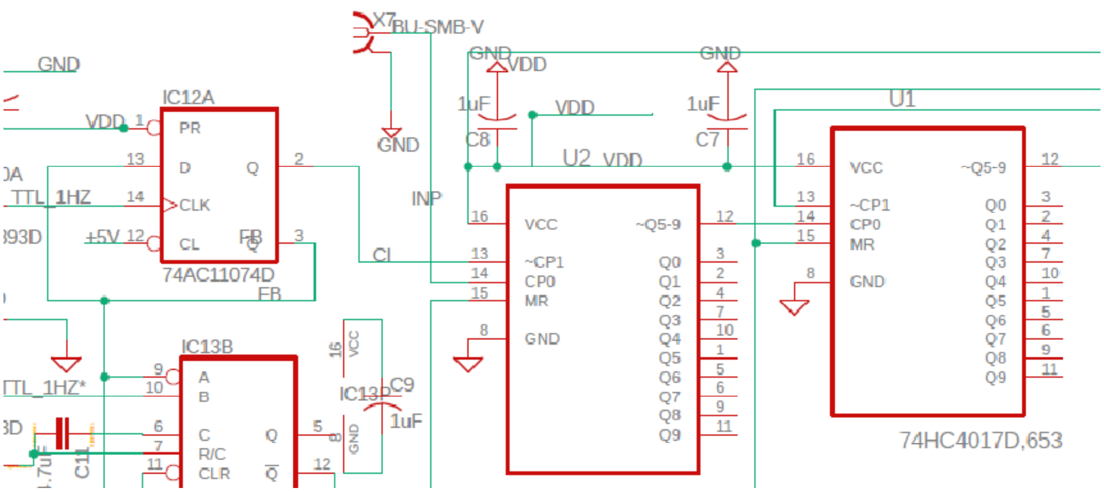


Figure 65. the first two decade counters to divide by 100

The Q output of the D flip flop goes to pin 13; such that the clock is enabled only in the half cycle when Q is LOW. This happens for 1 second of each 2 seconds.

The Q5-9 output of the first decade counter (U2) is taken as a clock to the next decade counter (U1). It means that the U2 outputs a pulse every 100 input pulses. **Thus, the unit count of the first digit in our counter expresses 100 Hz, or 0.1 kHz as required.**

4. Before the next count enable gate is generated, a master RESET command is generated to all counter stages to assure that the next count starts from zero. This Master RESET pulse is generated as follows:
   a. The Q* pulse is connected to the input (A) of the 74123D (monostable multivibrator) such that it enables its +ve edge trigger only while Q* is low, on condition that the clear input is HIGH (fourth row of the truth table).

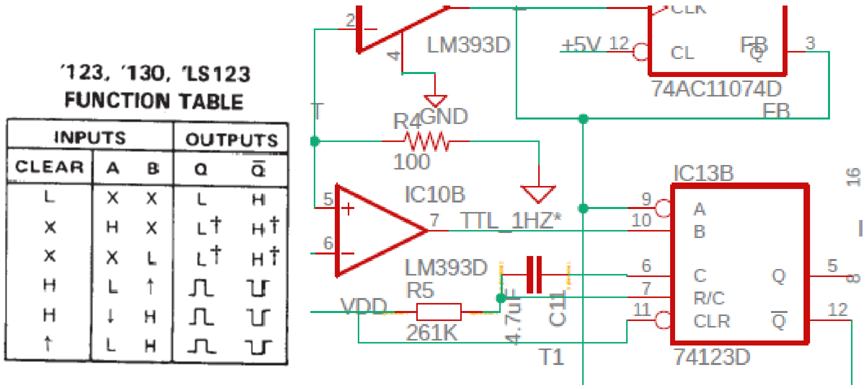


Figure 66. Triggereing the first Monostable Multivibrator (IC13B)

b. The first MMV is triggered by the 1 Hz clock to generate a 453.88 ms positive pulse.

c. The 453.88ms pulse is used to trigger the second MMV (IC13A) to generate a 10 ms positive pulse, delayed by 453.88 ms from the clock edge. This 10 ms pulse is the Master RESET pulse used to reset all counters before the new gate starts. See Figure 67 below.

