POLITECNICO di MILANO 1863

RF Project Report

Author: ***Hamed Lotfalizadeh***

Personal Code: ***10946486***

Academic Year: **2023/24**

Mail Address:

Hamed.Lotfalizadeh@mail.poilimi.it

January 20, 2024

Contents

1 Introduction **5**

1.1 ***Conversion Receivers*** 5

1.2 ***Applied Wave Research(AWR)*** 6

1.3 ***About the RF Project*** 7

1.4 ***The Structure of the Report*** 7

2 Assumptions **8**

3 Parameter Calculation **10**

3.1 Circuit evaluation of Mixer parameters 10

3.1.1 Information of the Project 10

3.1.2 Rat-race Hybrid 10

3.2 Circuit evaluation of LNA parameters 11

3.2.1 Information of the Project 11

3.2.2 90 Degree Hybrid 11

3.3 Parameters in AWR 11

3.3.1 Results of Mixer after Replacement 13

3.3.2 Results of LNA after Replacement 13

4 Evaluation **14**

4.1 Recall of Error Vector Magnitude (EVM) 14

4.2 Recall of Phase Noise (NP) 14

4.3 Choice of the Local Oscillator phase noise mask 15

4.3.1 Information of the Project 15

4.3.2 Discuss the Results 15

4.4 Degradation Due to an Image Interferer 17

5 Conclusions and Final Results **18**

List of Figures

1 Blocks of the front-end of the receiver . . . 8
2 Blocks of the front-end of the receiver in AWR simulating environment . . . 9
3 Rat-race Hybrid . . . 10
4 Hybrid 90 degree . . . 11
5 New Values in AWR . . . 12
6 Replacing new Element Option . . . 12
7 Searching newly Designed Structure . . . 13
8 Mixer schematic in AWR simulating environment . . . 14
9 Mixer Parameters 1 . . . 15
10 Mixer Parameters 2 . . . 15
11 Spectrum . . . 16
12 Rat-race Hybrid . . . 16
13 LNA Parameters 1 . . . 17
14 LNA Parameters 2 . . . 17
15 EVM Value for Different RF Input power . . . 18
16 EVM without Noise Phase Mask . . . 18
17 Phase mask configuration . . . 19
18 Phase mask 0 . . . 19
19 Phase mask 1 . . . 20
20 Phase mask 2 . . . 21
21 Phase mask 3 . . . 22
22 Phase mask 4 . . . 23
23 Phase Noise Masks . . . 23
24 Enable Measurements . . . 24
25 Different Image Power Values and their EVM for Phase Mask 3 . . . 25
26 IF and RF Spectrum Plots with Phase Mask3 . . . 26
27 Final Values for all Parameters . . . 27

1 Introduction

1.1 *Conversion Receivers*

A conversion receiver is a type of radio receiver that converts received radio frequency (RF) signals to an intermediate frequency (IF) before further processing. The RF front-end is a crucial component of such a receiver, responsible for handling the initial reception and processing of RF signals. Here are some key aspects and components typically found in the RF front-end of a conversion receiver:

Antenna:
The antenna is the first element in the RF front-end, capturing the RF signals from the airwaves.
Low Noise Amplifier (LNA):
The LNA amplifies the weak RF signals captured by the antenna. It is designed to introduce minimal noise to maintain a good signal-to-noise ratio.
Bandpass Filter:
The bandpass filter helps select the desired frequency range and reject unwanted signals and noise outside that range.
Mixer:
The mixer is responsible for frequency conversion. It mixes the RF signal with a local oscillator (LO) signal to generate the intermediate frequency (IF). This process allows the receiver to convert the RF signal to a lower, more manageable frequency.
Local Oscillator (LO):
The LO generates a stable signal at a known frequency. Its frequency is adjusted to ensure the desired intermediate frequency after mixing.
Image Reject Filter:
This filter helps eliminate the possibility of receiving signals at the image frequency, which is a potential issue in conversion receivers.
Automatic Gain Control (AGC):
AGC circuits adjust the gain of the RF front-end to maintain a relatively constant signal level at the mixer output, compensating for variations in received signal strength.
Mixing and Filtering Stages:
Depending on the receiver architecture, there may be multiple mixing and filtering stages to further process the IF signal and extract the desired information.
Intermediate Frequency Amplifiers:
These amplifiers boost the signal level after mixing to prepare it for further processing in subsequent stages of the receiver.
Automatic Frequency Control (AFC):
AFC circuits help to automatically adjust the local oscillator frequency to keep the receiver tuned accurately to the desired station.
RF Front-end Control Circuitry:
This includes components for tuning, selecting frequency bands, and controlling various parameters of the RF front-end.
Power Supply:
A stable and clean power supply is essential for optimal performance of the RF front-end components. The design and optimization of the RF front-end depend on factors such as the desired frequency range, bandwidth, sensitivity, selectivity, and the intended application of the conversion receiver. Engineers need to carefully balance these factors to achieve the best overall performance.

1.2 *Applied Wave Research(AWR)*

AWR Corporation, previously recognized as Applied Wave Research and subsequently acquired by National Instruments, is a leading electronic design automation (EDA) software company. Specializing in the development, marketing, sales, and support of engineering software, the company offers a computer-based platform tailored for designing hardware in the realm of wireless and high-speed digital products. AWR's software is particularly employed in radio frequency (RF), microwave, and high-frequency analog circuit and system design. Common use cases span a range of applications such as the design of cellular and satellite communications systems, along with defense electronics applications encompassing radar, electronic warfare, and guidance systems.

AWR software encompasses a variety of design tools, including the Cadence AWR Design Environment platform, AWR Microwave Office software, AWR Visual System Simulator (VSS) for communications and radar systems design, AWR AXIEM 3D Planar EM Analysis, and AWR Analyst 3D FEM EM Analysis. These tools are instrumental in addressing the complexities of electrical and physical co-design, utilizing RF-aware device models, electromagnetic (EM) analysis, and specialized circuit simulation technology. The suite of tools also provides valuable design support aids. In the realm of RF product development, where challenges abound, the incorporation of system-level analysis becomes essential. This allows for the simulation of behaviors within radar and communications links, ensuring a comprehensive approach to RF product design.The AWR suite comprises several specialized tools catering to the diverse needs of RF/microwave engineers:

AWR Design Environment Platform:

Purpose: Provides an integrated platform with RF/microwave circuit, system, and EM simulation technologies, along with design automation. Functionality: Enables engineers to develop physically realizable electronics, streamlining the path to manufacturing.

AWR Microwave Office Software:

Purpose: Circuit design software featuring an intuitive interface, innovative design automation, and powerful harmonic-balance circuit simulation. Benefits: Enhances engineering productivity and accelerates design cycles, ensuring efficient and effective circuit design.

AWR VSS Software:

Purpose: RF/wireless communications and radar system design software. Features: Supports VSWR-aware modeling of RF and DSP blocks, facilitating time-domain, frequency-domain, and circuit-envelope analyses.

AWR AXIEM Analysis:

Purpose: 3D planar method-of-moments (MoM) EM analysis simulator. Application: Addresses passive structures, transmission lines, large planar antennas, and patch arrays. Advantages: Delivers accuracy, capacity, and speed for characterizing and optimizing passive components on various platforms like RF PCBs, modules, LTCCs, MMICs, RFICs, and antennas.

