FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
MASTER'S PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

521327S Radio Engineering 2
Design Exercise Report

Group 06

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LIST of FIGURES

LIST of SYMBOLS and ABBREVIATIONS

α	roll-off factor
S	Scattering parameter
ACPR	Adjacent Channel Power Ratio
ADS	Advanced Design System
BPF	Band Pass Filter
BW	Band Width
dB	Decibels (relative to a 1 Watt)
dBm	Decibels (relative to a 1 mWatt)
DQPSK	Differential Quadrature Phase Shift Keying
EVM	Error Vector Magnitude
IF	Intermediate Frequency
IIP	Input Intercept Point
IMD	Intermodulation Distortion
LNA	Low Noise Amplifier
LO	Local Oscillator
MDS	Minimum Detectable Signal
NF	Noise Figure
OIP	Output Intercept Point
PA	Power Amplifier
RF	Radio Frequency
SAW	Surface Acoustic Wave
SNR	Signal to Noise Ratio
TOI	Third Order Intercept

1 Receiver Design

1.1 Receiver specifications

To begin, the different system specifications of the receiver should be determined.
The main specifications of the receiver were given as:

- Center frequency of the system tuning range 10 GHz.
- Bandwidth of the main lobe between first nulls of the pulse shaped signal 20 MHz.
- The system has 15 channels.
- Sensitivity at least -87 dBm.
- SNR requirement at the output of the IF-stage at least +9 dB.
- Signal level at the output of the IF-stage at least +4 dBm.
- At the output of the IF-stage the 1 dB compression point greater than +17 dBm.
- The IF-frequency must be 618 MHz.

The MDS (P_{sens}) is -87 dBm and the minimum output power level ($P_{out,min}$) is +4 dBm. Therefore, the gain of the receiver is

$$G_{RX} \geq \frac{P_{out,min}}{P_{sens}} \implies G_{RX} \geq 91dB$$

The total bandwidth of the receiver is

$$BW = \text{Number of channels} \times BW_{\text{Single Channel}} \implies BW = 300MHz$$

Hence, since most of L3 Narda Miteq mixers are lossy ones, we partition the gain such that the RF stage takes $\frac{1}{3}$ of the total gain (around 20 or 30 dB) reserve $\frac{2}{3}$ for the IF stage and add some margin to tolerate the losses of the filters and mixer.

The minimum SNR at the output (SNR_{min}) should be at least +9 dB,therefore

$$P_{sens} = N_{in} + SNR_{min} = KTBW + NF + SNR_{min} \implies NF = P_{sens} - KTBW + SNR_{min} = 4.97dB$$

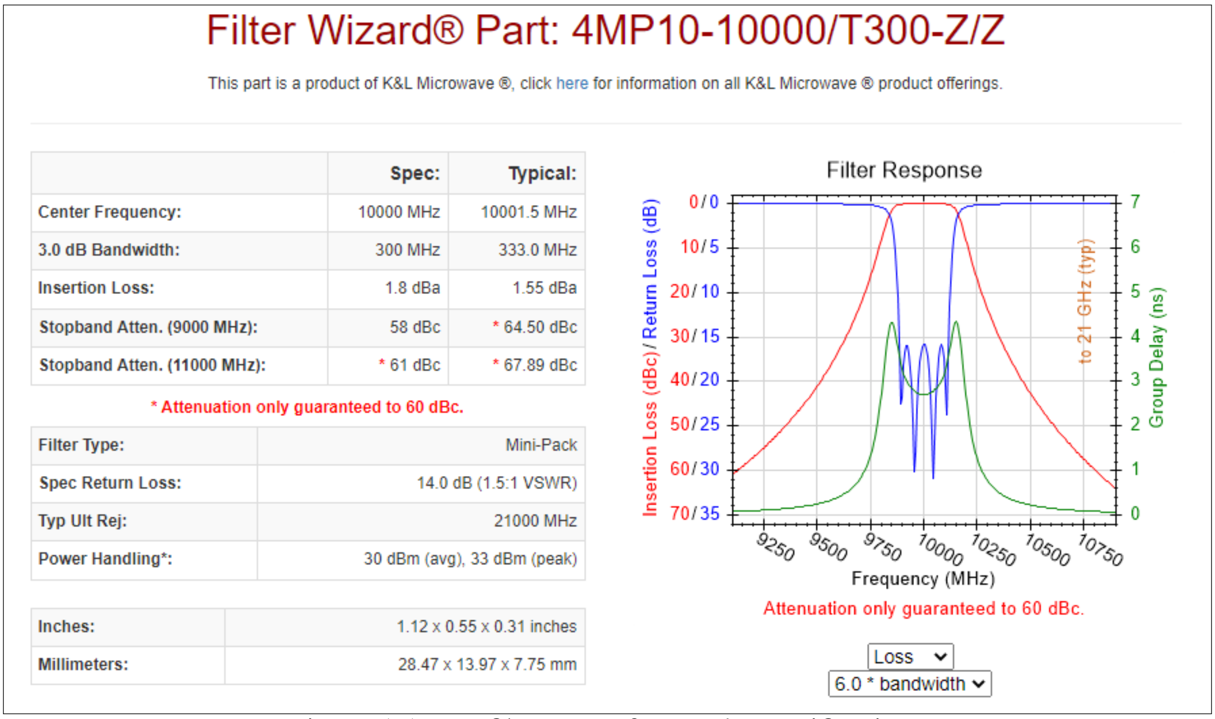
This means that to reach the SNR requirement, we should have $NF \leq 4.97dB$.

1.2 Components selection

1.2.1 Filters

1.2.1.1 RF filters

In selecting the RF filter, the attenuation of filter in the passband and insertion loss is taken into account. RF filter attenuation is equal to NF of the filter and since the first component in the chain has the most effect on the total NF, it should be selected carefully. The filter should also ensure the rejection of spurious frequencies out of RF frequency range. The passband of the filter should be equal to the total system bandwidth of 300 MHz and centered around RF frequency (10 GHz). The filter with part number 4MP10-10000/T300-Z/Z was selected as it meets the required specifications, as shown in Figure 1.1.



Filter Wizard® Part: 4MP10-10000/T300-Z/Z

This part is a product of K&L Microwave ®, click here for information on all K&L Microwave ® product offerings.

	Spec:	Typical:
Center Frequency:	10000 MHz	10001.5 MHz
3.0 dB Bandwidth:	300 MHz	333.0 MHz
Insertion Loss:	1.8 dBa	1.55 dBa
Stopband Atten. (9000 MHz):	58 dBc	* 64.50 dBc
Stopband Atten. (11000 MHz):	* 61 dBc	* 67.89 dBc

* Attenuation only guaranteed to 60 dBc.

Filter Type:	Mini-Pack
Spec Return Loss:	14.0 dB (1.5:1 VSWR)
Typ Ult Rej:	21000 MHz
Power Handling*:	30 dBm (avg), 33 dBm (peak)

Inches:	1.12 x 0.55 x 0.31 inches
Millimeters:	28.47 x 13.97 x 7.75 mm

Figure 1.1: RF filter manufacturer's specifications

The RF filter has been modeled in ADS using its typical values and the Chebyshev filter model, and tested against the s-parameters provided by the manufacturer, as shown in Figure 1.2. With some trial and error to determine the order of the Chebyshev filter, the modeled filter resembles the operation of the real filter, as shown in Figure 1.3.

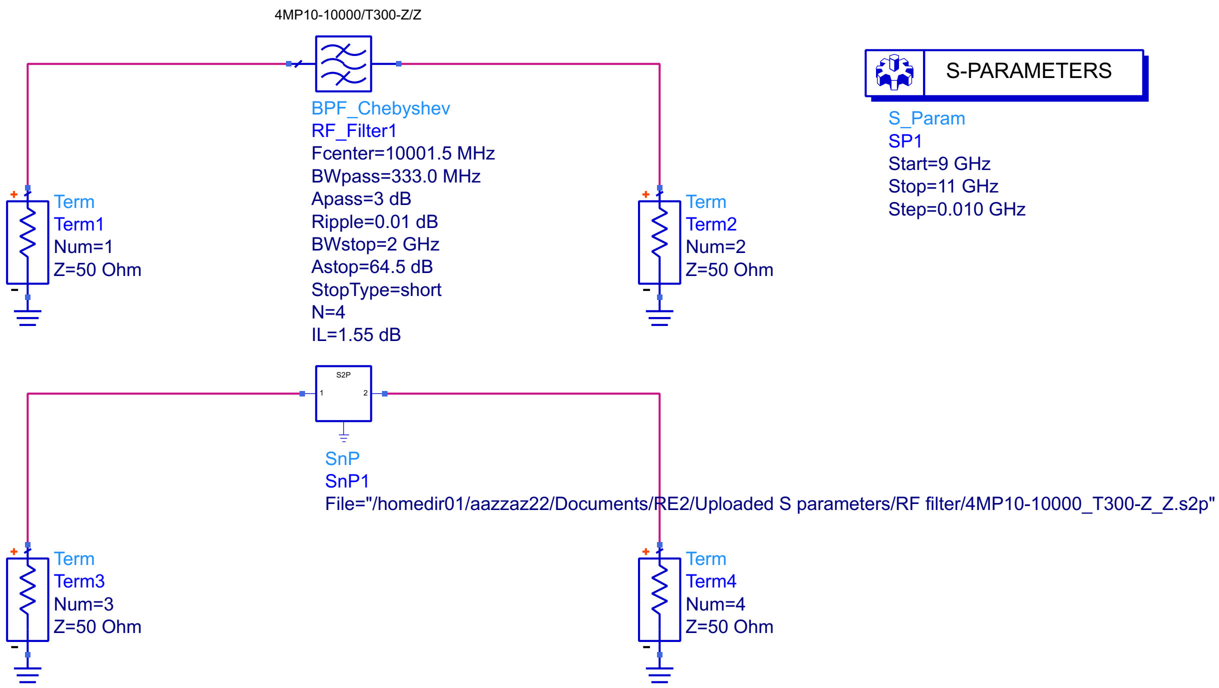


Figure 1.2: RF filter comparison test bench

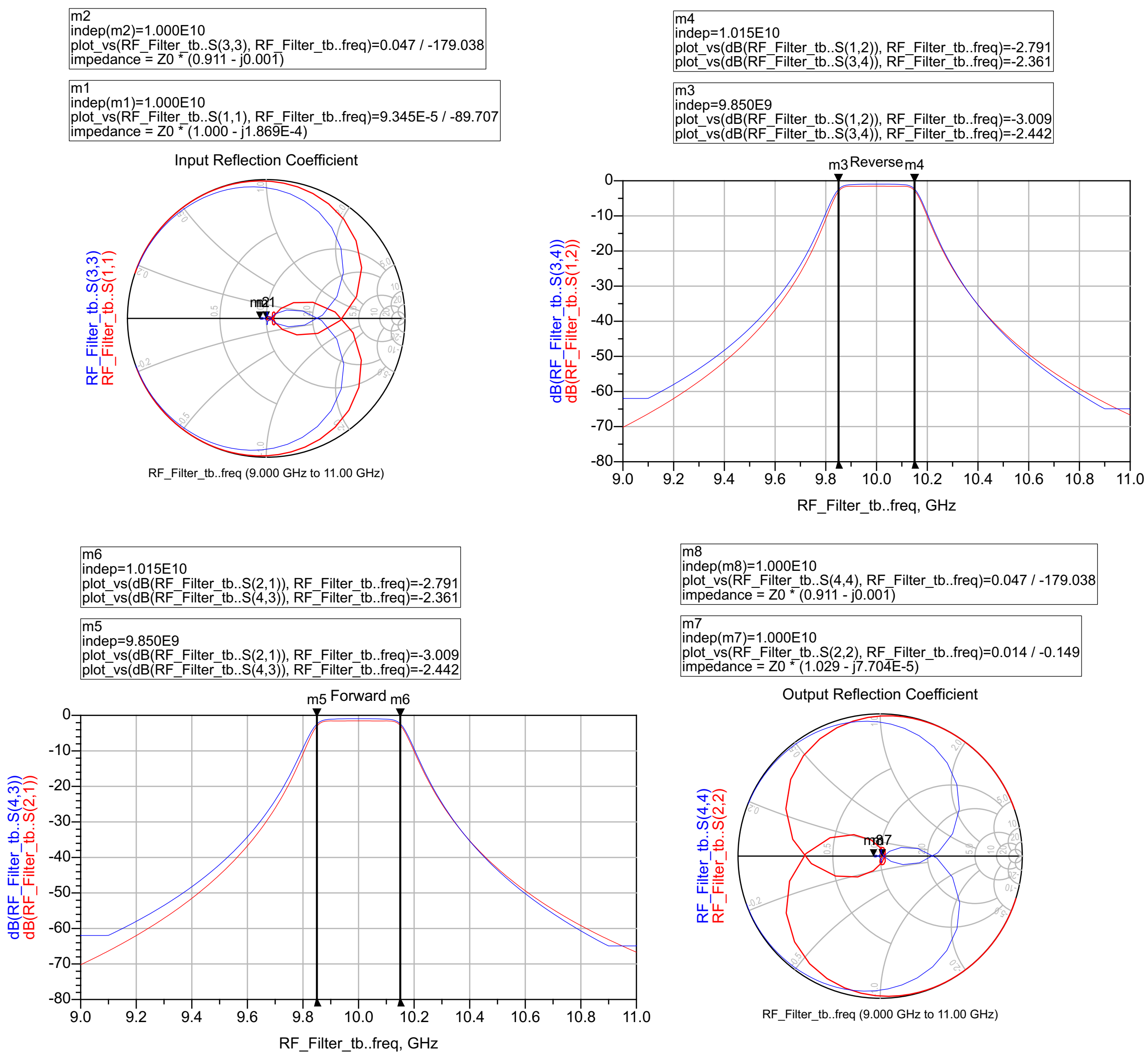
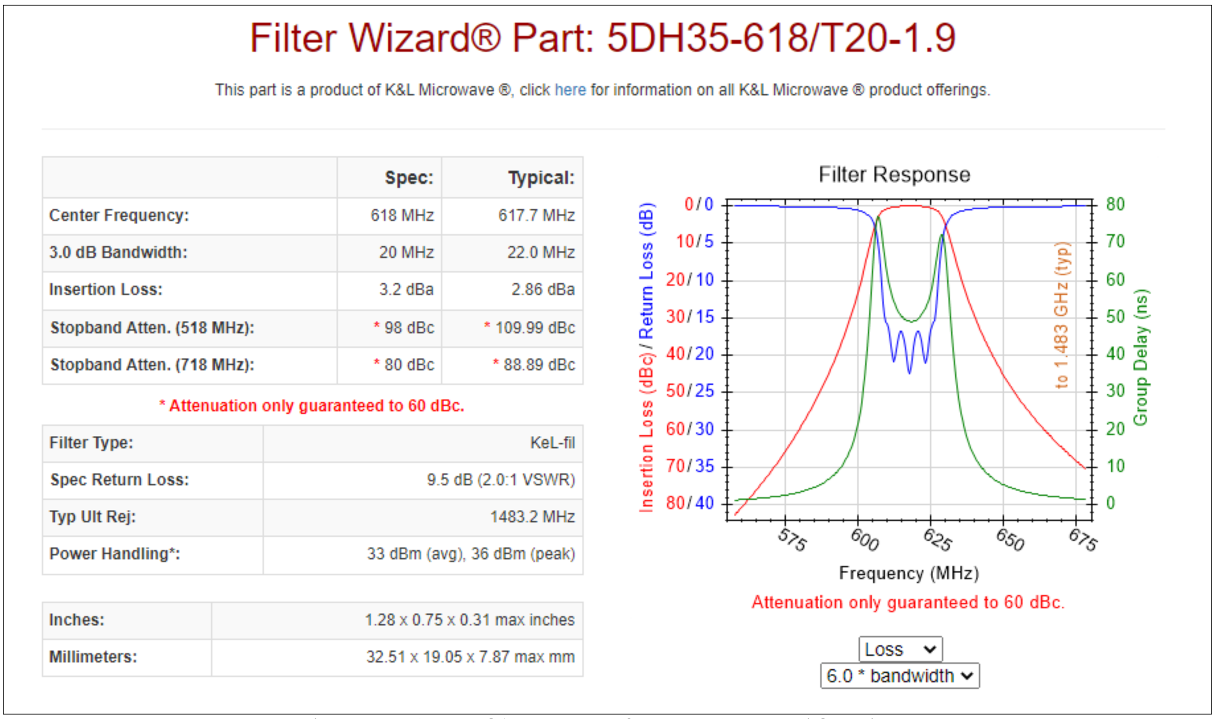