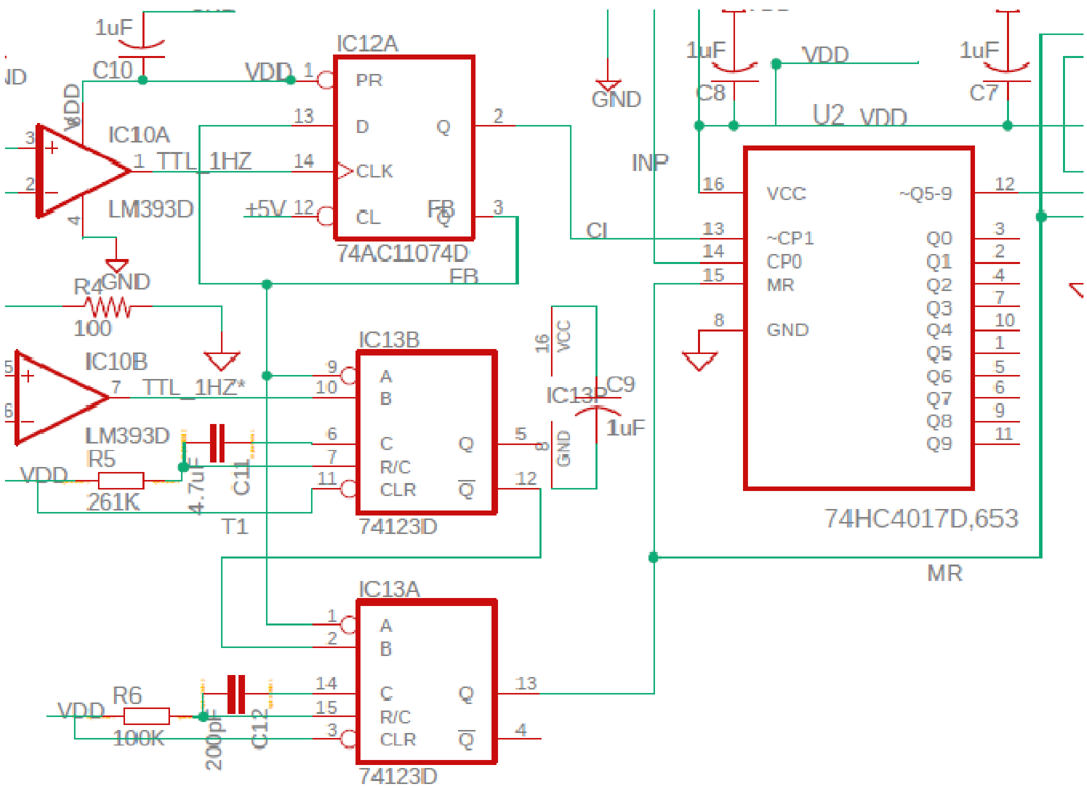


Figure 67. Master RESET Pulse Generation

5. Six identical cascaded decade counter stages with 7 segment display drivers are used to count the signal frequency. Figure 68 shows the most significant five digit counters of those six.