AWR Analyst Software:

Purpose: 3D finite-element method (FEM) EM simulation and analysis software. Functionality: Accelerates high-frequency product development from early physical design characterization to full 3DEM verification. Advancements: Utilizes advanced solver technology for fast and accurate analysis of complex 3D structures and interconnects in modern high-frequency electronics. Together, these tools provide a comprehensive set of capabilities, addressing key aspects of RF and microwave design, from circuit simulation to system-level analysis and electromagnetic characterization. The integration of these tools aims to empower engineers in developing efficient and optimized designs for high-frequency electronics.

1.3 *About the RF Project*

The objective of this project is to thoroughly comprehend the architecture of the RF front-end in a conversion receiver, encompassing components such as an amplifier, RF filter, mixer, local oscillator, IF filter, and so on. The emphasis will be on elucidating the operation and configuration of these blocks and circuits. To initiate this exploration, the primary focus will involve obtaining parameters for the Low Noise Amplifier (LNA) and Mixer through circuit simulations and replacing their new models in the circuit. Following this, the report will proceed to assess the RF front-end's performance by conducting simulations in the absence and presence of phase noise within the AWR software. Subsequent sections will provide a comprehensive elaboration of the details. It is worth noticing that in this report, we only discuss some of the components in the RF front-end of a conversion receiver introduced in 1.1.

1.4 *The Structure of the Report*

The remaining sections of the report are structured as follows: Section II outlines the assumptions and parameters. In Section III, we calculate the parameters for the Mixer and Low Noise Amplifier. The results of the evaluation, focusing on EVM and NP, are deliberated in Section IV. Lastly, Section V provides a summary of the outcomes of this study and presents the conclusion.

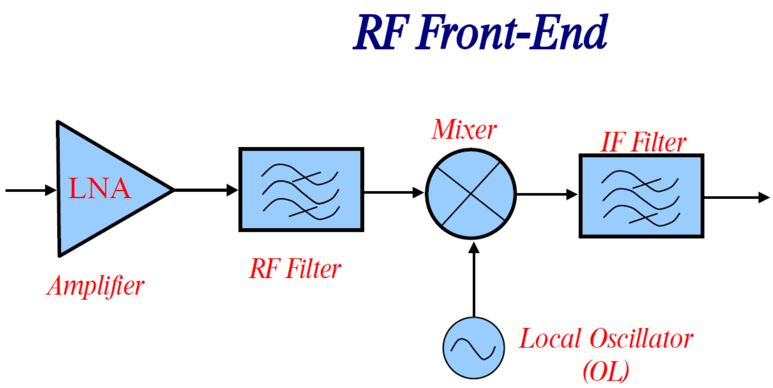


Figure 1: Blocks of the front-end of the receiver

2 Assumptions

In our study, as illustrated in Fig. 1, the front-end of the receiver comprises five blocks: an amplifier, RF filter, mixer, local oscillator, and an IF filter. In this simulation the value of parameters are considered as: Input RF carrier frequency: $4.25GHz$, Modulation: $16-QAM$ with data rate $R = 94.8Mbit/s$, (Bandwidth $32MHz$), Intermediate frequency: $500MHz$, and Local Oscillator frequency: $3.75GHz$ It is worth mentioning that the parameters which should be considered for different block are:

LNA:

▶Gain(dB)
▶Noise Figure(dB)
▶3^{rd} Intercept Power (dBm)
▶Power at 1 dB compression $(P1dB)$

Mixer:

⊗ Conversion loss (dB)
⊗ Equivalent noise temperature (SSB) $(°K)$
⊗ 3^{rd} Intercept Power at input (dBm)
⊗ Power at 1 dB compression at input (P1dB)

Local Oscillator:

∼ Output power (dBm)
∼ Oscillation frequency (MHz)
∼ Phase noise $(mask)$

This study encompasses three categories of parameters: the first set is immutable, the second set is adjustable, and the third, or final, set requires modification to align with the conditions of the problem. A detailed presentation of these parameters is available in the following table for reference.

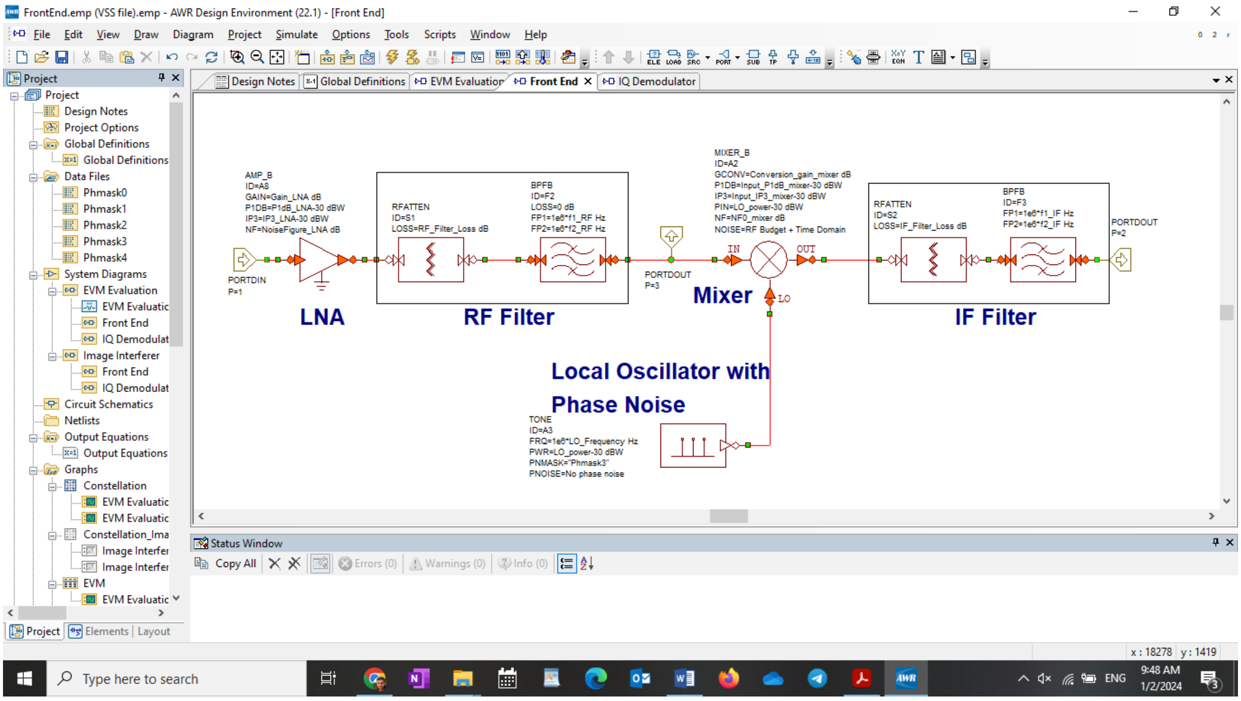


Figure 2: Blocks of the front-end of the receiver in AWR simulating environment

Type one	Type two	Type three
$F_C = 4250$	$G_{LNA} = 12.8$	RF input power=-100
Signal Band=32	$NF_{LNA} = 2.98$	$P_{LO} = 15$
$F_{LO} = 3750$	P1dB LNA=18.9	-
RF Filter B=2× Signal Band	IP3 LNA=27.4	-
IF Filter B=1.5× Signal Band	$G_{CM} = -5.3$	-
$F_{IF} = 500$	$T_{SSB} = 268$	
$F_I = 3250$	Input P_{1dB} mixer=12.78	-
RF Filter Loss=0.5	IIP3 mixer=14-Conversion gain mixer	-
IF Filter Loss=1.5	-	-

In Fig.2, the overall schematic of the problem is presented. Based on the assumption that we can either used the certain parameters or calculate the parameters, it is better go through the problem and regenerate them by calculation. Therefore, in the next section the mentioned parameters will be discussed.