Figure 1.3: RF filter comparison results

1.2.1.2 IF filters

Similarly, the If filter has been selected to have a bandwidth of one channel (20 MHz) centered around the IF frequency (618 MHz) and a reasonable insertion loss. The filter with the part number 5DH35-618/T20-1.9 has been selected as it meets the specifications, as shown in Figure 1.4. The IF filter has been modeled in ADS using the Chebyshev filter model and tested against the s-parameters provided by the manufacturer, as shown in Figure 1.5, and its operation resembles the operation of the real filter, as shown in Figure 1.6.



	Spec:	Typical:
Center Frequency:	618 MHz	617.7 MHz
3.0 dB Bandwidth:	20 MHz	22.0 MHz
Insertion Loss:	3.2 dBa	2.86 dBa
Stopband Atten. (518 MHz):	* 98 dBc	* 109.99 dBc
Stopband Atten. (718 MHz):	* 80 dBc	* 88.89 dBc

* Attenuation only guaranteed to 60 dBc.

Filter Type:	KeL-fil
Spec Return Loss:	9.5 dB (2.0:1 VSWR)
Typ Ult Rej:	1483.2 MHz
Power Handling*:	33 dBm (avg), 36 dBm (peak)

Inches:	1.28 x 0.75 x 0.31 max inches
Millimeters:	32.51 x 19.05 x 7.87 max mm

Figure 1.4: IF filter manufacturer's specifications

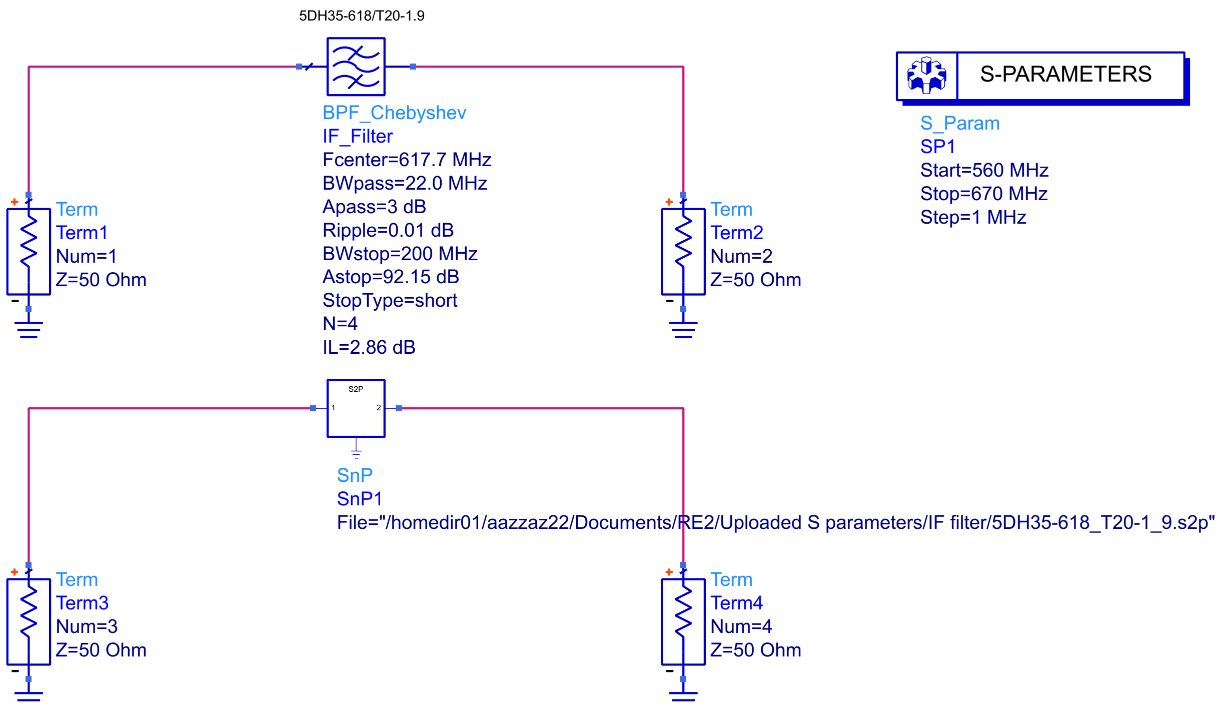


Figure 1.5: IF filter comparison test bench

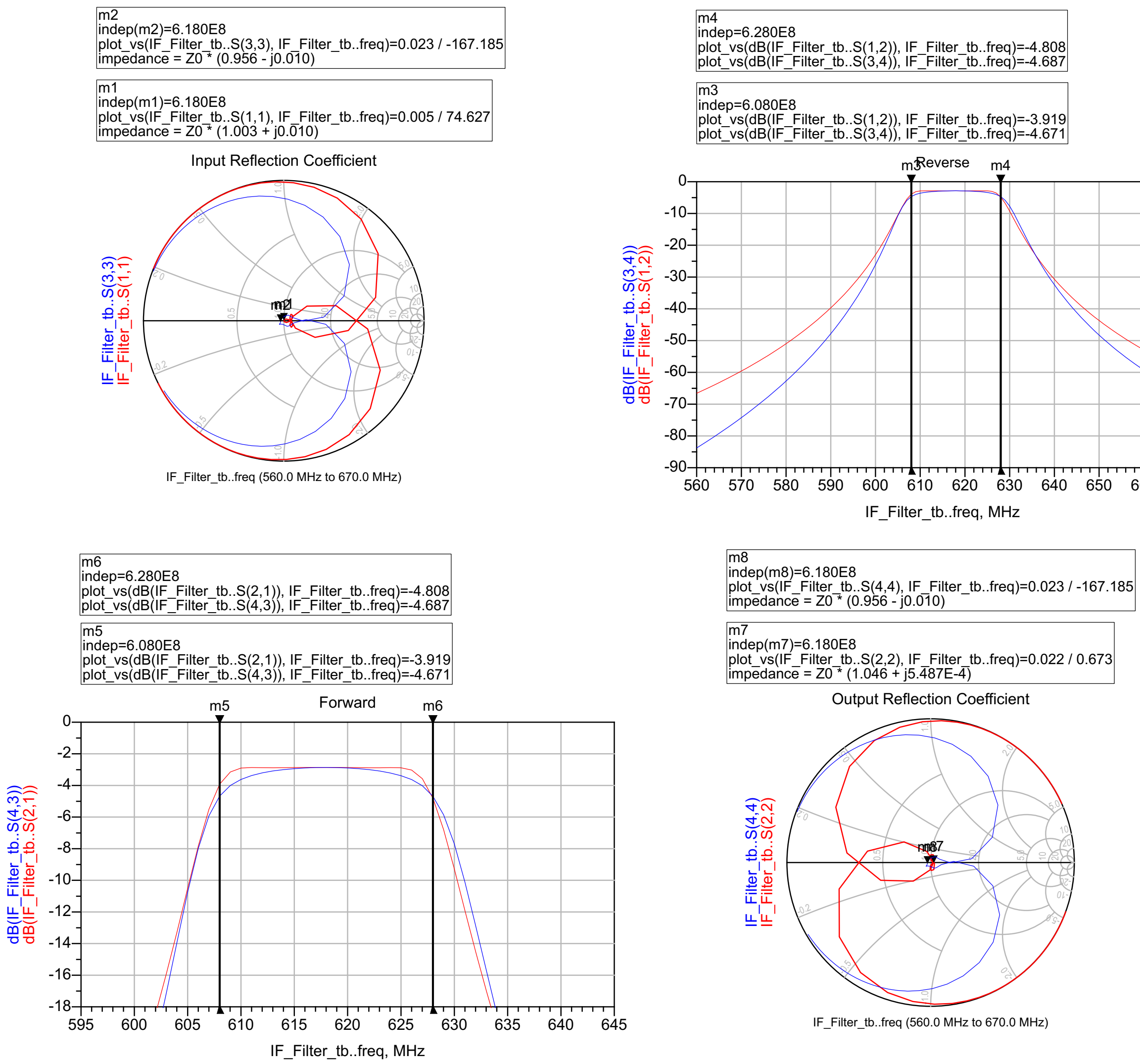


Figure 1.6: IF filter comparison results

There are minor differences between the response of modeled RF and IF filters and the manufacturer's response. The main difference is that the stop band rejection of the real filters is guaranteed only to 60 dBc but the modeled filters extends to 70 dBc and beyond. This difference might result in extra attenuation of any interference near the cutoff of the filters which might result in the simulation performing better than reality.

1.2.2 RF Amplifier (LNA)

The RF amplifier (LNA) is selected to operate over the system's total bandwidth and provide high enough gain with minimum noise figure deterioration. The selected amplifier has the part number NSM3-08001200-11 and its specs are shown in Figure 1.7. The RF amplifier has a surface mount package, as shown in Figure 1.8, with three leads and the body used as a ground.

Model	Quote	Freq Min (MHz)	Freq Max (MHz)	Gain Min (dB)	Gain Flatness (dB+/-)	Noise Figure (dB)	Noise Temperature (K)	Input VSWR	Output VSWR	P1dB Out (dBm)	IP3 Out Typ (dBm)	V1 Nom. (V)	Curr1 Nom (mA)	Data sheet
NSM3-08001200-11	Quote	8000	12000	24	1	1.1	84	2	2	8	18	15	80	PDF

Figure 1.7: RF amplifier manufacturer's specifications

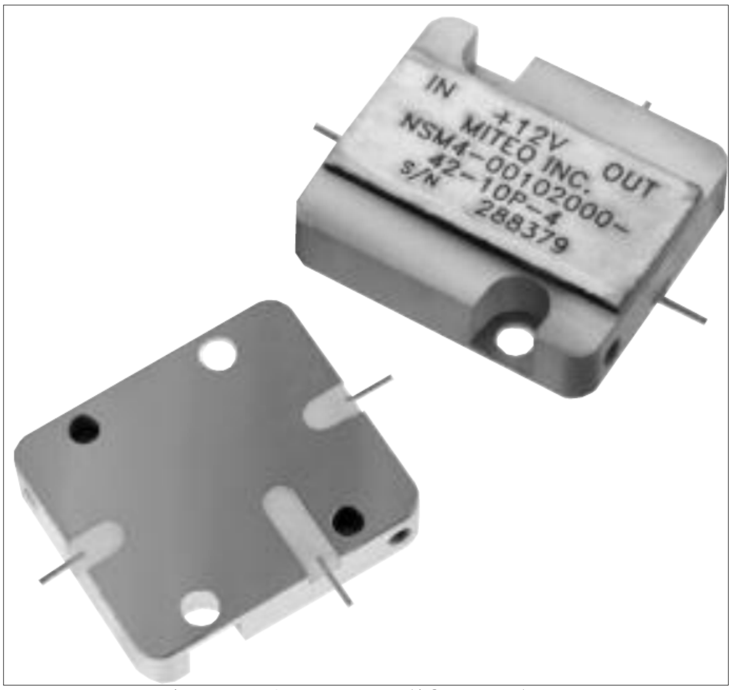


Figure 1.8: RF amplifier package

1.2.3 IF Amplifier

The IF amplifier is selected to operate over a single channel bandwidth and mainly provide high enough gain and higher compression point. The selected amplifier has the part number NSM3-00100200-14-10P-4 and its specs are shown in Figure 1.9. The mixer has two ranges for the LO power, the lower range of 10 dBm is selected The IF amplifier has the same package as the RF one, a surface mount package, as shown in Figure 1.8, with three leads and the body used as a ground.