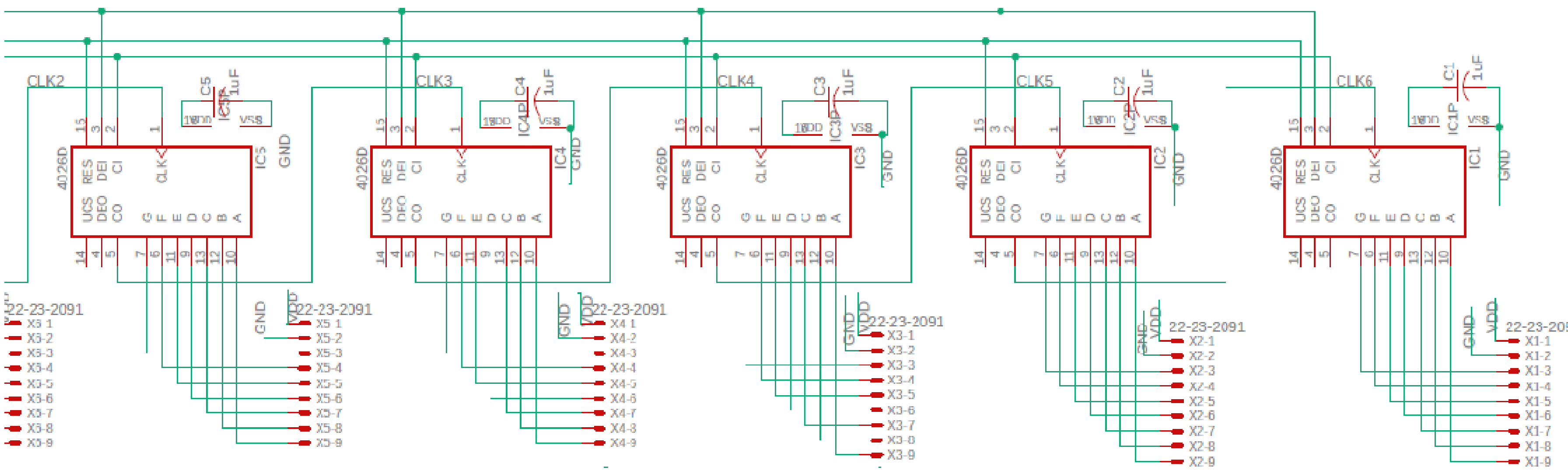


Figure 68. The 5 MSB Decade Counters with 7 segment LED drivers

6. Figure 69 shows the schematic of the second counter PCB containing the six seven segment displays of our counter.

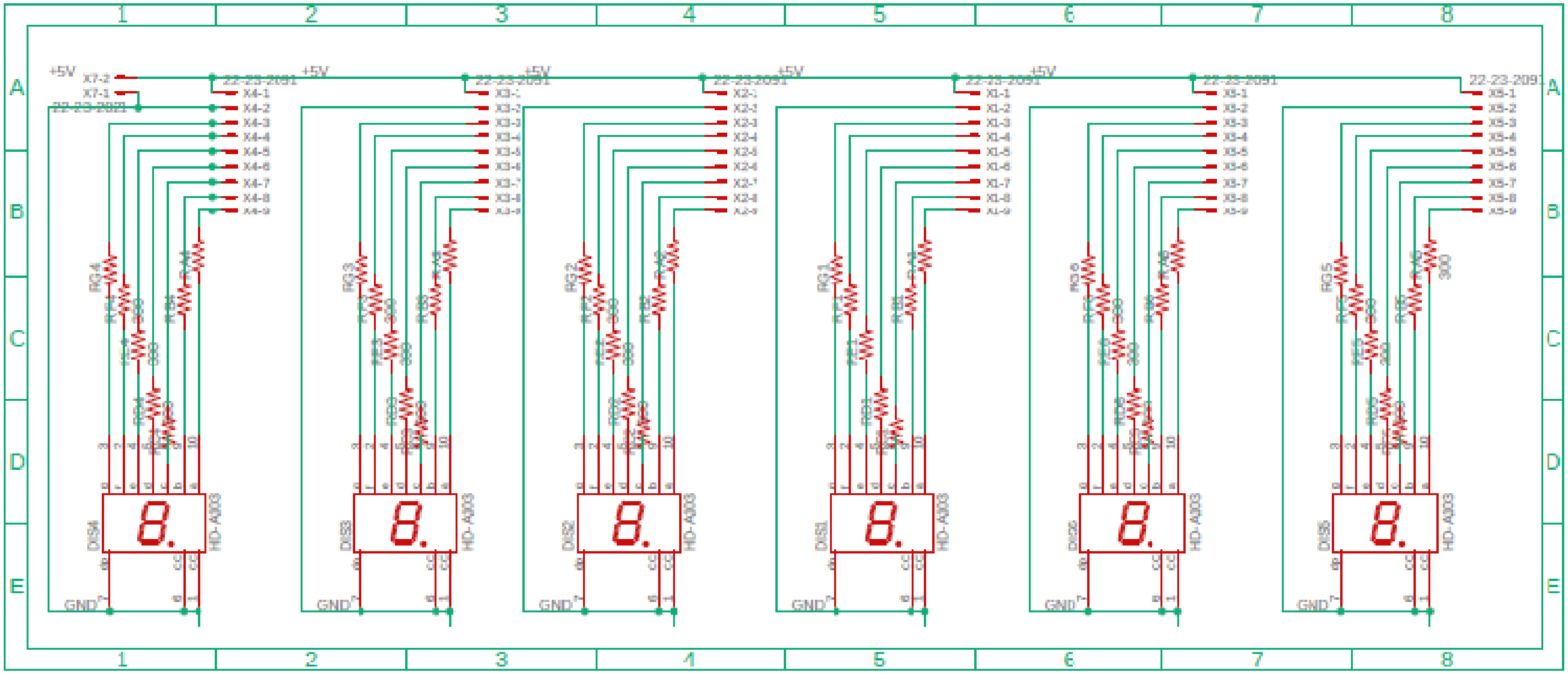


Figure 69. The Counter Display PCB Schematic Drawing

7. Figures 70 through 72 show the PCB layout drawings of the First Counter PCB, while Figures 73 through 75 show the PCB layout drawings of the Second Counter PCB