3 Parameter Calculation

In this section, the focus will be on designing and calculating the parameters of Mixer and LNA, respectively.

3.1 Circuit evaluation of Mixer parameters

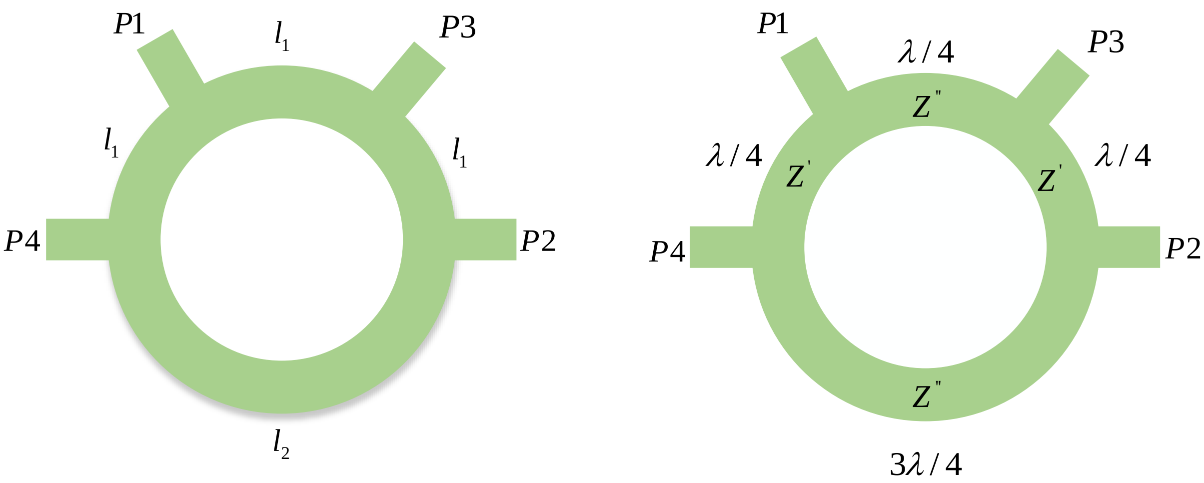
3.1.1 Information of the Project

– The circuits are defined in the file named Mixer_circuit.emp.
– The balanced configuration with 2 diodes and a 180°hybrid is used.
– Initially the hybrid is represented with an ideal component:
— All the circuit elements are assigned and must not be modified
— The simulations include a filter at IF which is not part of the mixer
— The ideal hybrid must be replaced with a Rat-race hybrid to be dimensioned.

3.1.2 Rat-race Hybrid

In Fig. 3(a), the rat-race coupler, recognized as a hybrid ring coupler, is depicted. This device assumes a crucial role in RF (Radio Frequency) and microwave systems, especially in communication circuits, as highlighted. Functioning as a 3 dB coupler, it evenly disperses power across its output ports. Unlike the magic tee, the rat-race coupler stands out for its ease of implementation in planar technologies like microstrip and stripline, with practical applications extending to waveguide configurations.

As depicted in Fig.3(b), the core structure of the rat-race coupler features four ports strategically positioned around the upper half of a ring. Each port is precisely spaced one-quarter wavelength apart from its neighboring ports. The lower half of the ring measures three-quarters of a wavelength, and the ring itself exhibits a characteristic impedance that is a factor of $\sqrt{2}$ compared to the port impedance. Specifically, with details provided, Z' and Z'' are 70.707Ω each. Additionally, the lengths of $l_1 = \lambda/4$ and $l_2 = 3\lambda/4$ amount to 17.647 and 52.941, respectively.



(a) General Schematic

(b) Schematic with details

Figure 3: Rat-race Hybrid

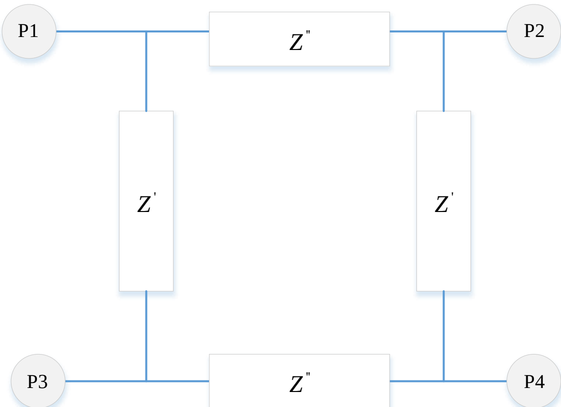
3.2 Circuit evaluation of LNA parameters

3.2.1 Information of the Project

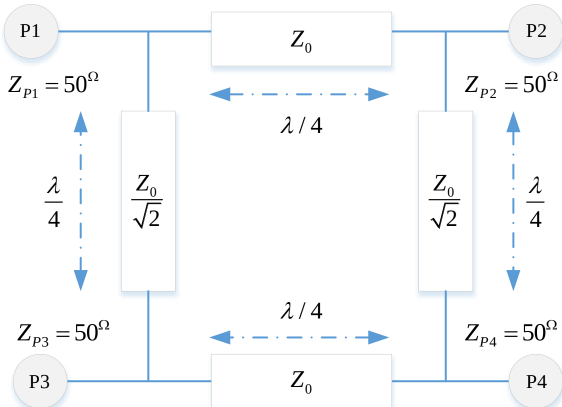
– All schematics are included in the file named *LNA_circuit.emp*.
– The balanced configuration is used for the LNA. The identical amplifiers employ a FET device represented with a non-linear model in MWOffice. The device is properly biased and suitable values of Γ_S and Γ_L are realized at its terminal by means of ideal components (Ltuner).
– The balanced configuration employs two 90°hybrids. Initially these hybrids are represented by and ideal model.
– It is requested to replace the ideal hybrids with Branch Line hybrids whose scheme is available in the schematic "Branch Line Hybrid".
– The hybrid is dimensioned by assigning the proper values to the variables representing the characteristic impedances and the lengths – To replace the ideal hybrids, select the network "Branch Line Hybrid" in the "NET" parameter of the subcircuits in the Balanced schematic.