Model	Quote	Freq Min (MHz)	Freq Max (MHz)	Gain Min (dB)	Gain Flatness (dB+/-)	Noise Figure (dB)	Noise Temperature (K)	Input VSWR	Output VSWR	P1dB Out (dBm)	IP3 Out Typ (dBm)	V1 Nom. (V)	Curr1 Nom (mA)	Data sheet
NSM3-00100200-14-10P-4	Quote	100	2000	30	1	1.4	111	2	2	10	20	15	150	PDF

Figure 1.9: IF amplifier manufacturer's specifications

1.2.4 Mixer

The mixer is selected to operate over the system's total RF bandwidth and provide low conversion loss with minimum noise figure deterioration. The selected mixer has the part number DB0418HW6 and its specs are shown in Figure 1.10. The mixer has a drop in substrate package, as shown in Figure 1.11, with three leads and the body used as a ground.

Model	Quote	RF Freq Min (MHz)	RF Freq Max (MHz)	LO Freq Min (MHz)	LO Freq Max (MHz)	IF Freq Min (MHz)	IF Freq Max (MHz)	Conversion Loss Typical dB	Conversion Gain Typical dB	LO to RF Isolation Typical (dB)	LO to IF Isolation Typical (dB)	RF to IF Isolation Typical (dB)	LO Power Min (dBm)	LO Power Typ (dBm)	LO Power Max (dBm)	IP3 In Typ (dBm)	IP3 Out Typ (dBm)	P1dB In Typ (dBm)	P1dB Out Typ (dBm)	RF VSWR Typical	LO VSWR Typical	IF VSWR Typical	Single Bal.	Double Bal.	Triple Bal.
DB0418HW6	Quote	4000	18000	4000	18000	0	2000	8		30	20	25	17	20	23	23	15	13	5	1.5	1.25	2	0	1	0

ble Bal.	Triple Bal.	Quad IF	Image Reject	Image Rejection (dB)	Low Noise	SSB Noise Figure Typical (db)	Sub Harmonic	Active Device	V1 Min (V)	V1 Nom. (V)	V1 Max (V)	Curr1 Nom (mA)	NxM 1X1 (dB)	NxM 1X2 (dB)	NxM 1X3 (dB)	NxM 2X1 (dB)	NxM 2x2 (dB)	NxM 2X3 (dB)	NxM 3X1 (dB)	NxM 3X2 (dB)	NxM 3X3 (dB)	Op. Temp Low (°C)	Op. Temp High (°C)	Package	Surface Mount	Package	Hermetic	ROHS	Outline Drawing
	0	0	0		0	7.5	0	0					0	-53	-57	-25	-60	-68	-12	-48	-55	-54	85	Drop In Substrate	0	Drop In Substrate	0	0	

Figure 1.10: Mixer manufacturer's specifications

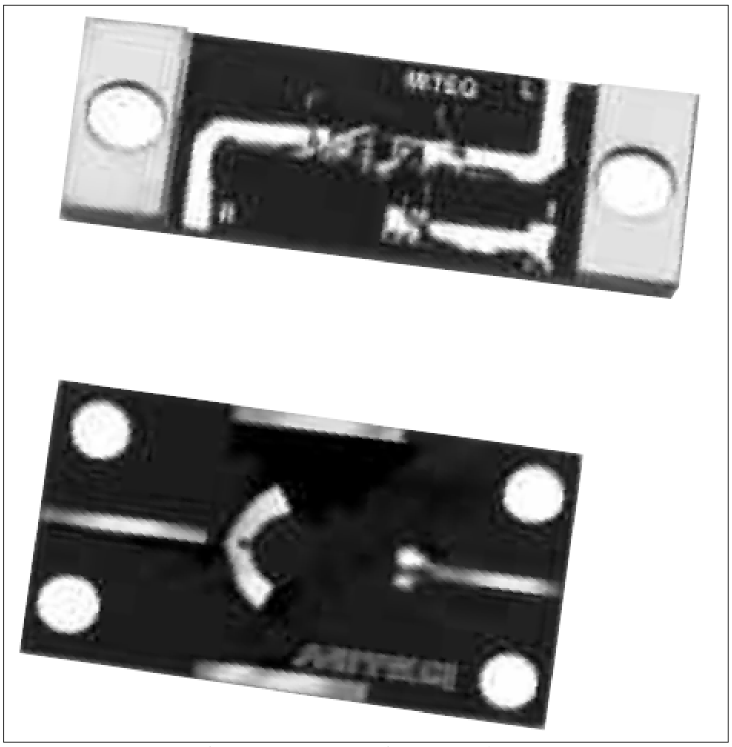


Figure 1.11: Mixer package

All the selected components for the receiver are surface mount devices with either pins (RF filters, RF and IF amplifiers, mixer) or castellated edges (mixer,IF filter) which restricted the components selection but this gives a more accurate idea about the performance of the receiver if it is implemented in reality.

1.3 Budget Simulation

The budget simulation is performed to determine the total gain, noise figure, output power and the 1 dB compression point of the receiver chain. Figure 1.12 shows the whole modeled receiver chain. Parameterization of the components is carried out as per the given typical specifications. Figures 1.13 and 1.14 show the results for the budget simulation. At the sensitivity level (-87 dBm), the results are:

- The output power is 12.898 dBm which surpasses the +4 dBm specified.
- The receiver noise figure is 3.018 dB which is well below the calculated 4.97 dB.
- The total gain of the receiver is 99.898 dB which is above the calculated 91 dB.
- The SNR of the receiver is 12.898 - 2.154 = 10.744 dB which meets the specified 9 dB.
- The output 1 dB compression point is 19.977 dB which surpasses the required +17 dBm.

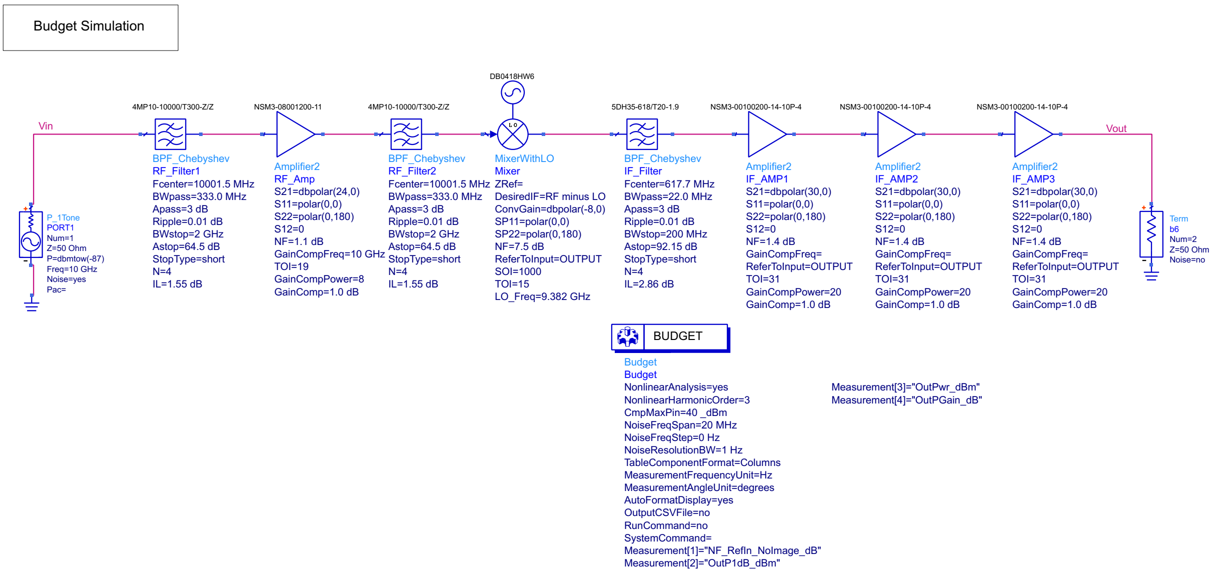


Figure 1.12: Budget simulation schematic

Measurements Tables

Meas_Name	RF_Filter1	RF_Amp	RF_Filter2
NF_RefIn_NoImage_dB	1.549	2.649	2.655
OutP1dB_dBm	1000.000	30.950	29.400
OutPwr_dBm	-88.550	-64.550	-66.100
OutPGain_dB	-1.550	22.450	20.900

Meas_Name	Mixer	IF_Filter
NF_RefIn_NoImage_dB	2.743	2.852
OutP1dB_dBm	4.337	1.477
OutPwr_dBm	-74.100	-76.960
OutPGain_dB	12.900	10.040

Meas_Name	IF_AMP1	IF_AMP2	IF_AMP3
NF_RefIn_NoImage_dB	2.936	2.936	2.936
OutP1dB_dBm	19.790	19.977	19.977
OutPwr_dBm	-46.960	-16.960	12.898
OutPGain_dB	40.040	70.040	99.898

Summary Tables

System_Name	System_Value
SystemInN0_dBm	-173.855
SystemInNPwr_dBm	-100.844
SystemInP1dB_dBm	-79.063
SystemNF_dB	3.018
SystemOutN0_dBm	-70.857
SystemOutNPwr_dBm	2.154
SystemOutP1dB_dBm	19.977
SystemPGain_SS_dB	100.040
SystemPGain_dB	99.898
SystemPOut_dBm	12.898
SystemS11_dB	-80.588
SystemS11_mag	9.345E-5
SystemS11_phase	-89.707
SystemS12_dB	-400.000
SystemS12_mag	0.000
SystemS12_phase	0.000
SystemS21_dB	99.898
SystemS21_mag	98829.416
SystemS21_phase	-5.675
SystemS22_dB	-315.399
SystemS22_mag	1.698E-16
SystemS22_phase	180.000

Setup_Name	Setup_Value
System_AnalysisType	1.000
System_NoiseResBW	1.000
System_NoiseSimBW	2.000E7
System_NoiseSimFStep	2.000E7
System_PilotFreq	1.000E10
System_PilotPwr_dBm	-87.000
System_RefR	50.000
System_SourceFreq	1.000E10
System_SourcePwr_dBm	-87.000
System_SourceTemp	25.000

Figure 1.13: Budget simulation results

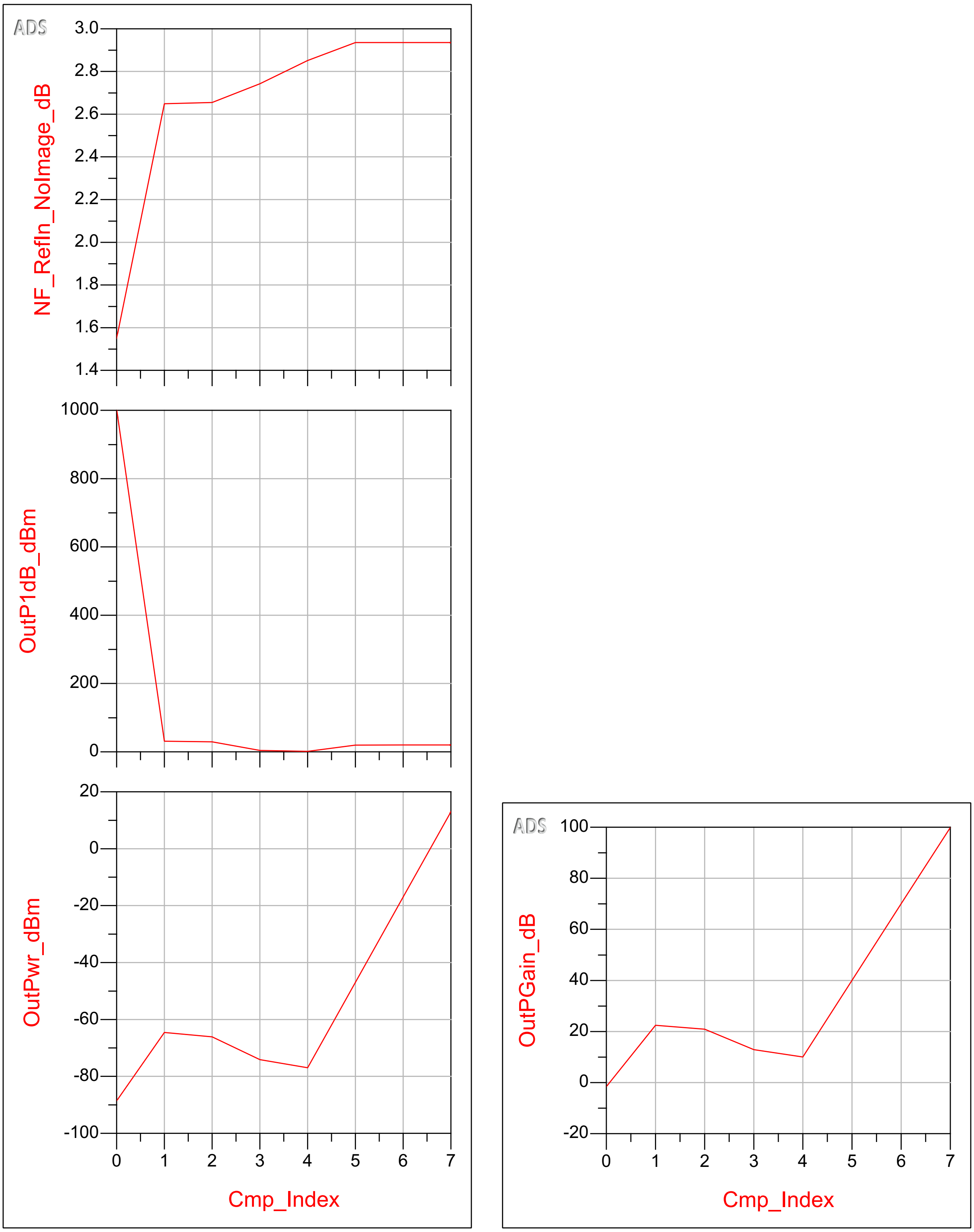


Figure 1.14: Budget simulation results in plots

In case of a -20 dBm input signal level, using the measured gain, the output signal would be + 79.898 dBm which surpasses the output 1dB compression point of the receiver. Therefore, for a -20 dBm input signal, the use of an AGC is mandatory to avoid the compression of the receiver by lower the gain of the RF or IF stages.