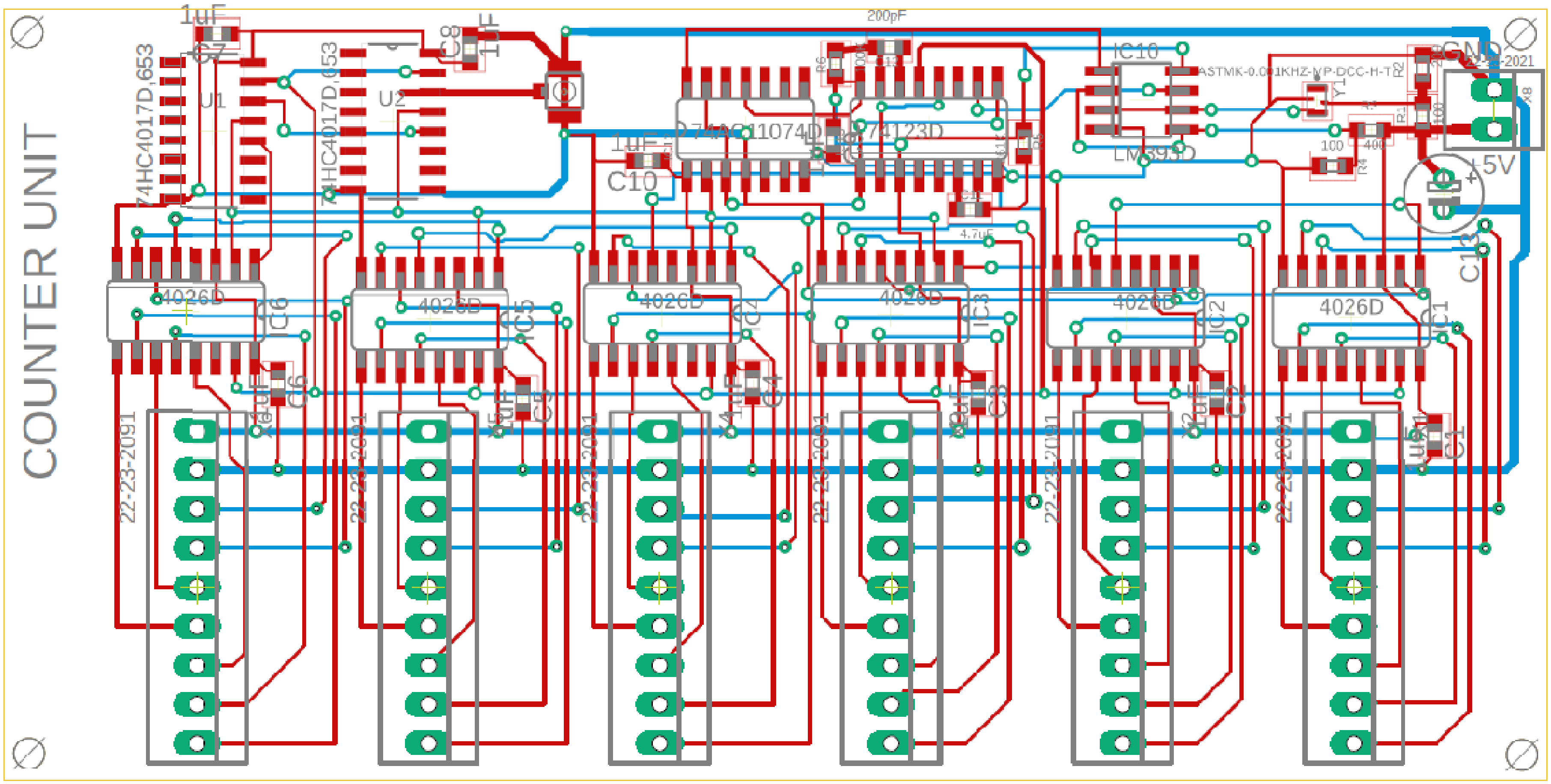


Figure 70. The First Counter PCB Layout Drawing

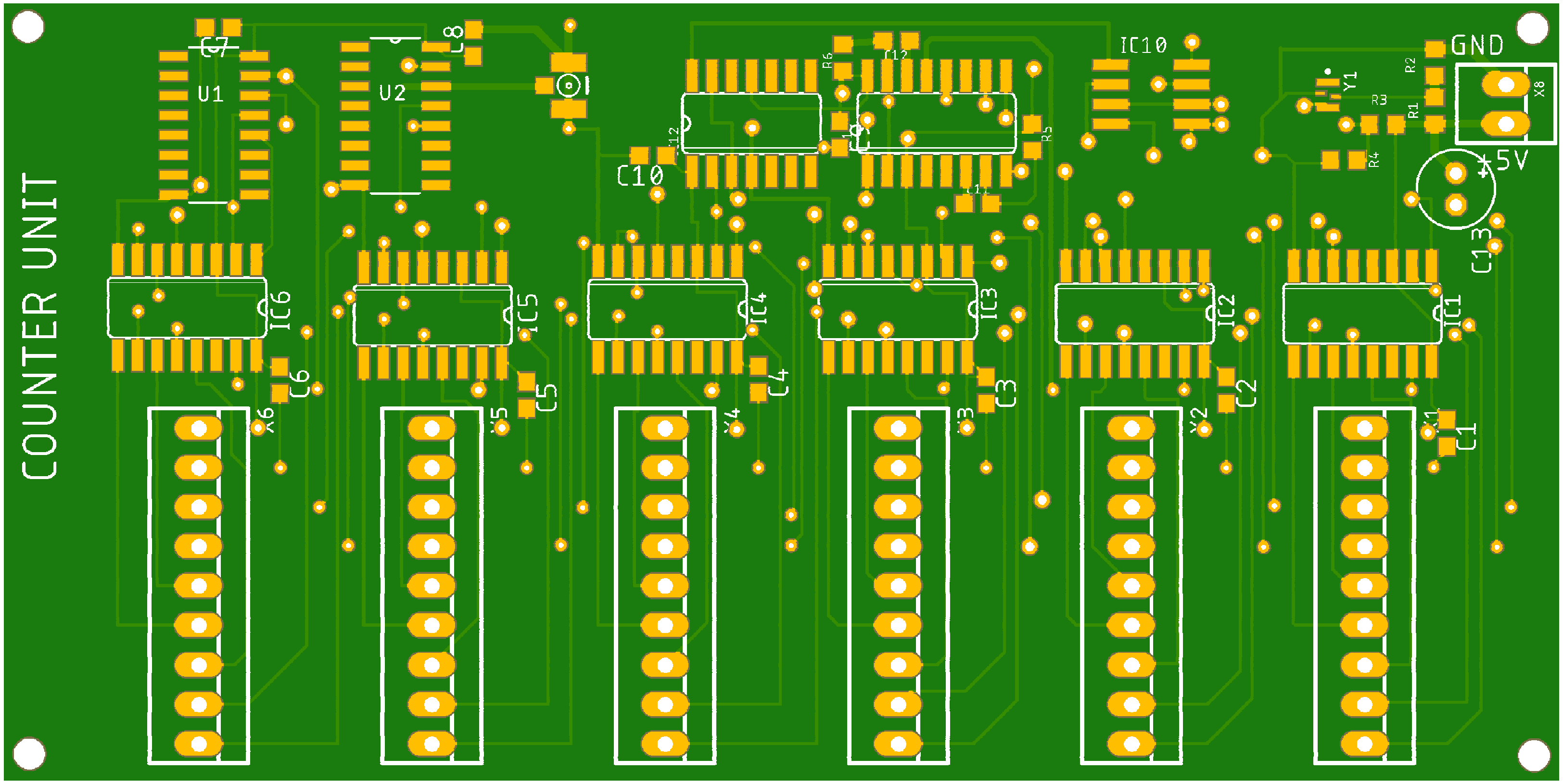


Figure 71. The First Counter PCB Layout TOP View