3.2.2 90 Degree Hybrid

The couplers with C=3 dB are identified with the word Hybrid. To realize a hybrid as shown in Fig.4(a) of branch-line type the characteristic impedance of the lines must be: $Z' = Z_0\sqrt{1-0.5} = 35.3553\Omega$, $Z'' = Z_0\sqrt{0.5/0.5} = 50\Omega\,(Z_0 = 50\Omega)$. Therefore, the final design of the 90 degree hybrid is shown in Fig.4(b), now, based on the information given, the length of the lines can be calculated as $\lambda = c/f_c = 70.588$, $l = \lambda/4 = 17.647$



(a) General Schematic

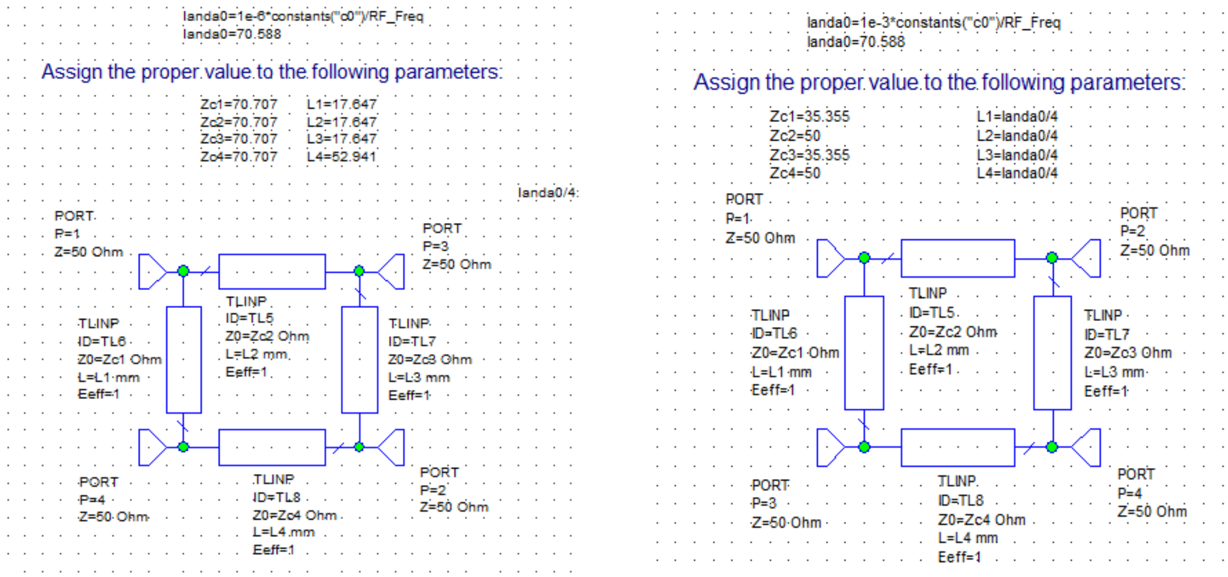


(b) Schematic with details

Figure 4: Hybrid 90 degree

3.3 Parameters in AWR

In Fig. 5(a) and Fig. 5(b), the designed parameters for the Rat-race Hybrid and Branch Line Hybrid were incorporated into AWR. The subsequent phase involves substituting the new components in their designated positions. This can be accomplished by right-clicking on the element to be modified and selecting the "Swap Elements" option, as illustrated in Fig. 6. This section outlines the process of



(a) Rat-race Hybrid in AWR (b) Branch Line Hybrid in AWR

Figure 5: New Values in AWR

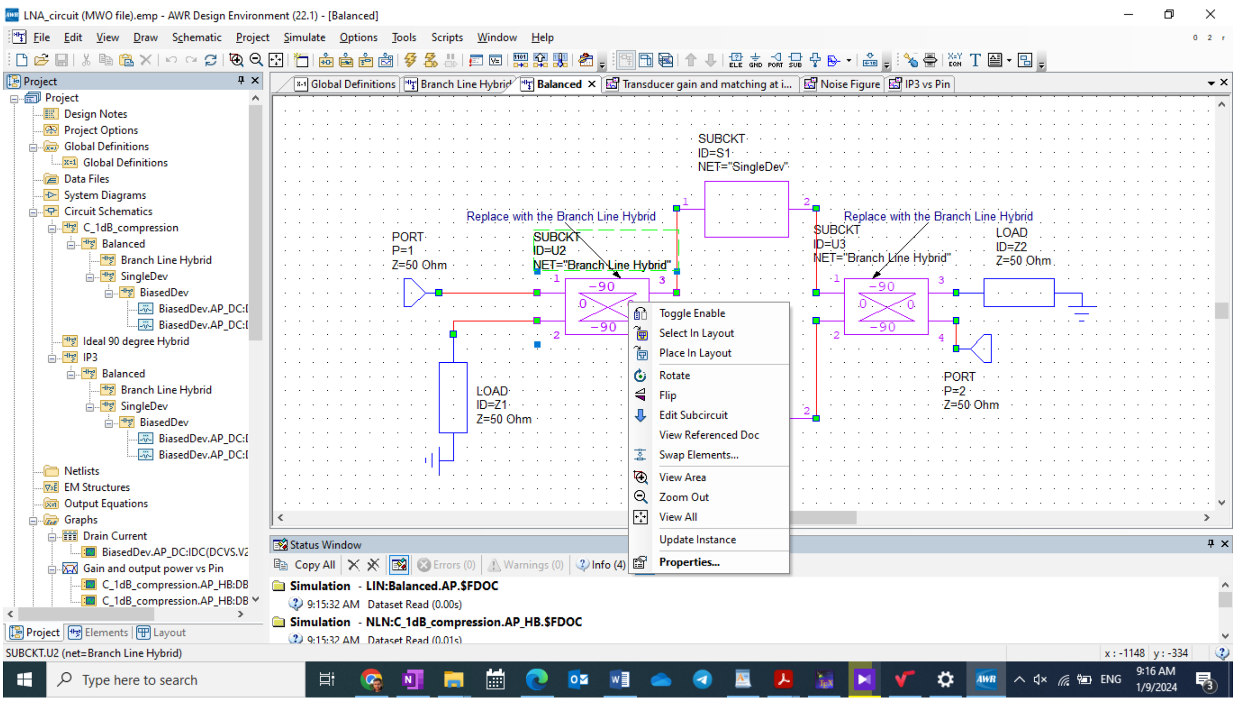


Figure 6: Replacing new Element Option

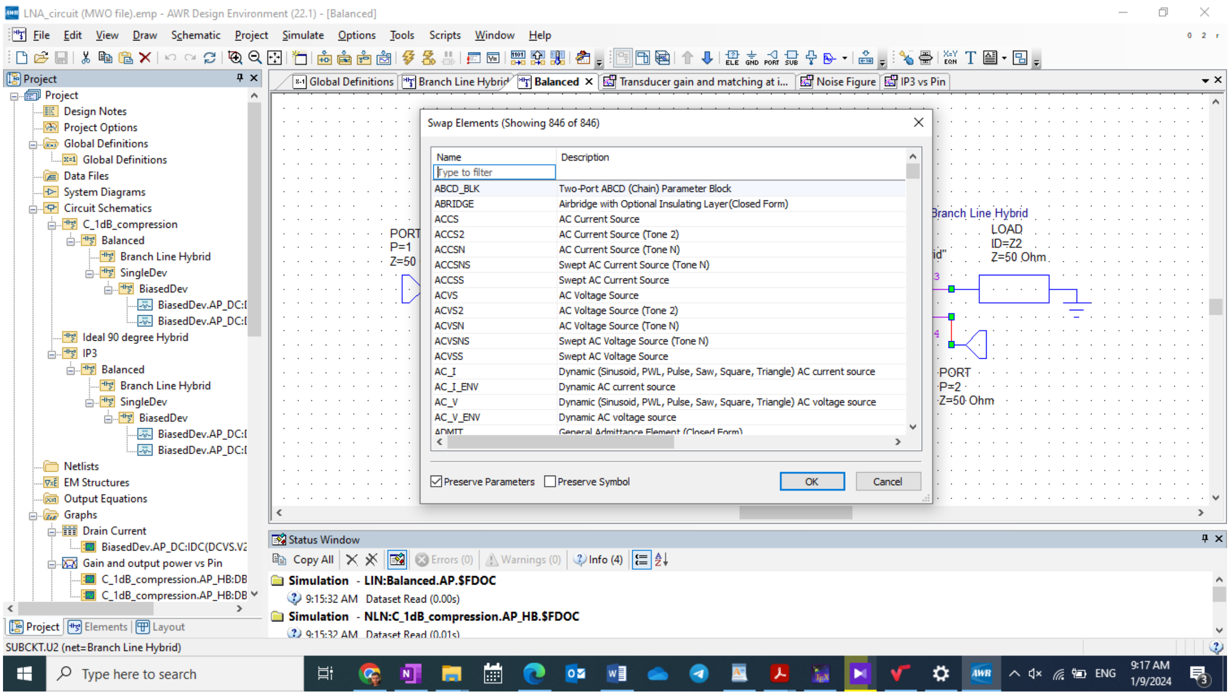


Figure 7: Searching newly Designed Structure

adding the newly designed element to the structures through a straightforward search, as depicted in Fig. 7.