1.4 Spurious responses Simulation

A spurious response of a receiver refers to an unwanted, extraneous signal that is received by the receiver and interpreted as a valid signal. These signals are often generated by various sources, such as other transmitters operating on nearby frequencies, atmospheric or environmental conditions, or the internal components of the receiver itself.

Spurious responses can cause interference, distortion, and even complete loss of the desired signal. They are typically characterized by their frequency, amplitude, and phase, and can be minimized through careful design and testing of the receiver. Various techniques are used to mitigate spurious responses, including filtering, shielding, and frequency tuning. In this receiver, the second RF filter (RF_Filter2 in all the schematics) was added to attenuate the self-mixing of the LO due the finite LO to RF rejection.

1.4.1 $f_{IF} = 618\ MHz$

In this section, the receiver chain schematic from the budget simulation was used except the mixer model. The frequency of the local oscillator signal of the receiver is set to a value that is used if the receiver receives a useful signal at the center frequency of the system frequency band. The maximum level for the input signals causing spurious responses is -45 dBm. Performance criterion for the spurious responses at the output of the IF-stage must be below -95 dBm. For the spurious response test shown in Figure 1.15, three frequencies were used, $f_{IF} = 618MHz$, $f_{LO} = 9.382GHz$, and RF frequency was set at the image $f_{Image} = f_{LO} - f_{IF} = 8.764GHz$. In addition, the center frequency of the IF filter was changed to 200 MHz.

As shown in Figure 1.16, all the spurious responses are well below the specified -95 dBm and with lower spurious tones than the previous test.

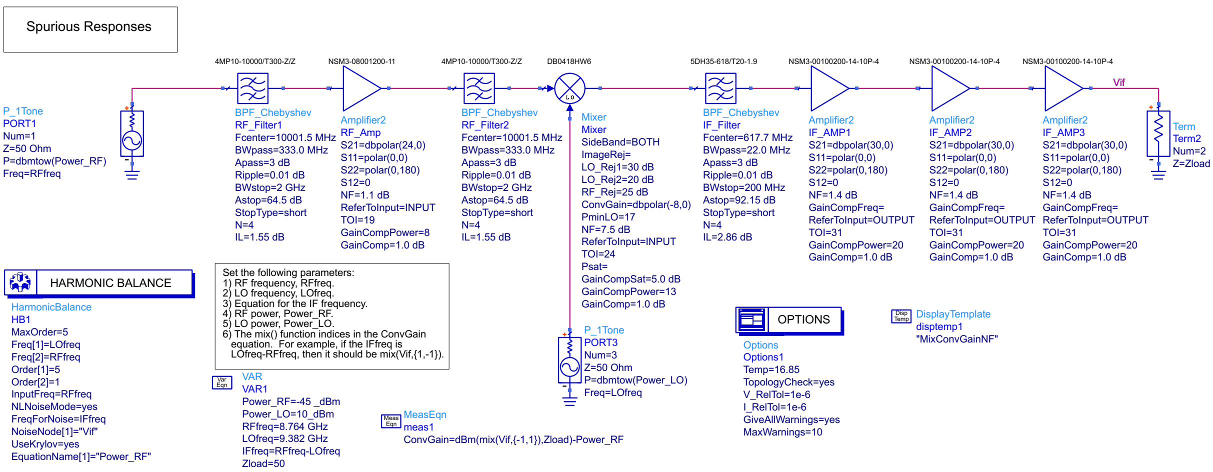


Figure 1.15: Spur simulation schematic with $f_{IF} = 618MHz$

1.4.2 $f_{IF} = 200\ MHz$

In this section, the previous spurious response test is repeated with a 200 MHz IF frequency. For the test shown in Figure 1.17, three frequencies were used, $f_{IF} = 200MHz$, $f_{LO} = 9.8GHz$, Eqn IF_spectrum=dBm(HB.Vif)

freq	Mix	
	Mix(1)	Mix(2)
0.0000 Hz	0	0
618.0 MHz	1	-1
8.764 GHz	0	1
9.382 GHz	1	0
10.00 GHz	2	-1
18.15 GHz	1	1
18.76 GHz	2	0
19.38 GHz	3	-1
27.53 GHz	2	1
28.15 GHz	3	0
28.76 GHz	4	-1
36.91 GHz	3	1
37.53 GHz	4	0
46.29 GHz	4	1
46.91 GHz	5	0

freq	IF_spectrum
0.0000 Hz	-433.061
618.0 MHz	-103.484
8.764 GHz	-327.454
9.382 GHz	-137.534
10.00 GHz	-430.976
18.15 GHz	-341.321
18.76 GHz	-185.312
19.38 GHz	-441.984
27.53 GHz	-405.474
28.15 GHz	-426.257
28.76 GHz	-427.420
36.91 GHz	-434.677
37.53 GHz	-306.962
46.29 GHz	-430.089
46.91 GHz	-436.783

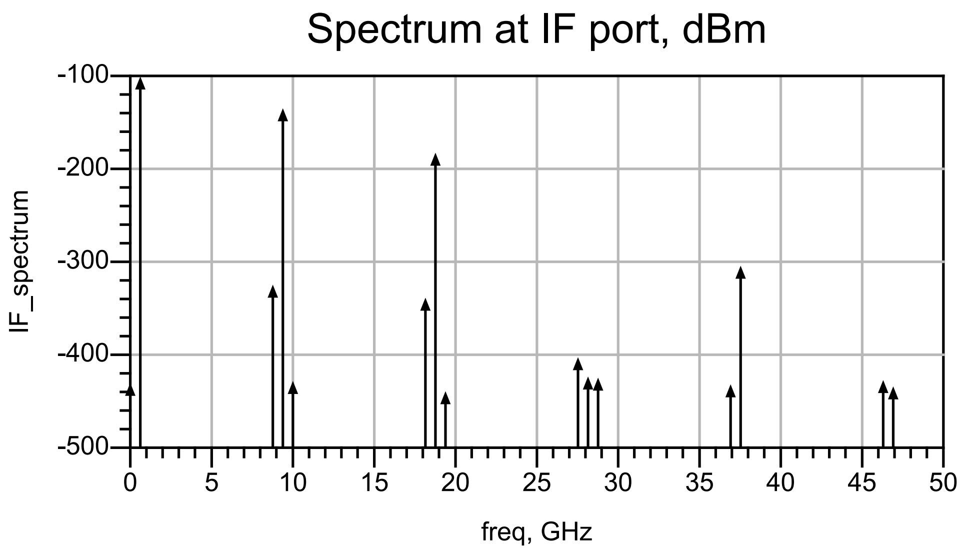


Figure 1.16: Spur simulation results with $f_{IF} = 618MHz$

and RF frequency was set at the image $f_{Image} = f_{LO} - f_{IF} = 9.6GHz$.

As shown in Figure 1.18, not the spurious responses are below the specified -95 dBm. The result IF signal at 200 MHz is setting at -20.806 dBm. By reducing the IF frequency, the frequency of the image spur will also be reduced and it will fall closer to the RF signal. Thus, the image signal will be closer to the center of the RF filters and it will experience less attenuation and it would fold/mix down with the LO and resulting in a higher IF spur.

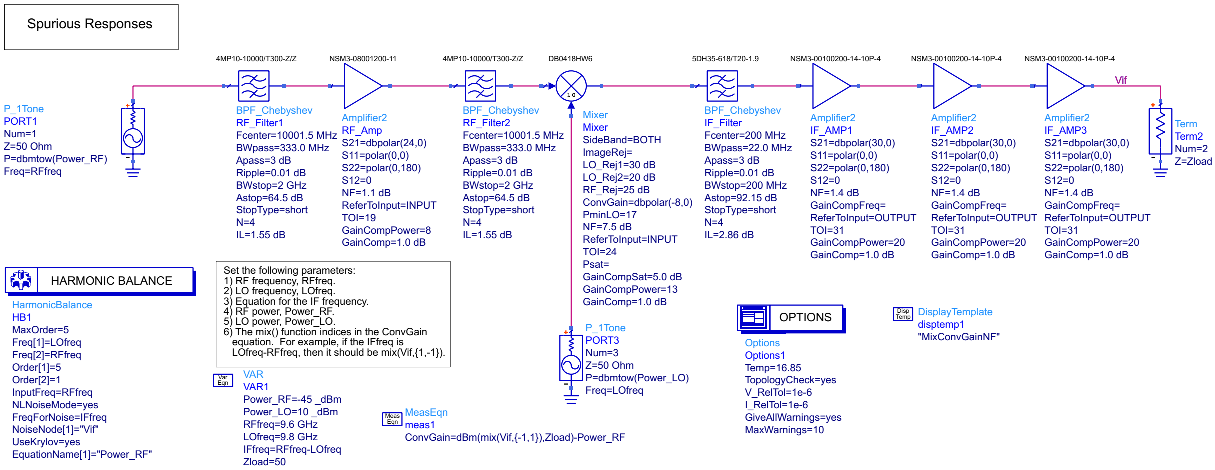


Figure 1.17: Spurious responses simulation schematic with $f_{IF} = 200MHz$

Eqn IF_spectrum=dBm(HB.Vif)

freq	Mix	
	Mix(1)	Mix(2)
0.0000 Hz	0	0
200.0 MHz	1	-1
9.600 GHz	0	1
9.800 GHz	1	0
10.00 GHz	2	-1
19.40 GHz	1	1
19.60 GHz	2	0
19.80 GHz	3	-1
29.20 GHz	2	1
29.40 GHz	3	0
29.60 GHz	4	-1
39.00 GHz	3	1
39.20 GHz	4	0
48.80 GHz	4	1
49.00 GHz	5	0

freq	IF_spectrum
0.0000 Hz	-349.623
200.0 MHz	-20.806
9.600 GHz	-242.782
9.800 GHz	-139.376
10.00 GHz	-349.237
19.40 GHz	-261.000
19.60 GHz	-133.966
19.80 GHz	-340.695
29.20 GHz	-242.978
29.40 GHz	-346.153
29.60 GHz	-348.110
39.00 GHz	-249.163
39.20 GHz	-310.074
48.80 GHz	-356.302
49.00 GHz	-348.274

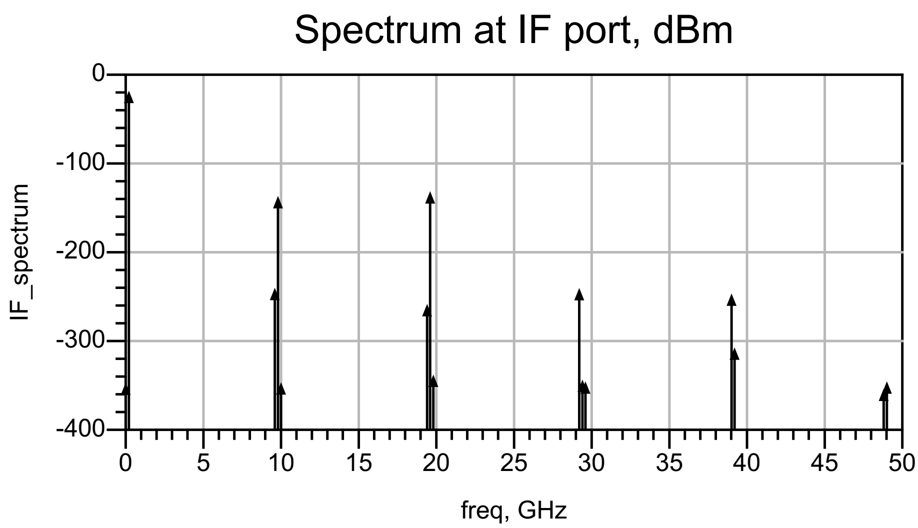


Figure 1.18: Spurious responses simulation results with $f_{IF} = 200MHz$

1.5 TOI Simulation

The third-order intercept point (IP3/TOI) is a measure of the linearity of a system or device, such as an amplifier or a mixer. It is defined as the point at which the third-order intermodulation products (IM3) generated by two input signals become equal in power to the fundamental signal. In other words, the third-order intercept point is the input power level at which the third-order intermodulation products generated by two input signals will be equal in power to the desired signal. A higher third-order intercept point indicates better linearity and less distortion in the device.

Two input signals both at level -40 dBm are fed to the input connector of the antenna. The frequency of the first signal is 10 MHz and the frequency of the second signal is 20 MHz away from the carrier frequency (10 GHz) so that they both are located on the same side in frequency band in respect to the carrier frequency. Hence the two input tones at the frequencies of 10010 MHz and 10020 MHz were used, as shown in Figure 1.19.

The result of the TOI, Figure 1.19 is shown in Figure 1.21 and the equations used to obtain these results are presented in Figure 1.20. The equations were configured to measure the high and lower TOIs by setting the input arguments to the *Mix* function (*TOIoutput_low* and *TOIoutput_high* equations). From the results, the output referred TOIs are 10.46 dBm which meets the specified +9 dBm. When referring the TOIs to the input, we get 0 dBm.