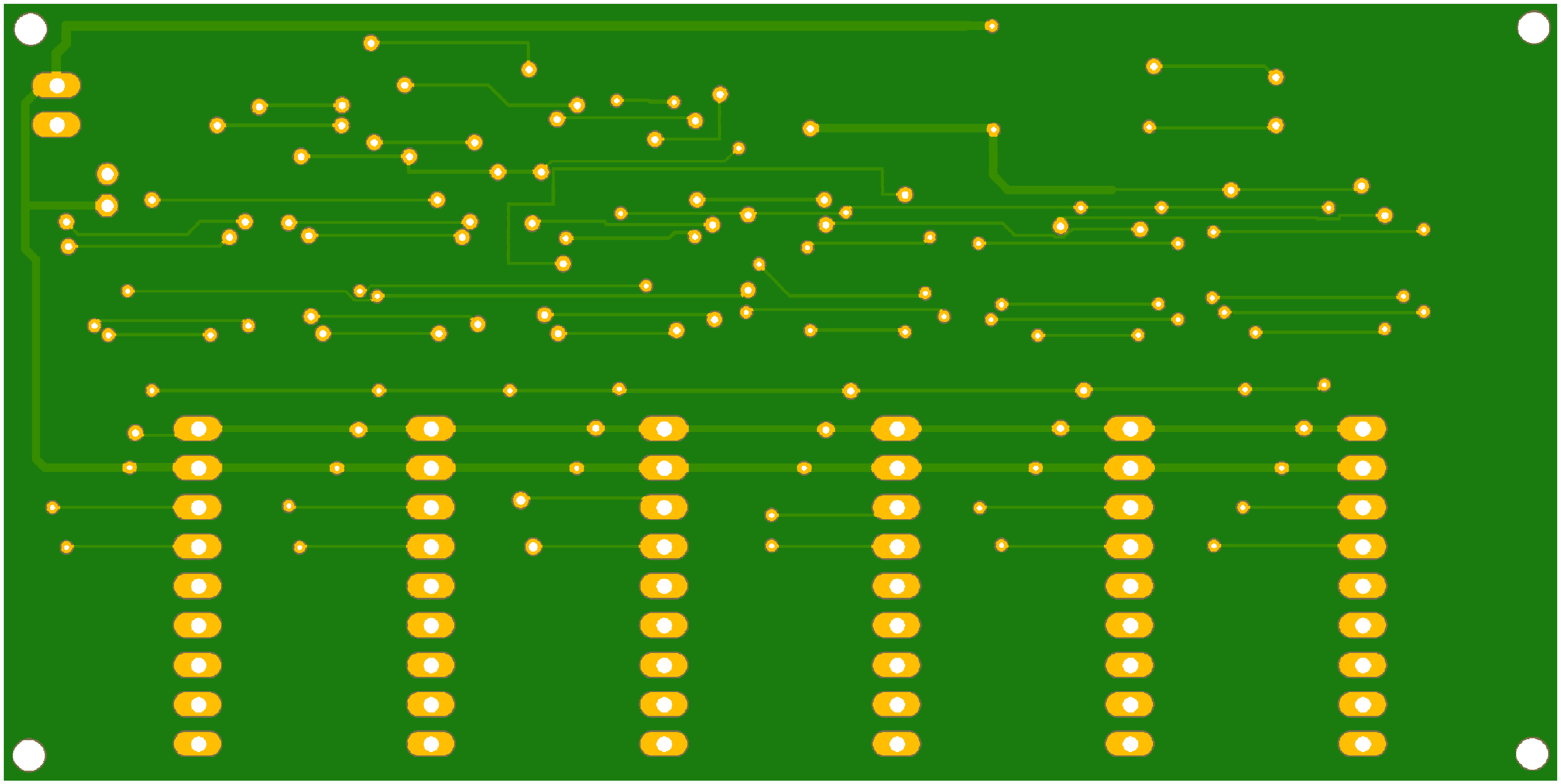


Figure 72. The First Counter PCB Layout BOTTOM View

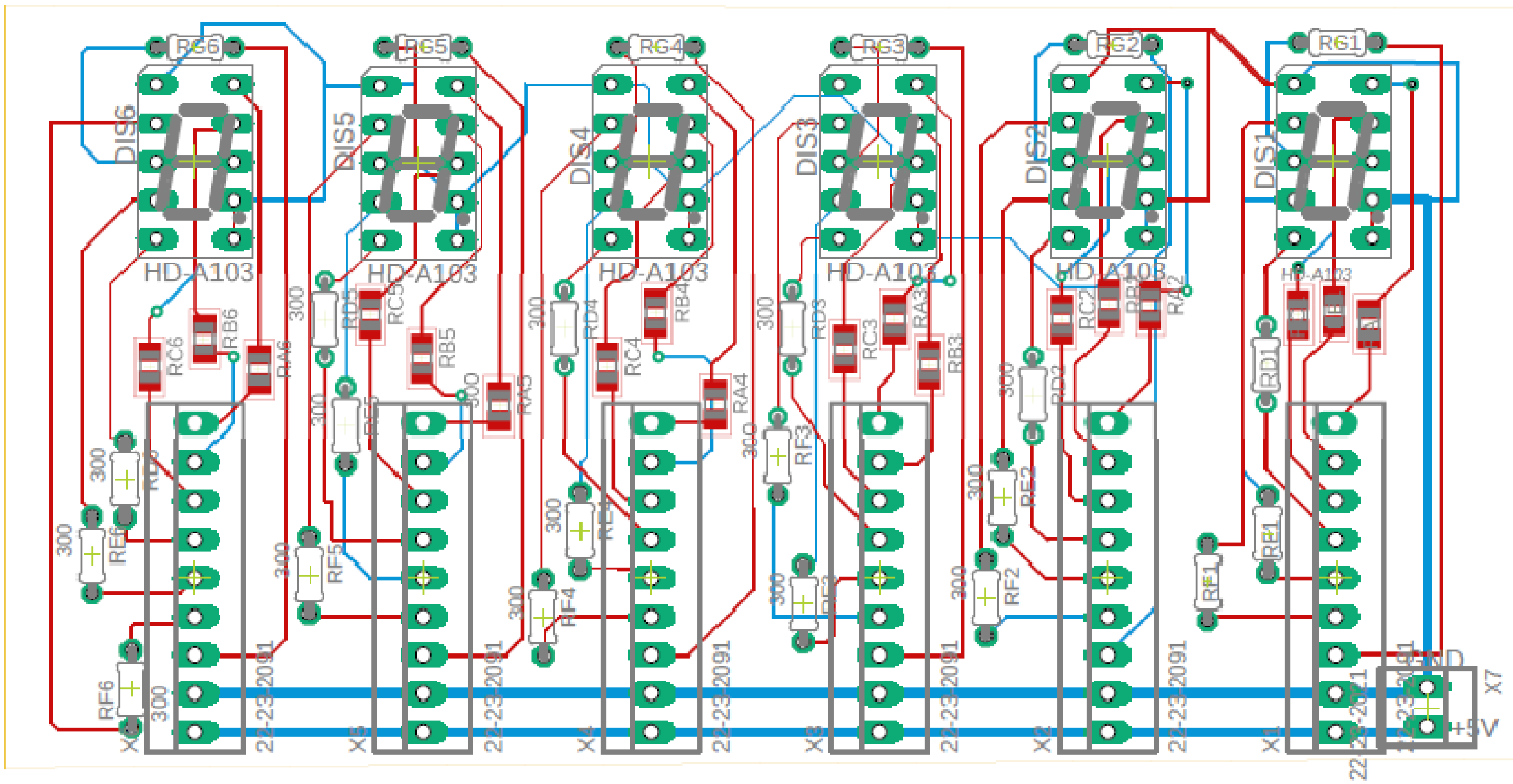


Figure 73. The Second Counter PCB Layout Drawing