3.3.1 Results of Mixer after Replacement

After replacement of the newly designed Mixer as Fig.8 , the following parameters have been extracted from AWR.

For newly designed mixer parameters including, Conversion Gain Vs Local Oscillator Power, Output IP3 Vs Local Oscillator power, P1dB Evaluation for PL0 Equal to normal, Noise Temperature, and spectrum plots are shown in Fig.9(a), Fig.9(b), Fig.10(a), Fig.10(b), and Fig.11 respectively.

3.3.2 Results of LNA after Replacement

After replacing the branch line hybrid, and before starting the simulations, as shown in Fig.12, the proper value of the gate voltage -0.4114 is obtained by tuning the global variable “vg”, so that the drain current is equal to the nominal value (ID=33mA) and it is activated in the circuit.

For newly designed LNA parameters including, Transducer gain and matching at input and output, Gain and output power vs Pin, IP3 vs Pin, and Noise Figure plots are shown in Fig.13(a), Fig.13(b), Fig.14(a), and Fig.14(b) respectively.

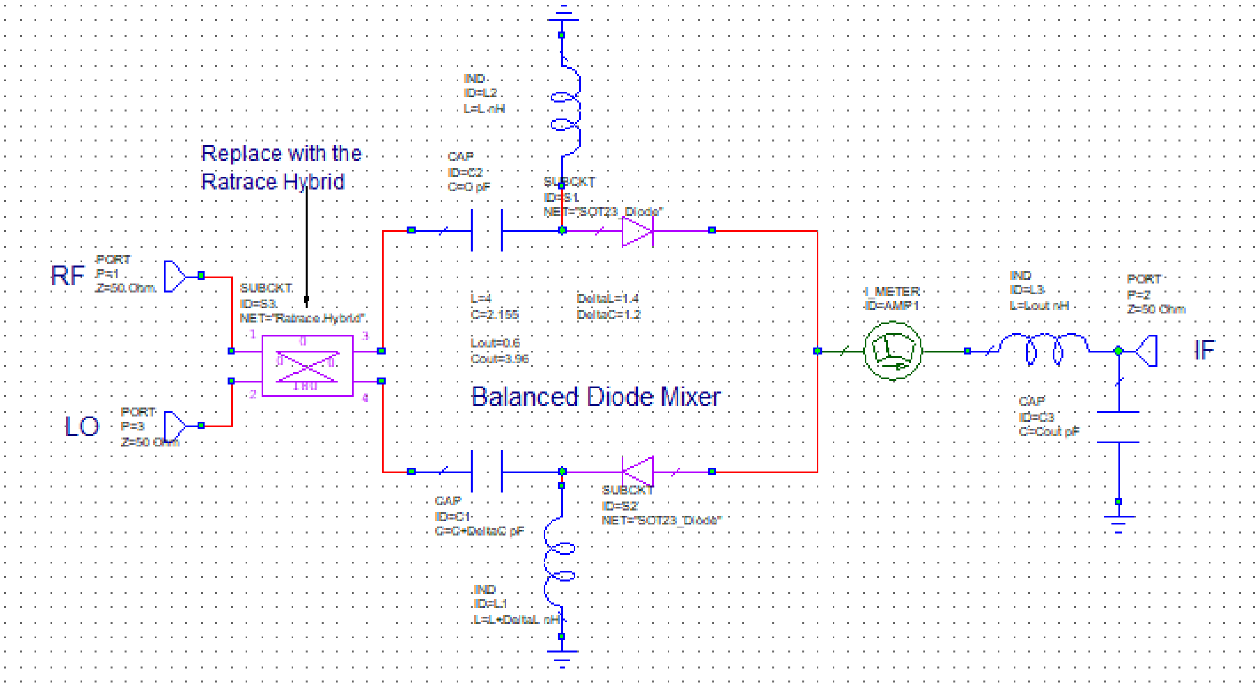


Figure 8: Mixer schematic in AWR simulating environment

4 Evaluation

4.1 Recall of Error Vector Magnitude (EVM)

In digital communications the received signal can be represented by a vector which may assume a limited number of positions. The set of possible positions defines the ideal constellation diagram.

Whatever disturb overlapping the signal produces a displacement between the ideal constellation and the one produced by the actual received signal.

Such displacement is an indication of the signal quality degradation due to various sources (including non-linearities).

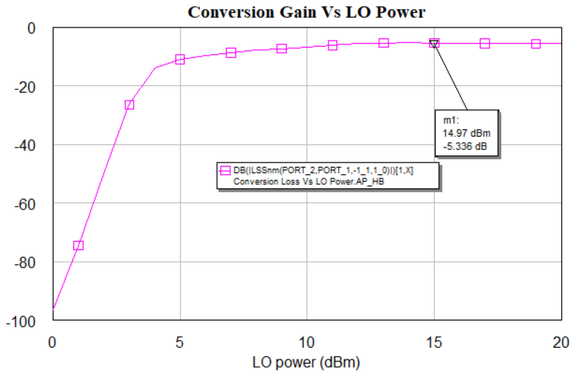
The parameter used for quantifying the above displacement is the error vector magnitude (EVM).

In this section, depicted in Fig.15, we conducted an EVM evaluation for various RF input power values. As indicated in Fig.16, fine-tuning the RF input power to -73.31 resulted in achieving the desired EVM evaluation of 5%, fulfilling the targeted objective of this project.

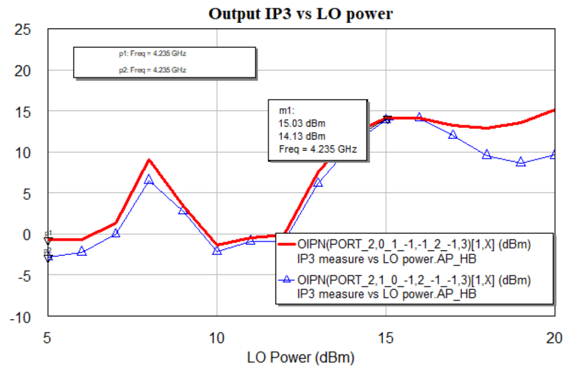
4.2 Recall of Phase Noise (NP)

Phase noise (PN) represents the effects of the instantaneous phase fluctuations (jitter) of the sinusoidal signal produced by a real oscillator. When the oscillator affected by PN is used in a mixer, the random variations of the LO phase are transferred to the carrier frequency of the translated signal. When this signal is de-modulated, the extracted information is distorted (quality degraded).