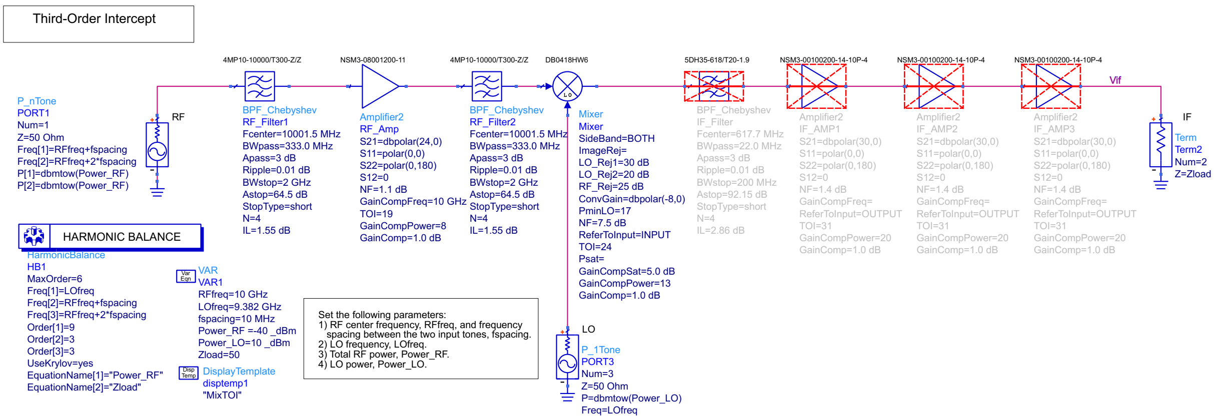


Figure 1.19: TOI simulation schematic

Eqn Order=abs(Mix(1))+abs(Mix(2))+abs(Mix(3))

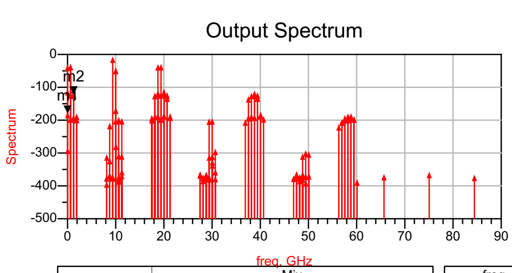
Eqn TOIoutput_high=1.5*dBm(mix(Vif,{-1,0,1}),Zload)-0.5*dBm(mix(Vif,{-1,-1,2}),Zload)
Eqn TOIoutput_low=1.5*dBm(mix(Vif,{-1,1,0}),Zload)-0.5*dBm(mix(Vif,{-1,2,-1}),Zload)

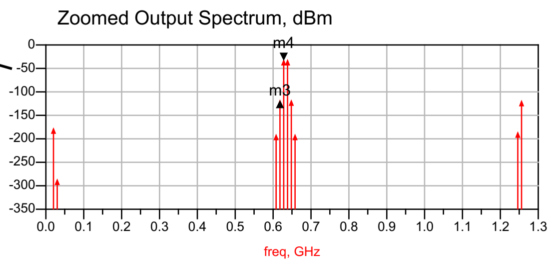
Eqn TOIinput_low =TOIoutput_low-P_gain_transducer
Eqn TOIinput_high=TOIoutput_high-P_gain_transducer
Eqn Spectrum=dBm(Vif,Zload[0])
Eqn P_gain_transducer=Pload_dBm-(Power_RF)

Eqn m1index=find_index(freq,indep(m1))
Eqn m2index=find_index(freq,indep(m2))
Eqn low_index=if (m1index<m2index) then m1index else m2index
Eqn high_index=if (m2index>m1index) then m2index else m1index

Eqn Pload_W1=0.5*(mag(mix(Vif,{-1,1,0}))**2) *real(1/Zload)
Eqn Pload_W2=0.5*(mag(mix(Vif,{-1,0,1}))**2) *real(1/Zload)
Eqn Pload_dBm=10*log(Pload_W1 +Pload_W2)+30

Figure 1.20: TOI simulation equations





m4
freq=628.0 MHz
Spectrum[low_index::high_index]=-32.551

m3
ind Delta=-10.000E6
dep Delta=-86.025
Delta Mode ON

Fundamental Frequencies	Available Source Power From Both Fundamentals dBm	Output Power in Both Fundamentals dBm	Conversion Gain, dB
628.0000 M 638.0000 M	-40.00	-29.542	10.458

Low and High Side Output TOI Points, dBm		Low and High Side Input TOI Points, dBm	
10.462	10.459	0.003	0.001

These become invalid as the mixer is driven into compression.

freq	Mix		
	Mix(1)	Mix(2)	Mix(3)
0.0000 Hz	0	0	0
10.000 MHz	0	-1	1
20.00 MHz	0	-2	2
30.00 MHz	0	-3	3
608.0 MHz	-1	3	-2
618.0 MHz	-1	2	-1
628.0 MHz	-1	1	0
638.0 MHz	-1	0	1
648.0 MHz	-1	-1	2
658.0 MHz	-1	-2	3
1.246 GHz	-2	3	-1
1.256 GHz	-2	2	0
1.266 GHz	-2	1	1
1.276 GHz	-2	0	2
1.286 GHz	-2	-1	3
1.884 GHz	-3	3	0
1.894 GHz	-3	2	1
1.904 GHz	-3	1	2
1.914 GHz	-3	0	3
8.106 GHz	3	0	-2
8.116 GHz	3	-1	-1
8.126 GHz	3	-2	0
8.734 GHz	2	1	-2
8.744 GHz	2	0	-1
8.754 GHz	2	-1	0
8.764 GHz	2	-2	1
9.362 GHz	1	2	-2
9.372 GHz	1	1	-1
9.382 GHz	1	0	0
9.392 GHz	1	-1	1
9.402 GHz	1	-2	2
9.990 GHz	0	3	-2
10.00 GHz	0	2	-1
10.01 GHz	0	1	0
10.02 GHz	0	0	1
10.03 GHz	0	-1	2
10.04 GHz	0	-2	3
10.63 GHz	-1	3	-1
10.64 GHz	-1	2	0
10.65 GHz	-1	1	1
10.66 GHz	-1	0	2
10.67 GHz	-1	-1	3
11.27 GHz	-2	3	0
11.28 GHz	-2	2	1
11.29 GHz	-2	1	2
11.30 GHz	-2	0	3
17.49 GHz	4	0	-2
17.50 GHz	4	-1	-1
17.51 GHz	4	-2	0
18.12 GHz	3	1	-2
18.13 GHz	3	0	-1
18.14 GHz	3	-1	0
18.15 GHz	3	-2	1
18.74 GHz	2	2	-2
18.75 GHz	2	1	-1
18.76 GHz	2	0	0

freq	Spectrum
0.0000 Hz	-34.620
10.000 MHz	-108.763
20.00 MHz	-178.165
30.00 MHz	-287.143
608.0 MHz	-191.713
618.0 MHz	-118.576
628.0 MHz	-32.551
638.0 MHz	-32.553
648.0 MHz	-118.578
658.0 MHz	-191.848
1.246 GHz	-186.524
1.256 GHz	-119.628
1.266 GHz	-113.613
1.276 GHz	-119.632
1.286 GHz	-186.885
1.884 GHz	-193.408
1.894 GHz	-183.868
1.904 GHz	-183.870
1.914 GHz	-193.415
8.106 GHz	-389.621
8.116 GHz	-371.426
8.126 GHz	-307.588
8.734 GHz	-361.714
8.744 GHz	-364.366
8.754 GHz	-318.690
8.764 GHz	-211.609
9.362 GHz	-369.078
9.372 GHz	-367.191
9.382 GHz	-9.866
9.392 GHz	-370.622
9.402 GHz	-371.363
9.990 GHz	-197.632
10.00 GHz	-165.207
10.01 GHz	-44.101
10.02 GHz	-44.103
10.03 GHz	-165.207
10.04 GHz	-274.835
10.63 GHz	-193.678
10.64 GHz	-302.735
10.65 GHz	-380.612
10.66 GHz	-373.439
10.67 GHz	-366.607
11.27 GHz	-197.700
11.28 GHz	-304.705
11.29 GHz	-352.286
11.30 GHz	-364.044
17.49 GHz	-194.312
17.50 GHz	-188.289
17.51 GHz	-194.307
18.12 GHz	-183.881
18.13 GHz	-120.530
18.14 GHz	-120.527
18.15 GHz	-183.879
18.74 GHz	-183.016
18.75 GHz	-113.614
18.76 GHz	-33.450
18.77 GHz	-113.614

Figure 1.21: TOI simulation results

1.6 Extra tasks

1.6.1 TOI measurements with the IF filter

In this tasks, the TOI simulation is performed again but with the IF filter being enables as shown in Figure 1.22. All the measurement equations were kept as the previous TOI simulation, as presented in Figure 1.20.

The results of this TOI measurements are shown in Figure 1.23. When adding the IF filter, there's a noticeable decrease in the TOI (about 10 dB decrease).

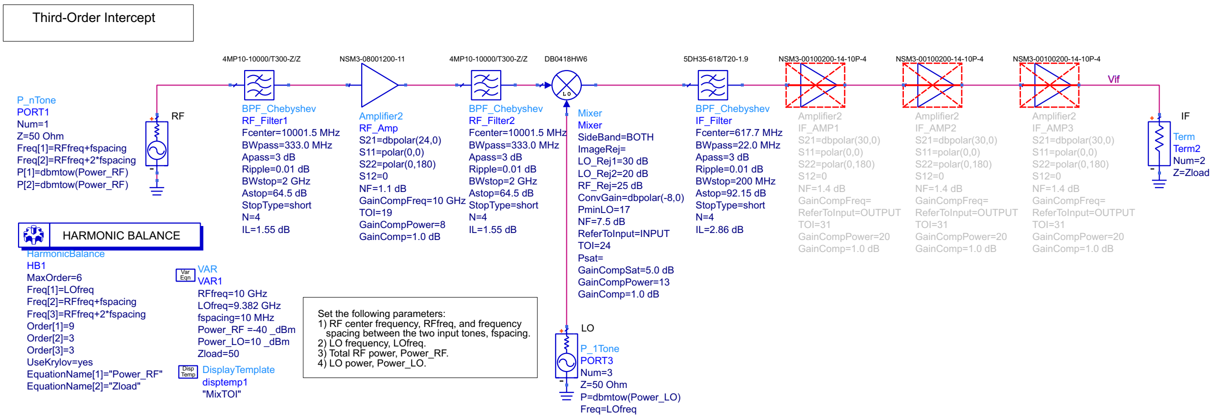


Figure 1.22: TOI simulation schematic with enabled IF filter

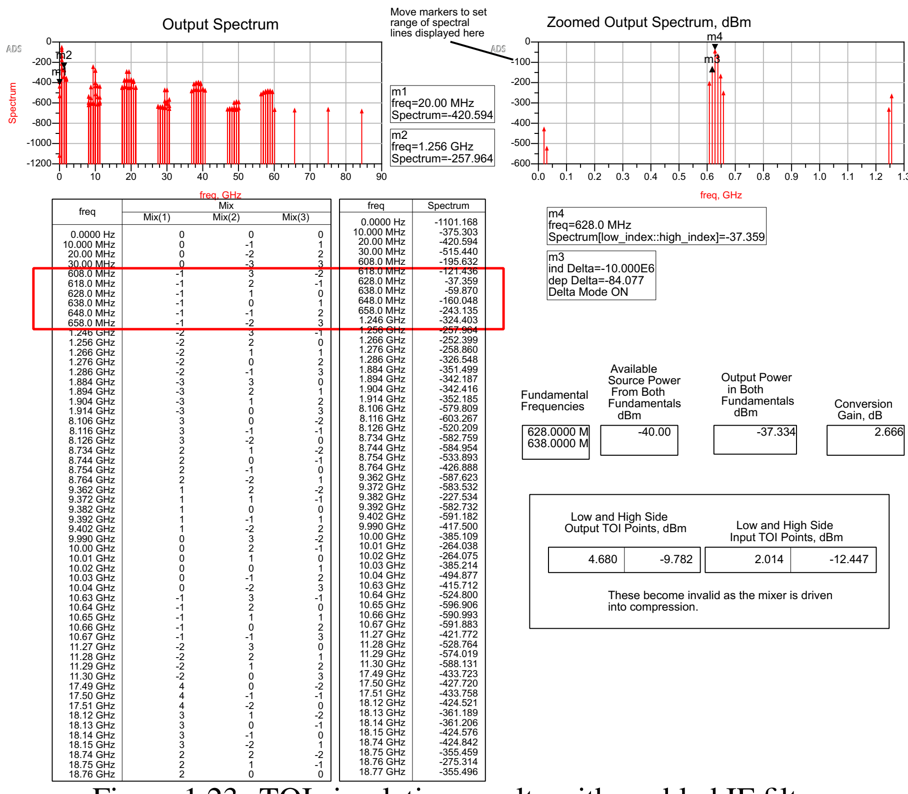


Figure 1.23: TOI simulation results with enabled IF filter

1.6.2 Equivalent noise bandwidth of the IF filter

In this task, the equivalent noise bandwidth of the IF filter is examined using the budget simulation. The simulation controller was configured to measure the noise bandwidth of the DUT, as shown in Figure 1.24.

The equivalent noise bandwidth is a measure of the effective noise bandwidth of the filter. It represents the bandwidth of an ideal rectangular filter that would produce the same level of noise power as the IF filter. The bandwidth obtained from the simulation results, shown in Figure 1.25 is 22.44 MHz which is a bit higher than the actual bandwidth of the IF filter.