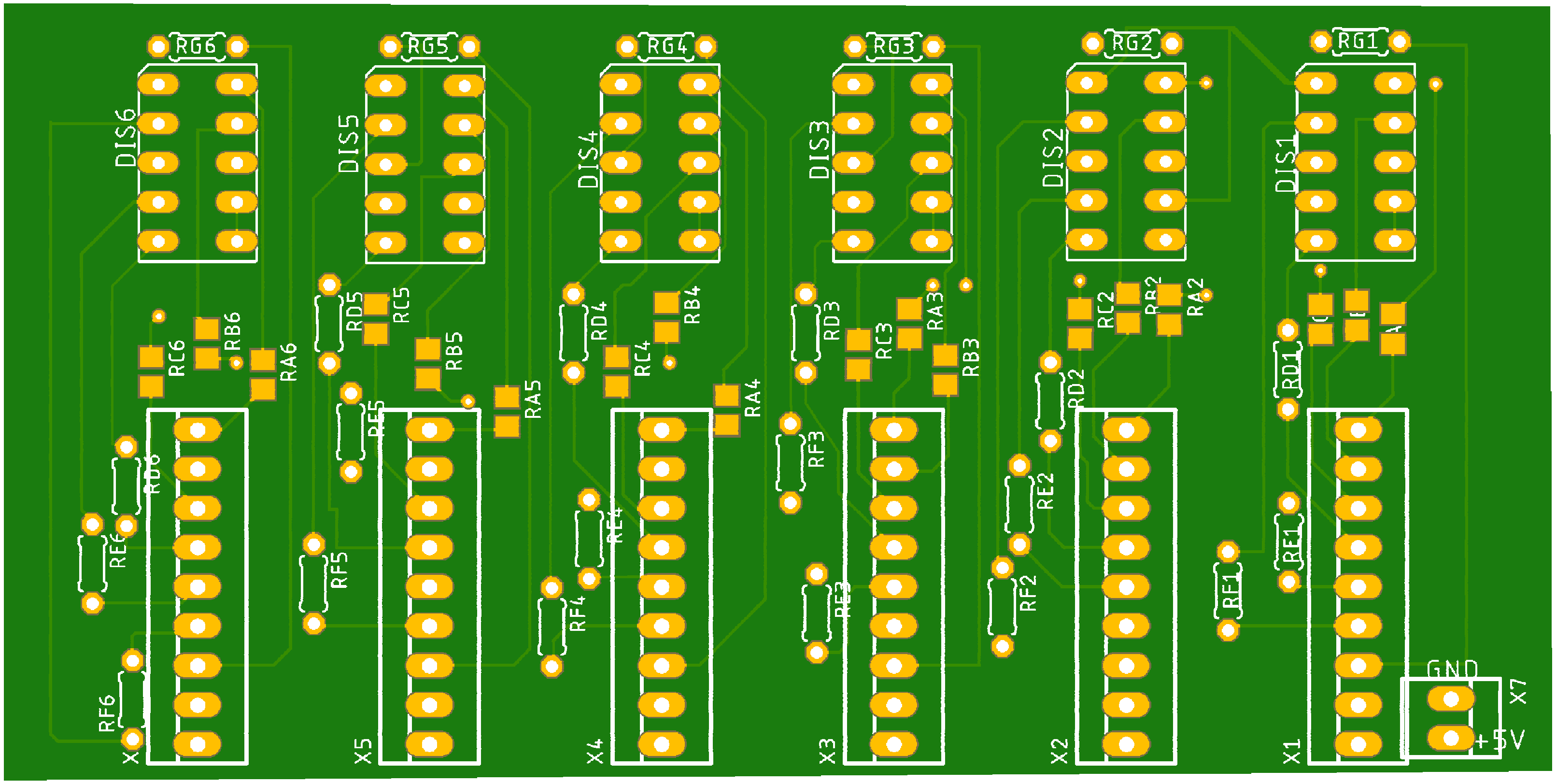


Figure 74. The Second Counter PCB Layout TOP View

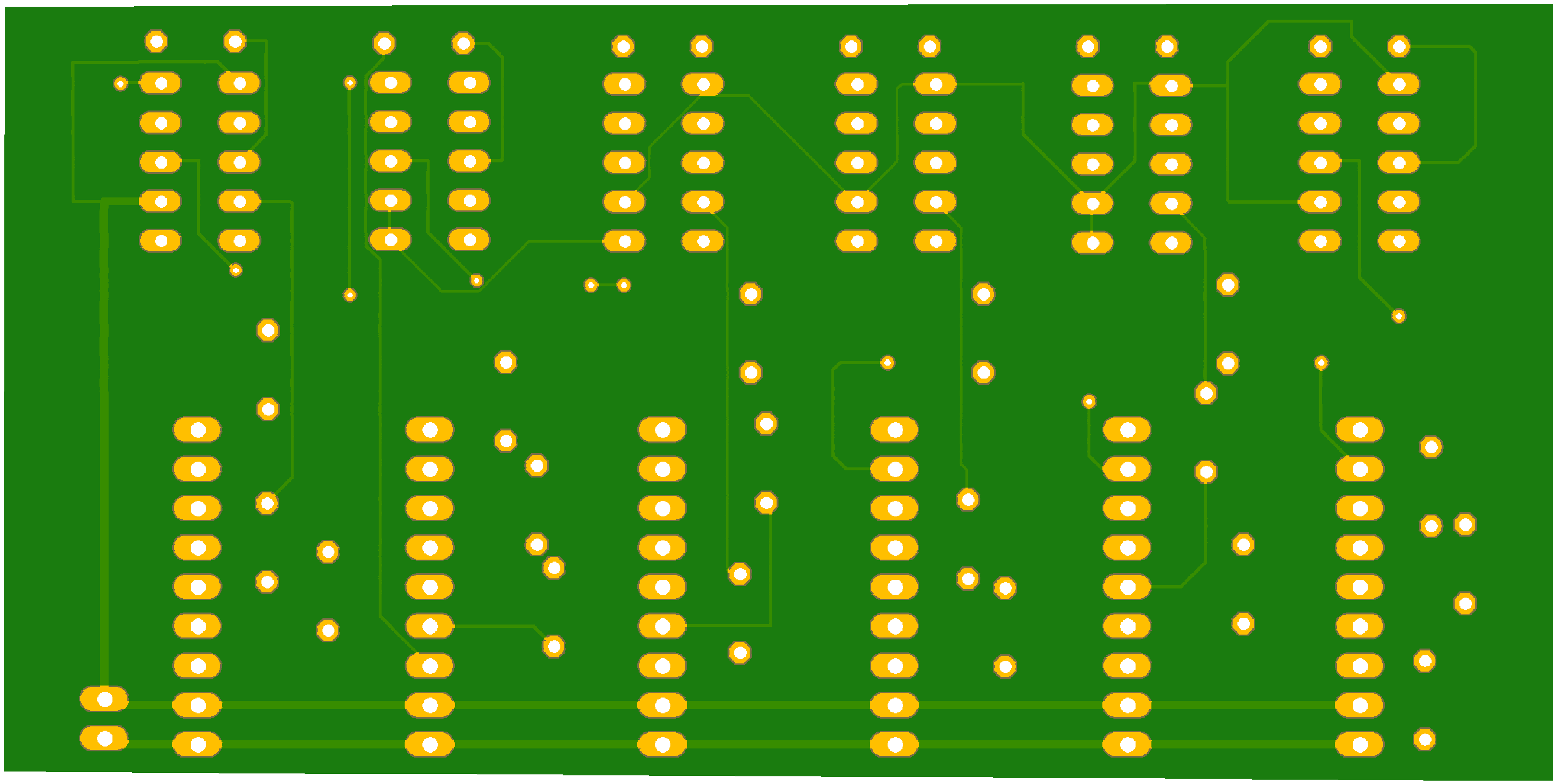


Figure 75. The Second Counter PCB Layout BOTTOM View

10. Mechanical Layout of the System

Figures 76 and 77 show two global views of the 6_PCB system. Simple spacers are used for fixation.