The degradation produced depends on the maximum deviation of the instantaneous phase of the carrier. It is independent on the power of the RF signal. Phase noise is practically defined by means of a mask representing the relative level of the power density produced by the oscillator at a distance Δf from the carrier frequency, for various values of Δf.

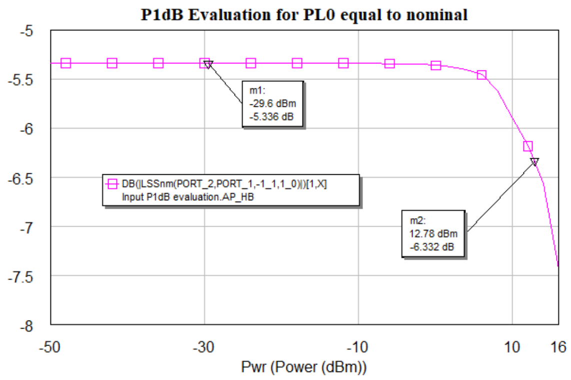


(a) Conversion Gain Vs Local Oscillator Power

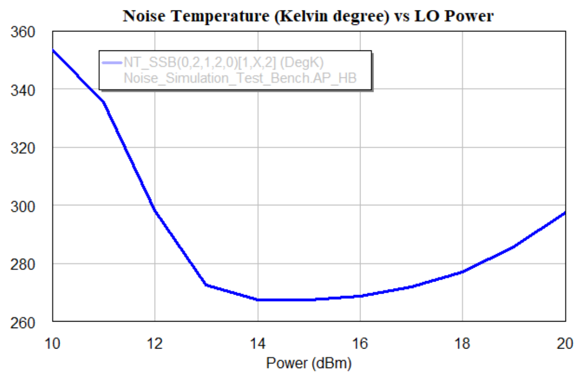


(b) Output IP3 Vs Local Oscillator power

Figure 9: Mixer Parameters 1



(a) P1dB Evaluation for PL0 Equal to normal



(b) Noise Temperature

Figure 10: Mixer Parameters 2

4.3 Choice of the Local Oscillator phase noise mask

4.3.1 Information of the Project

– In the previous simulations, the Local Oscillator (LO) is assumed ideal (no phase noise included).
– The acceptable level of Phase Noise is the one not modifying the performances obtained by the RF front-end with no PN present.
– To find this level (defined by the associated Mask), we consider the input RF power equal to the minimum value before found and evaluate EVM.
– If the measured EVM, including PN, is above 5% the phase noise is not negligible, and a better mask is required.
– Continue to reduce PN level until a mask is found with which the measured EVM is about 5% (i.e., it fluctuates between 4.9% and 5.1%). This is the required phase noise mask for the LO.

4.3.2 Discuss the Results

In the initial phase of this project, depicted in Fig.17, the results do not account for phase noise. Subsequently, by altering the phase of the noise from "No Phase Noise" to "Generate Phase Noise"

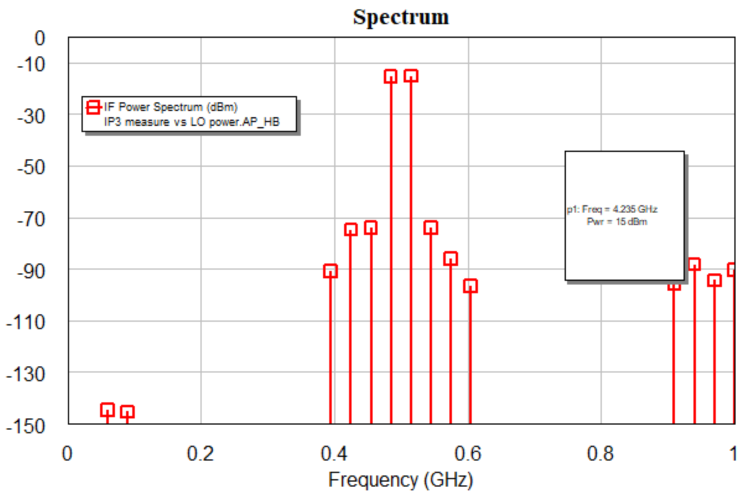
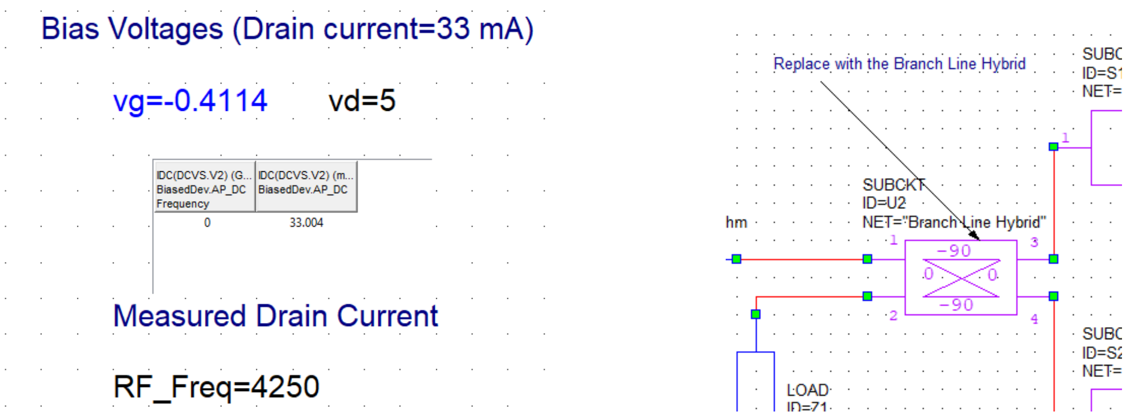