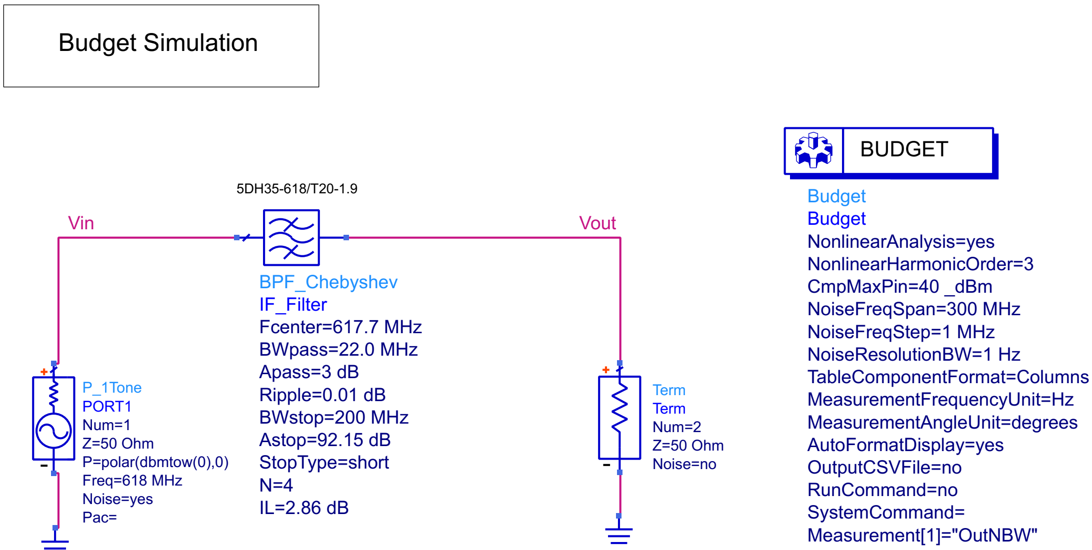


Figure 1.24: Budget simulation setup for the equivalent noise bandwidth of the IF filter

Meas_Name	IF_Filter
OutNBW	2.244E7

Setup_Name	Setup_Value
System_AnalysisType	1.000
System_NoiseResBW	1.000
System_NoiseSimBW	3.000E8
System_NoiseSimFStep	1.000E6
System_PilotFreq	6.180E8
System_PilotPwr_dBm	-6.268E-15
System_RefR	50.000
System_SourceFreq	6.180E8
System_SourcePwr_dBm	-6.268E-15
System_SourceTemp	25.000

System_Name	System_Value
SystemInN0_dBm	-173.855
SystemInNPwr_dBm	-89.083
SystemInP1dB_dBm	1000.000
SystemInSOI_dBm	1000.000
SystemInTOI_dBm	1000.000
SystemNF_dB	2.858
SystemOutN0_dBm	-173.914
SystemOutNPwr_dBm	-100.404
SystemOutP1dB_dBm	1000.000
SystemOutSOI_dBm	1000.000
SystemOutTOI_dBm	1000.000
SystemPGain_SS_dB	-2.860
SystemPGain_dB	-2.860
SystemPOut_dBm	-2.860
SystemS11_dB	-46.026
SystemS11_mag	0.005
SystemS11_phase	74.627
SystemS12_dB	-2.860
SystemS12_mag	0.719
SystemS12_phase	-5.899
SystemS21_dB	-2.860
SystemS21_mag	0.719
SystemS21_phase	-5.899
SystemS22_dB	-33.019
SystemS22_mag	0.022
SystemS22_phase	0.673

Figure 1.25: Budget simulation results for the IF filter

2 Transmitter Design

2.1 Transmitter specifications

To begin, the different system specifications of the receiver should be determined.
The main specifications of the receiver were given as:

- Data rate 32 Mbit/s
- Symbol rate 16 Msym/s.
- Center frequency of the system tuning range 10 GHz.
- Bandwidth of the main lobe between first nulls of the pulse shaped signal 20 MHz.
- Transmitter uses square-root raised cosine pulse shaping with the roll-off factor $\alpha = 0.25$.
- The system has 15 channels.
- ACPR of the transmitted signal must be at least -52 dBc in the channels adjacent to the main channel.
- Power of the useful signal must be at least +9 dBm.
- The rms-value of the error vector (EVM) must be under 5 %.

Similar to the receiver, the total bandwidth of the transmitter is

$$BW = \text{Number of channels} \times BW_{\text{Single Channel}} \implies BW = 300MHz$$

The roll off factor α is a parameter used in the design of the Square Root Raised Cosine pulse shaping filter, which is commonly used in digital communication systems to reduce the bandwidth of transmitted signals. The roll off factor determines the shape of the filter's frequency response, particularly how quickly the filter's frequency response rolls off to zero as the frequency increases. A higher roll off factor leads to a faster roll off, which results in a narrower bandwidth for the filtered signal, but also causes greater inter-symbol interference (ISI) between adjacent symbols. On the other hand, a lower roll off factor leads to a slower roll off, which results in a wider bandwidth for the filtered signal, but also reduces ISI. In general, the choice of roll off factor depends on the specific requirements of the communication system, such as the desired spectral efficiency, noise immunity, and channel characteristics. A typical value for the roll off factor in a communication system using SRRC pulse shaping is between 0 and 1, with higher values resulting in more aggressive filtering and lower values resulting in less aggressive filtering. The roll-off factor α of all SRRC filters in the transmitter is calculated as follows:

$$BW_{Channel} = \frac{1+\alpha}{T_{Symbol}} \implies \alpha = BW_{Channel}T_{Symbol} - 1 = \frac{BW_{Channel}}{Symbol\ Rate} - 1 = 0.25$$

2.2 Transmitter components selection

2.2.1 RF Amplifier

The transmitter amplifier is mostly optimized for high linearity and high output power. Accordingly, the power amplifier is needed to be selected to ensure a high linearity at high transmit power.

The amplifier with the part number LNA-40-08001200-30-20P is selected as the transmit amplifier PA as it meets all the required transmitter specifications (system bandwidth and frequency, high P_{1dB} and gain), as shown in Figure 2.1. Its TOI was set 11 dB higher than its 1dB compression to ensure the Convergence of the amplifier Chebyshev polynomial model. The PA has a metallic package with a connectorized interface for the input and output as shown in Figure 2.2.

Model	Quote	Freq Min (MHz)	Freq Max (MHz)	Gain Min (dB)	Gain Flatness (dB+/-)	Noise Figure (dB)	Noise Temperature (K)	Input VSWR	Output VSWR	P1dB Out (dBm)	IP3 Out Typ (dBm)	V1 Nom. (V)	Curr1 Nom (mA)	Data sheet
LNA-40-08001200-30-20P	Quote	8000	12000	40	1.5	3	0	2	2	20		15	325	PDF

Figure 2.1: PA manufacturer's specifications

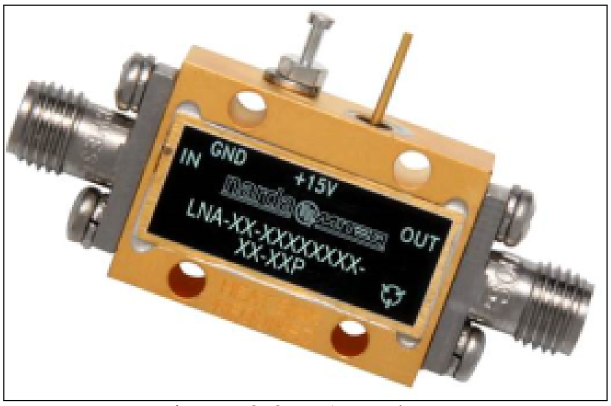


Figure 2.2: PA package

2.3 ACPR Test

ACPR stands for "Adjacent Channel Power Ratio", which is a measure of the amount of power that is emitted by a communication system in a frequency band adjacent to the primary frequency band. It is a critical parameter in wireless communication systems, particularly those that operate in frequency bands that are closely spaced. The ACPR is calculated by comparing the total power in a specified adjacent channel to the total power in the primary channel. It is typically expressed in decibels (dB) and is defined as the ratio of the power in the adjacent channel to the power in the primary channel, with a specified offset frequency.

In this transmitter, the ACPR schematic (test bench) shown in Figure 2.3 is configured to transmit as per the system specifications by setting the different variables and parameters in the Envelope simulation controller and other blocks.. The test bench simulates two paths. First, the ideal/undistorted path with only transmit and receive side filtering and is used to determine the ideal EVM and constellation points. Second, the real path with transmit and receive side filtering and the PA parametrized model, and this path is divided in the receive side into the lower, main, and upper channels. The available source power was set to -30 dBm in this simulation (see section 2.4 for details).

The results of the ACPR simulation are shown in Figures 2.4, 2.5, and 2.6 with the modified measurement expressions. The main channel power is 9.673 dBm which meets the specified minimum 9 dBm. All the ACPR measurements meets the specified maximum -52 dBc, since the upper and lower transmit ACPRs are -53.5 dBc and the lower and upper receive ACPRs are -57 dBc. There's about 4.5 dB of difference when including the transmit filtering.

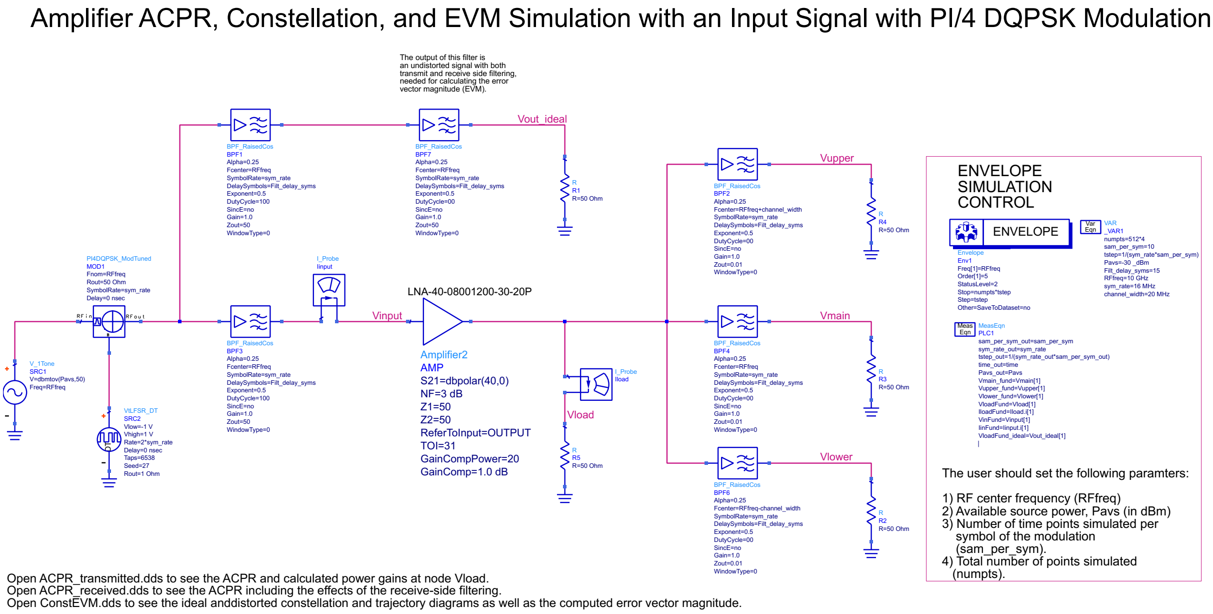
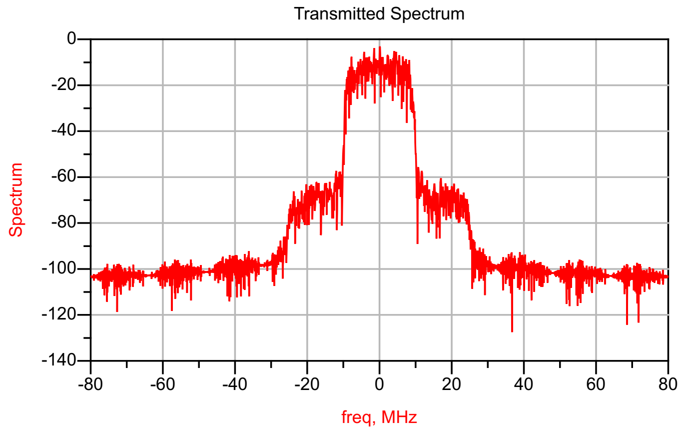
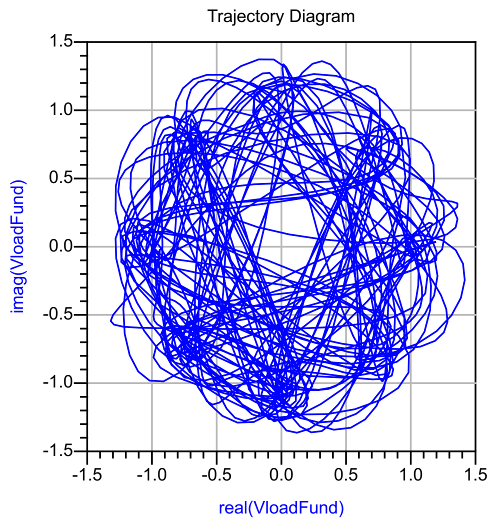


Figure 2.3: ACPR test schematic with a single valued of *Pavs*





Eqn Spectrum=dBm(fs(VloadFund,,,,,"Kaiser"))

Adjacent-Channel Power Ratio Calculations

Eqn mainlimits={-10 MHz,10 MHz}
Eqn UpChlimits={mainlimits+20 MHz}
Eqn LoChlimits={mainlimits-20 MHz}

The channel frequency limits are specified as an offset from the RF carrier frequency.