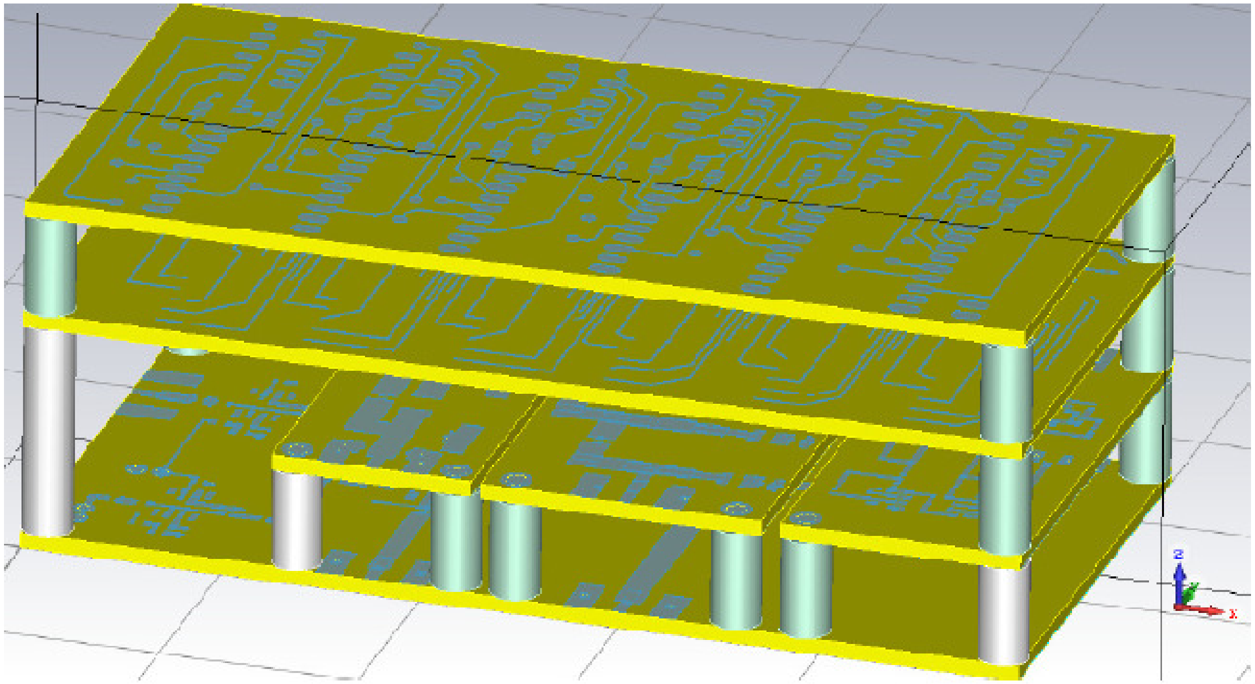


Figure 76. 3D view of the 6_PCB system

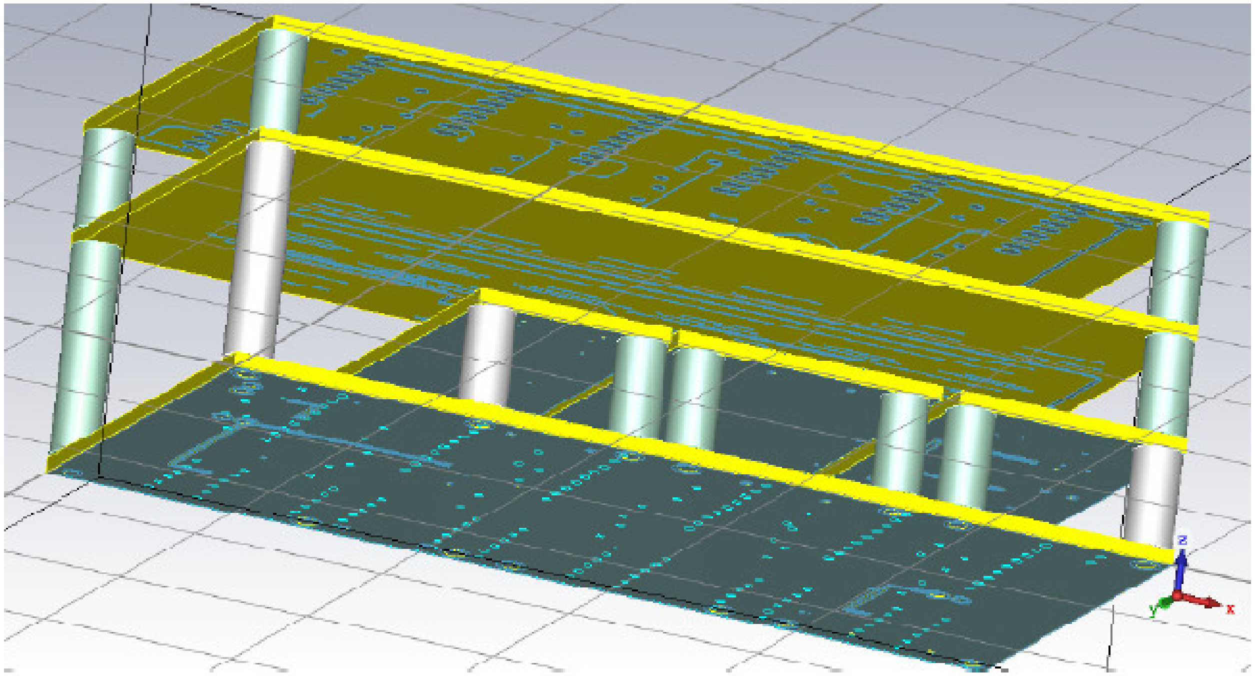


Figure 76. Another 3D view of the 6_PCB system