Figure 11: Spectrum

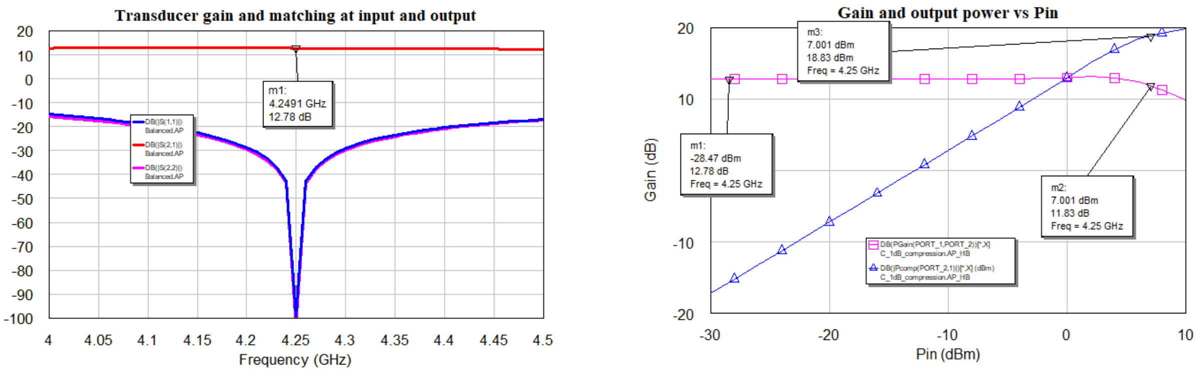


(a) Bias Voltage (b) Replaced Branch Line hybrid

Figure 12: Rat-race Hybrid

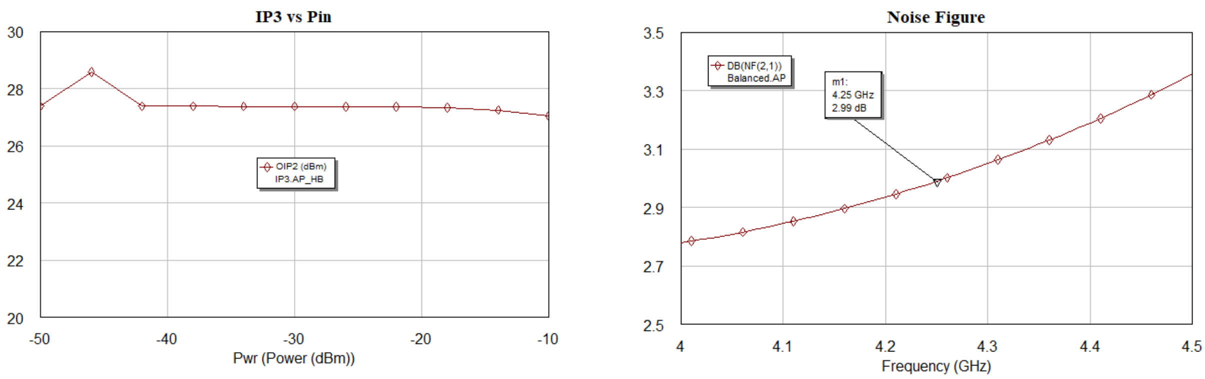
and selecting the optimal phase mask, we aim to elevate the noise power to a level where the EVM reaches 5.2%.

In the following, EVM Evaluation and Constellation results for Phase mask 0, Phase mask 1, Phase mask 2, Phase mask 3, and Phase mask 4 are depicted in Fig.18, Fig.19, Fig.20, Fig.21, and Fig.22, respectively. As it can be seen Phase mask 3 and 4 represented better results; Although, in the rest of this project Phase mask 3 is considered to be a trad-off between the costs and performance of the project. In Fig.22, different EVM values shown for different image power values. Furthermore, Phase noise mask plot is presented in Fig.25.



(a) Transducer gain and matching at input and output (b) Gain and output power vs Pin

Figure 13: LNA Parameters 1



(a) IP3 vs Pin (b) Noise Figure

Figure 14: LNA Parameters 2

4.4 Degradation Due to an Image Interferer

An image interferer is a signal at the input of the RF frontend, whose carrier frequency is equal to the image frequency of the mixer. This interferer should be eliminated by the image filter. In the practice, it appears at the input of the mixer, with a level depending on the filter selectivity. And finally, in Fig.26, the IF and RF spectrum plot presented to cover the requirements of this project in a proper way.

Even if the attenuation of the image filter is large, when the received RF signal is much weaker than the interferer level, the converted signal at IF is distorted. The quality of the demodulated signal at baseband is then degraded.

It is shown on Fig.24 that to have the result of some graphs, their measurements should be activated, and also the final values for all parameters of this project is presented in Fig.27,.

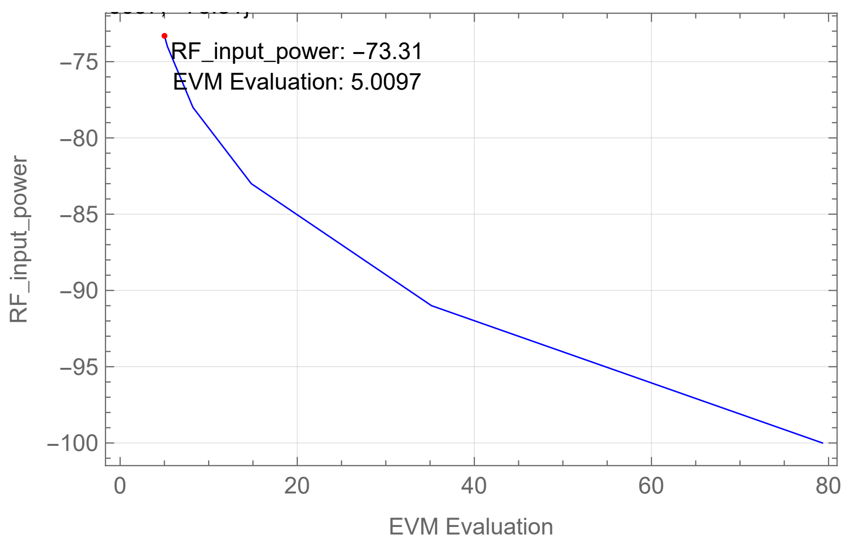
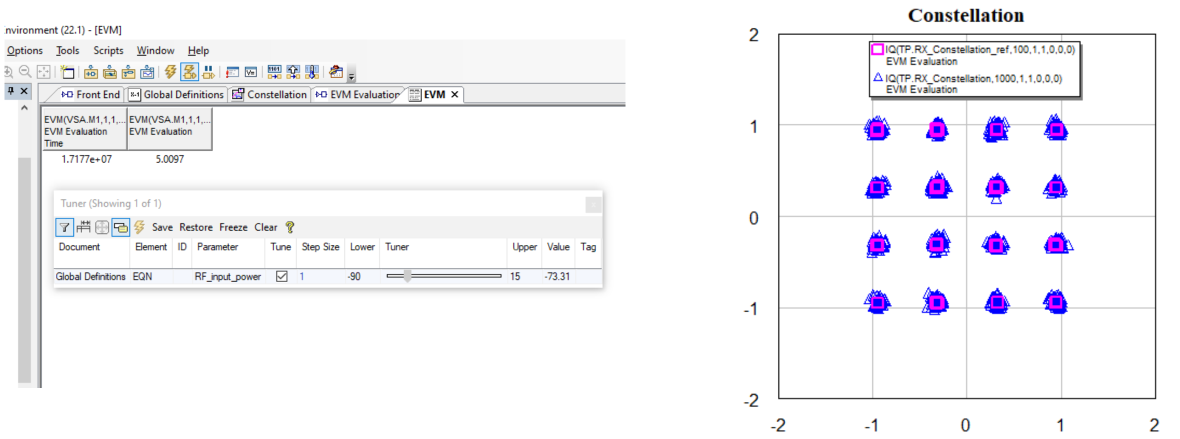


Figure 15: EVM Value for Different RF Input power



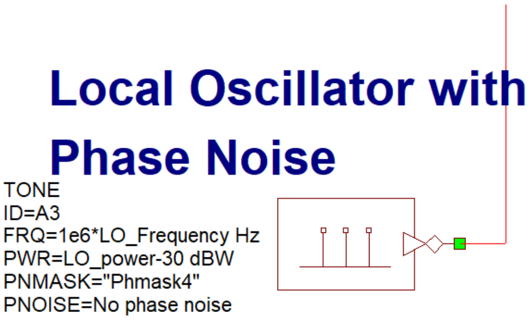
(a) Tuning RF input power

(b) Constellation

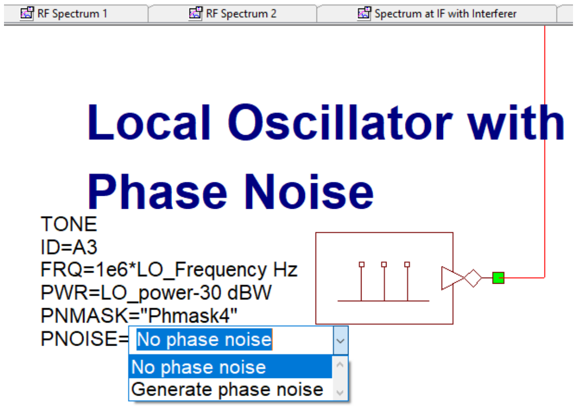
Figure 16: EVM without Noise Phase Mask

5 Conclusions and Final Results

In this comprehensive report, we meticulously scrutinized every essential facet of the project. Initially, we embarked on the design phase, creating new sections for both the Rat Race Hybrid and Branch Line Hybrid. Furthermore, a specific emphasis was placed on achieving a precise EVM range of 4.9% to 5.1%, necessitating the consideration of a 73.31 dB value. Lastly, when confronted with image interference and employing phase mask 3, the Image Power was meticulously set at -45 dB to ensure the attainment of an EVM within the range of 5.00% to 5.20%.