Lower Channel ACPR	Upper Channel ACPR
TransACPR(1)	TransACPR(2)
-53.509	-53.571

Eqn TransACPR=acpr_vi(VloadFund,IloadFund,mainlimits,LoChlimits,UpChlimits,"Kaiser")

Power Gain Calculations

Eqn Main_Channel_Power=channel_power_vi(VloadFund,IloadFund,mainlimits,"Kaiser")
Eqn Main_Channel_Power_dBm=10*log(Main_Channel_Power) +30

Eqn AveragePowerIn=mean(0.5*real(VinFund*conj(IinFund)))
Eqn Gain_transducer=Main_Channel_Power_dBm - Pavs_out
Eqn Gain_operating=10*log(Main_Channel_Power/AveragePowerIn)

Main_Channel_Power_dBm
9.927

Gain_transducer	Gain_operating
39.927	39.920

Gain_transducer is the ratio in dB of the power delivered to the load divided by the power available from the source. Gain_operating is the ratio in dB of the power delivered to the load divided by the power delivered to the amplifier. In this case, the amplifier's input impedance is 50 ohms, so both gains are identical.

See the ACPR_received.dds file to see the ACPR of the received signal (including the receive-side filtering). See also the ConstEVM.dds file to see the constellations and EVM calculation.

Figure 2.4: ACPR simulation results without receive side filtering effects

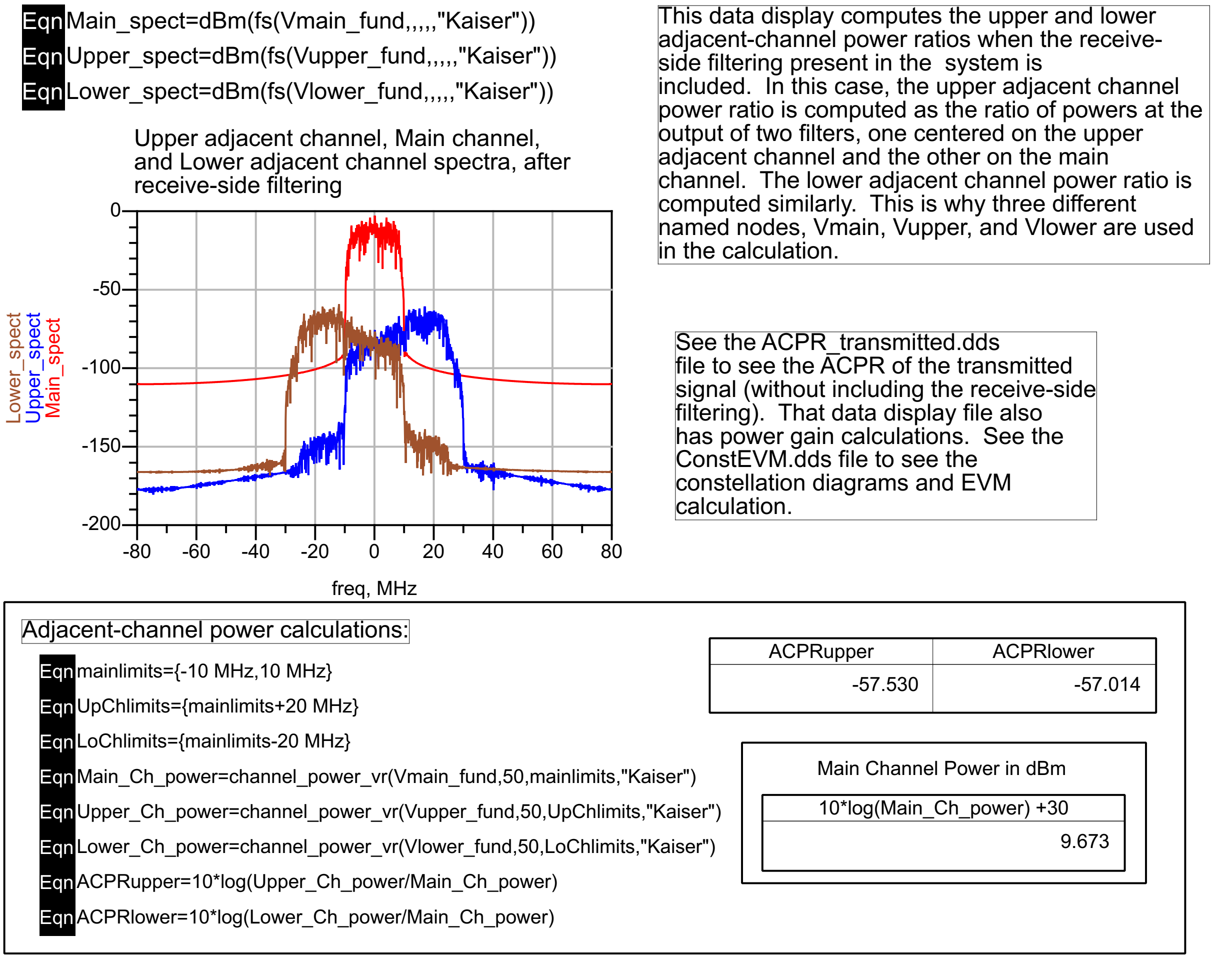


Figure 2.5: ACPR simulation results with receive side filtering effects

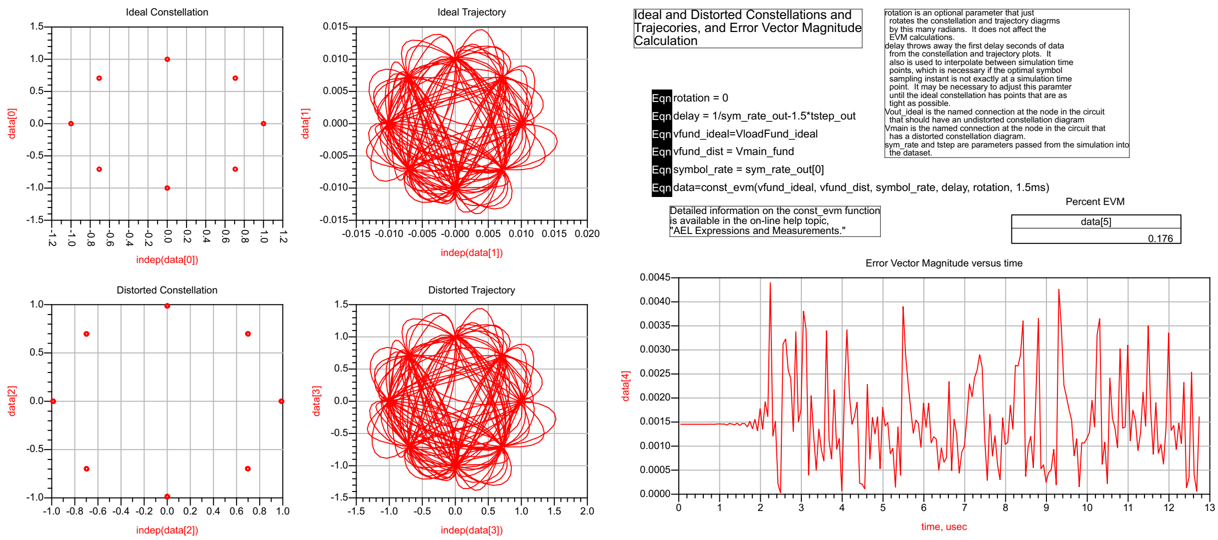


Figure 2.6: Constellation and EVM results of the ACPR simulation

2.4 ACPR Sweep Test

To determine the available source power ($Pavs$) that meets the specifications the provided ACPR schematic is modified to sweep $Pavs$, as shown in Figure 2.7. The -30 dBm value of $Pavs$ meets the specifications as shown in Figure 2.8.

The backoff needed at the power amplifier in order to fullfil the requirements could be calculated. The saturated power of the amplifier could be extracted from Figure 2.8 and markers m3 and m4 and it is $P_{sat,out} = 22.575dBm$ (could be approximated with $P_{1dB} = 20dBm$ of the PA) and $P_{sat,in} = -15dBm$. The operating power is $P_{avs} = -30dBm$, therefore the back off is 15 dB.

$$\text{Back off} = P_{sat,in} - P_{avs} = 15\ dB$$

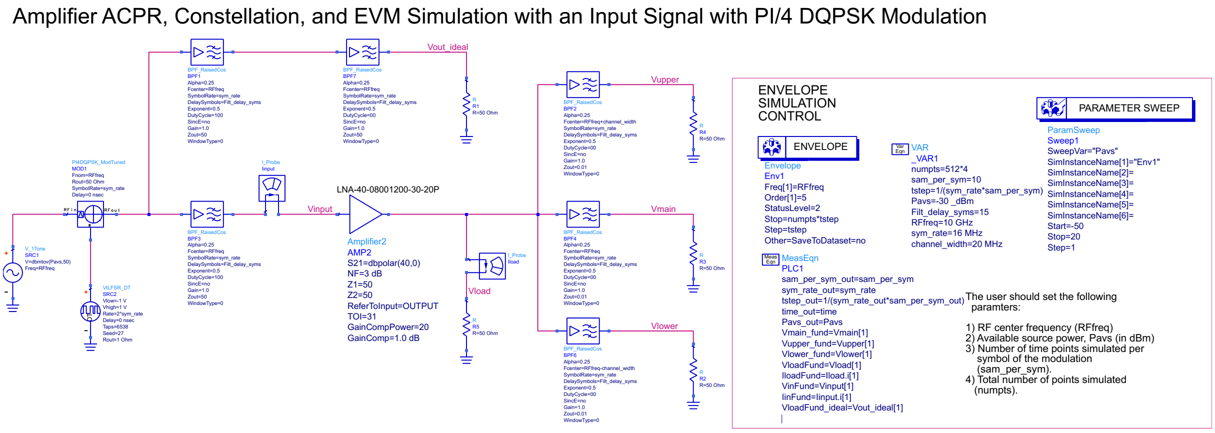
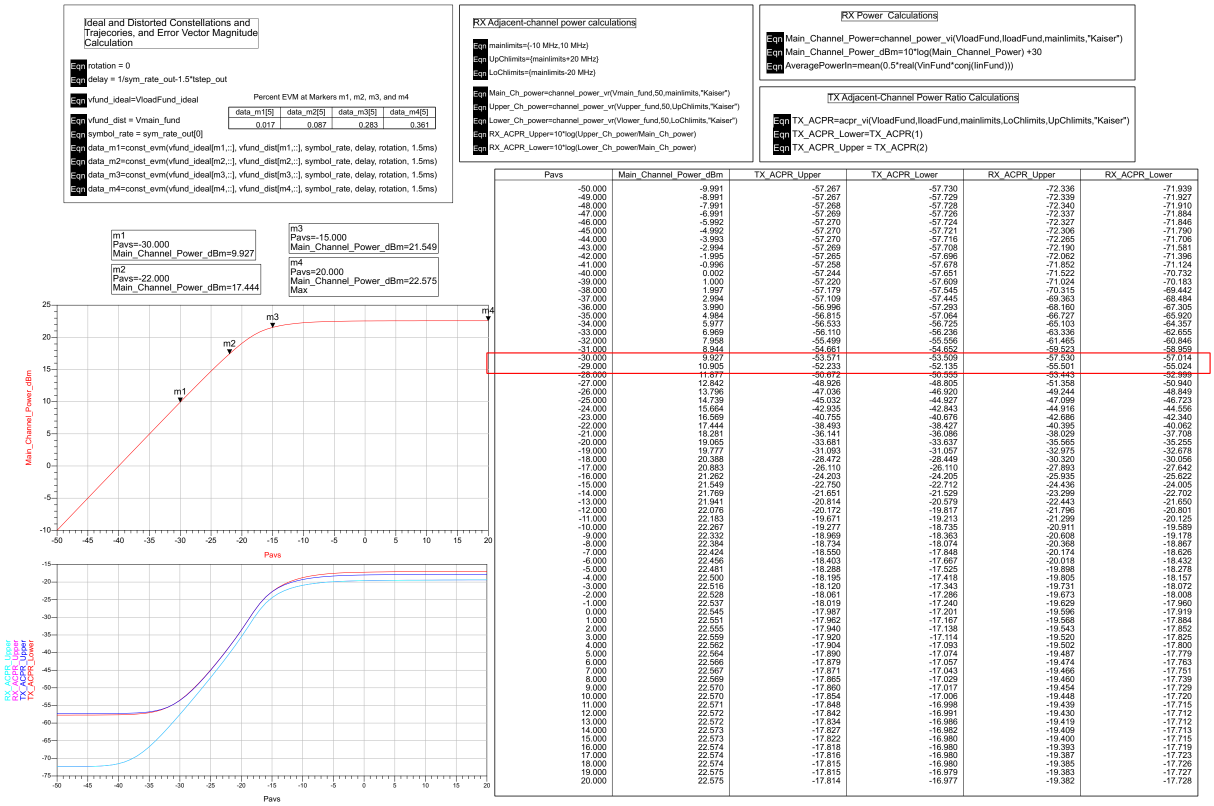


Figure 2.7: ACPR test schematic with sweeping $Pavs$



Pavs	Main_Channel_Power_dBm	TX_ACPR_Upper	TX_ACPR_Lower	RX_ACPR_Upper	RX_ACPR_Lower
-50.000	-9.991	-57.267	-57.730	-72.336	-71.939
-49.000	-8.991	-57.267	-57.729	-72.339	-71.927
-48.000	-7.991	-57.268	-57.728	-72.340	-71.910
-47.000	-6.991	-57.269	-57.726	-72.337	-71.884
-46.000	-5.992	-57.270	-57.724	-72.327	-71.846
-45.000	-4.992	-57.270	-57.721	-72.306	-71.790
-44.000	-3.993	-57.270	-57.716	-72.265	-71.706
-43.000	-2.994	-57.269	-57.708	-72.190	-71.581
-42.000	-1.995	-57.265	-57.696	-72.062	-71.396
-41.000	-0.996	-57.258	-57.678	-71.852	-71.124
-40.000	0.002	-57.244	-57.651	-71.522	-70.732
-39.000	1.000	-57.220	-57.609	-71.024	-70.183
-38.000	1.997	-57.179	-57.545	-70.315	-69.442
-37.000	2.994	-57.109	-57.445	-69.363	-68.484
-36.000	3.990	-56.996	-57.293	-68.160	-67.305
-35.000	4.984	-56.815	-57.064	-66.727	-65.920
-34.000	5.977	-56.533	-56.725	-65.103	-64.357
-33.000	6.969	-56.110	-56.236	-63.336	-62.655
-32.000	7.958	-55.499	-55.556	-61.465	-60.846
-31.000	8.944	-54.661	-54.652	-59.523	-58.959
-30.000	9.927	-53.571	-53.509	-57.530	-57.014
-29.000	10.905	-52.233	-52.135	-55.501	-55.024
-28.000	11.877	-50.672	-50.555	-53.443	-52.999
-27.000	12.842	-48.926	-48.805	-51.358	-50.940
-26.000	13.796	-47.036	-46.920	-49.244	-48.849
-25.000	14.739	-45.032	-44.927	-47.099	-46.723
-24.000	15.664	-42.935	-42.843	-44.916	-44.556
-23.000	16.569	-40.755	-40.676	-42.686	-42.340
-22.000	17.444	-38.493	-38.427	-40.395	-40.062
-21.000	18.281	-36.141	-36.086	-38.029	-37.708
-20.000	19.065	-33.681	-33.637	-35.565	-35.255
-19.000	19.777	-31.093	-31.057	-32.975	-32.678
-18.000	20.388	-28.472	-28.449	-30.320	-30.056
-17.000	20.883	-26.110	-26.110	-27.893	-27.642
-16.000	21.262	-24.203	-24.205	-25.935	-25.622
-15.000	21.549	-22.750	-22.712	-24.436	-24.005
-14.000	21.769	-21.651	-21.529	-23.299	-22.702
-13.000	21.941	-20.814	-20.579	-22.443	-21.650
-12.000	22.076	-20.172	-19.817	-21.796	-20.801
-11.000	22.183	-19.671	-19.213	-21.299	-20.125
-10.000	22.267	-19.277	-18.735	-20.911	-19.589
-9.000	22.332	-18.969	-18.363	-20.608	-19.178
-8.000	22.384	-18.734	-18.074	-20.368	-18.867
-7.000	22.424	-18.550	-17.848	-20.174	-18.626
-6.000	22.456	-18.403	-17.667	-20.018	-18.432
-5.000	22.481	-18.288	-17.525	-19.898	-18.278
-4.000	22.500	-18.195	-17.418	-19.805	-18.157
-3.000	22.516	-18.120	-17.343	-19.731	-18.072
-2.000	22.528	-18.061	-17.286	-19.673	-18.008
-1.000	22.537	-18.019	-17.240	-19.629	-17.960
0.000	22.545	-17.987	-17.201	-19.596	-17.919
1.000	22.551	-17.962	-17.167	-19.568	-17.884
2.000	22.555	-17.940	-17.138	-19.543	-17.852
3.000	22.559	-17.920	-17.114	-19.520	-17.825
4.000	22.562	-17.904	-17.093	-19.502	-17.800
5.000	22.564	-17.890	-17.074	-19.487	-17.779
6.000	22.566	-17.879	-17.057	-19.474	-17.763
7.000	22.567	-17.871	-17.043	-19.466	-17.751
8.000	22.569	-17.865	-17.029	-19.460	-17.739
9.000	22.570	-17.860	-17.017	-19.454	-17.729
10.000	22.570	-17.854	-17.006	-19.448	-17.720
11.000	22.571	-17.848	-16.998	-19.439	-17.715
12.000	22.572	-17.842	-16.991	-19.430	-17.712
13.000	22.572	-17.834	-16.986	-19.419	-17.712
14.000	22.573	-17.827	-16.982	-19.409	-17.713
15.000	22.573	-17.822	-16.980	-19.400	-17.715
16.000	22.574	-17.818	-16.980	-19.393	-17.719
17.000	22.574	-17.816	-16.980	-19.387	-17.723
18.000	22.574	-17.815	-16.980	-19.385	-17.726
19.000	22.575	-17.815	-16.979	-19.383	-17.727
20.000	22.575	-17.814	-16.977	-19.382	-17.728

Figure 2.8: ACPR simulation results with sweeping *Pavs*

2.5 EVM Test

EVM (Error Vector Magnitude) is a measure of the accuracy of a digital radio communication system. It is a metric that quantifies the difference between a transmitted signal and the corresponding received signal, in terms of both amplitude and phase. EVM is typically expressed as a percentage or in decibels (dB) and represents the difference between the ideal and actual received signal. The ideal signal is the one that would be received if there were no errors in the communication system. A high EVM value indicates that there is a high level of distortion in the received signal, which can result in poor quality of the communication. In contrast, a low EVM value indicates that the received signal is very close to the ideal signal and that the communication system is operating with high accuracy.

In this transmitter, the ACPR schematic (test bench) shown in Figure 2.11 has been modified by adding a SAW filter and configured to transmit as per the system specifications by setting the different variables and parameters in the Envelope simulation controller and other blocks. In addition, the amplifier is ensured to operate in the linear region, by lowering the available source power to -60 dBm.

To determine the shape factor of the SAW filter, a sweep of the shape factor is made, as shown in Figure 2.9. The results of the sweep are presented in Figure 2.10. To have an acceptable EVM (less than 5%), the shape factor should be set to 6 or 7. Increasing the shape factor results in a better lower/better EVM but reduces the attenuation in the adjacent channels which defeats the purpose of adding the SAW filter.

The shape factor in the EVM test was set, as shown in Figure 2.11. The results of the test are presented in Figure 2.12. With the shape factor set to 7 the percentage EVM is 4.170 % which meets the specs.

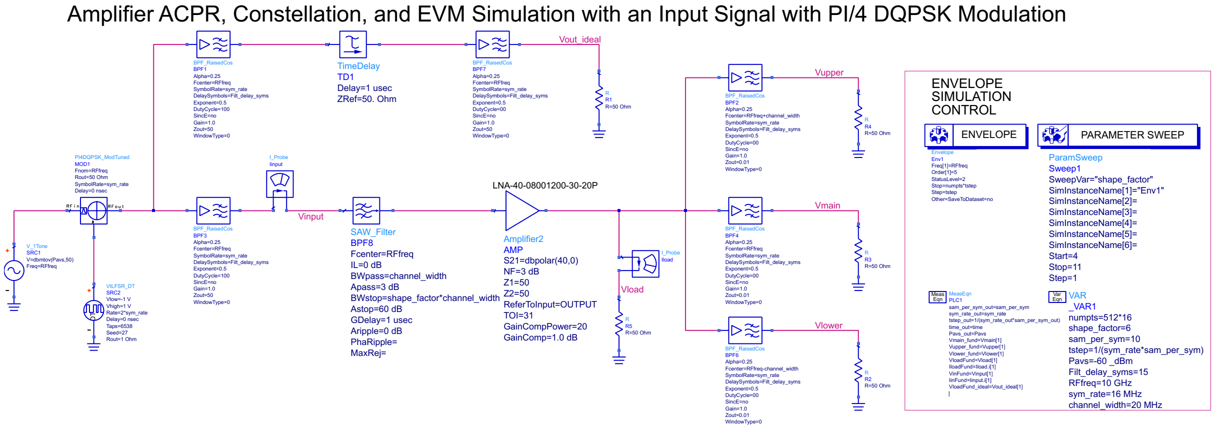


Figure 2.9: EVM test schematic with a sweep of the shape factor

Error Vector Magnitude Calculation

Eqn rotation = 0

Eqn delay = 1/sym_rate_out-1.5*tstep_out

Eqn vfund_ideal=VloadFund_ideal

Eqn vfund_dist = Vmain_fund

Eqn symbol_rate = sym_rate_out[0]

shape_factor_vals	Percentage_EVM
4	6.401
5	5.508
6	4.761
7	4.170
8	3.701
9	3.322
10	3.012
11	2.754

Eqn shape_factor_vals=[4::1::11]

Eqn data0=const_evm(vfund_ideal[0,::], vfund_dist[0,::], symbol_rate, delay, rotation, 1.5ms)

Eqn data1=const_evm(vfund_ideal[1,::], vfund_dist[1,::], symbol_rate, delay, rotation, 1.5ms)

Eqn data2=const_evm(vfund_ideal[2,::], vfund_dist[2,::], symbol_rate, delay, rotation, 1.5ms)

Eqn data3=const_evm(vfund_ideal[3,::], vfund_dist[3,::], symbol_rate, delay, rotation, 1.5ms)

Eqn data4=const_evm(vfund_ideal[4,::], vfund_dist[4,::], symbol_rate, delay, rotation, 1.5ms)

Eqn data5=const_evm(vfund_ideal[5,::], vfund_dist[5,::], symbol_rate, delay, rotation, 1.5ms)

Eqn data6=const_evm(vfund_ideal[6,::], vfund_dist[6,::], symbol_rate, delay, rotation, 1.5ms)

Eqn data7=const_evm(vfund_ideal[7,::], vfund_dist[7,::], symbol_rate, delay, rotation, 1.5ms)

Eqn Percentage_EVM = [data0[5],data1[5],data2[5],data3[5],data4[5],data5[5],data6[5],data7[5]]

Figure 2.10: EVM test results with a sweep of the shape factor

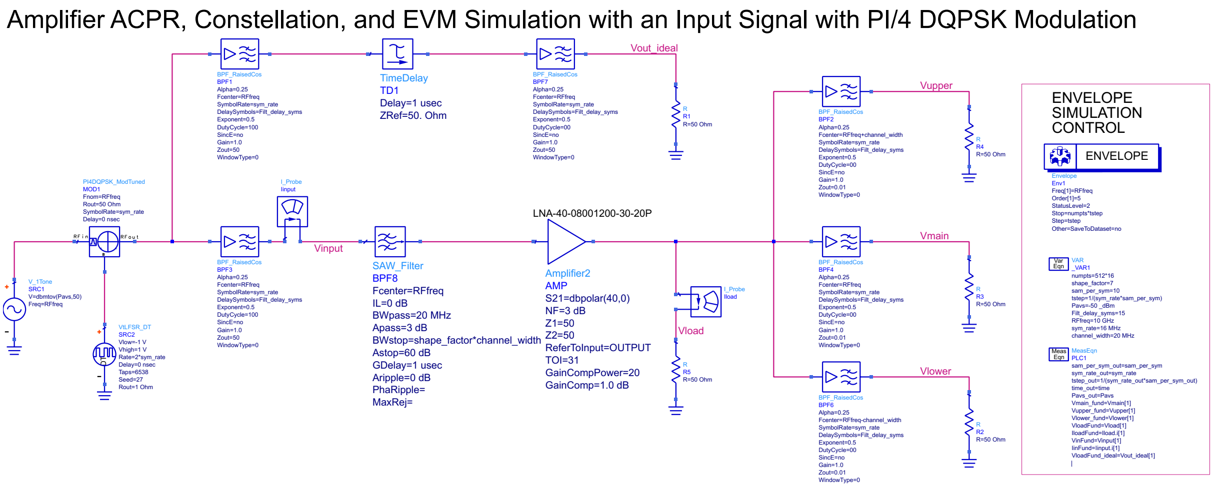


Figure 2.11: EVM test schematic with a single valued of the shape factor

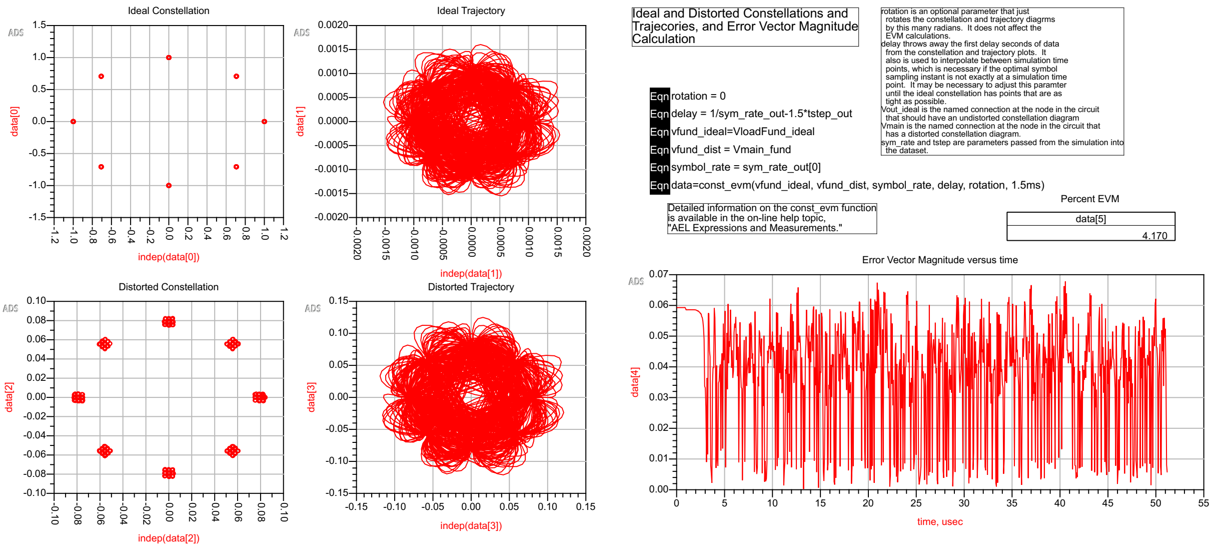


Figure 2.12: EVM test results with a single valued of the shape factor

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