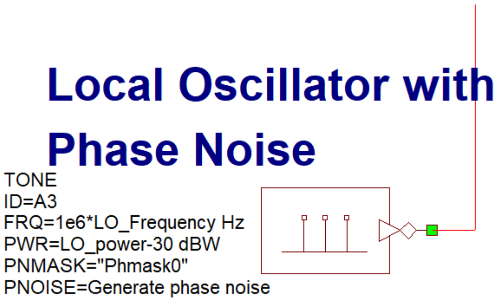


(a) General Schematic

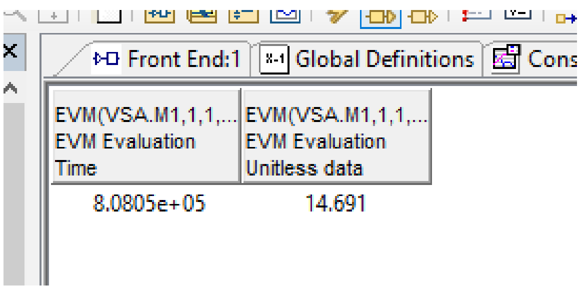


(b) Schematic with details

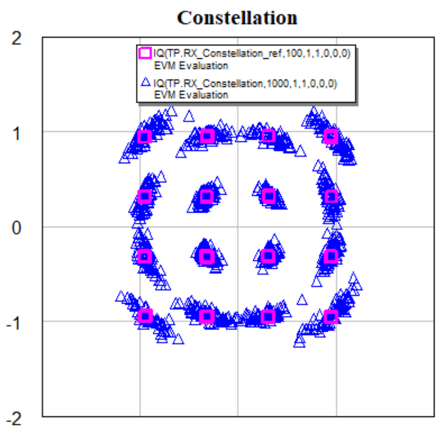
Figure 17: Phase mask configuration



(a) Phase mask 0

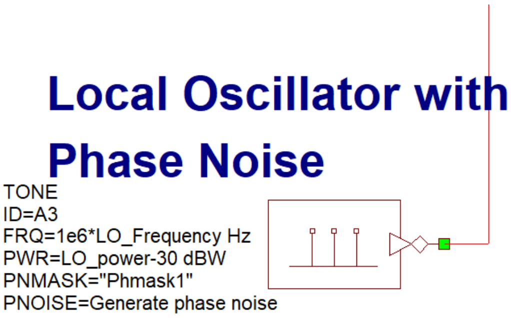


(b) EVM Evaluation

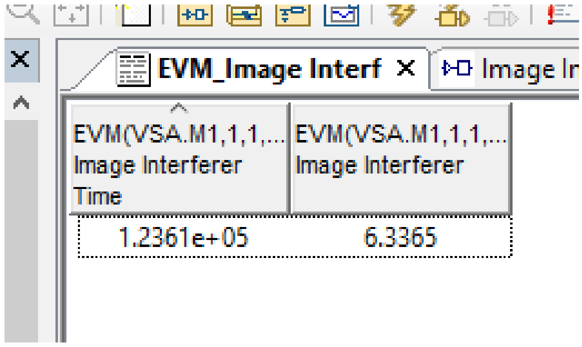


(c) Constellation

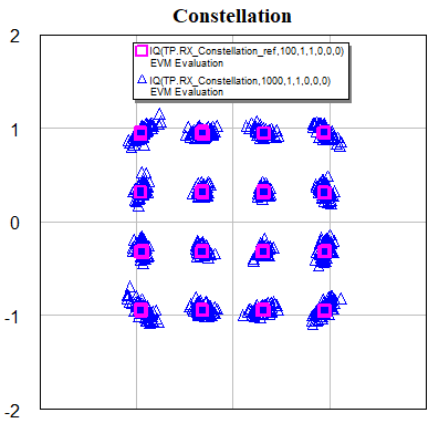
Figure 18: Phase mask 0



(a) Phase mask 1

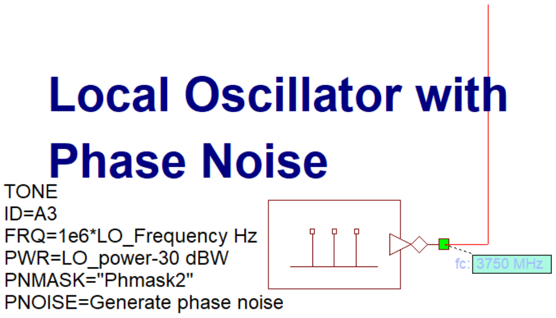


(b) EVM Evaluation

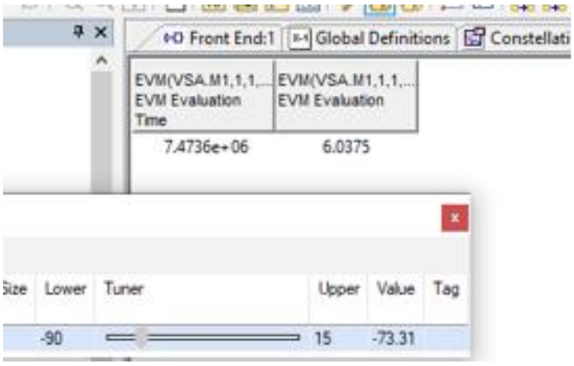


(c) Constellation

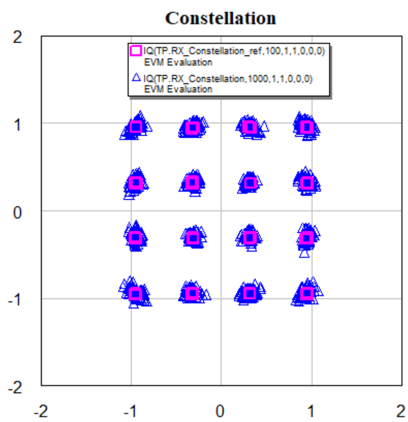
Figure 19: Phase mask 1



(a) Phase mask 2

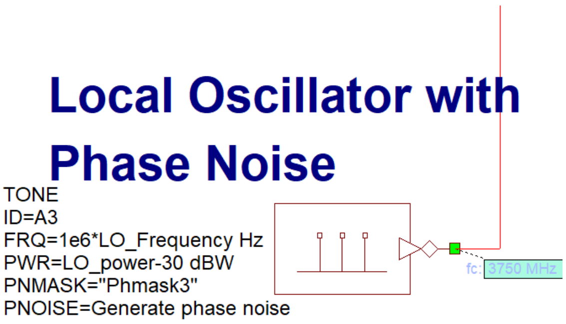


(b) EVM Evaluation

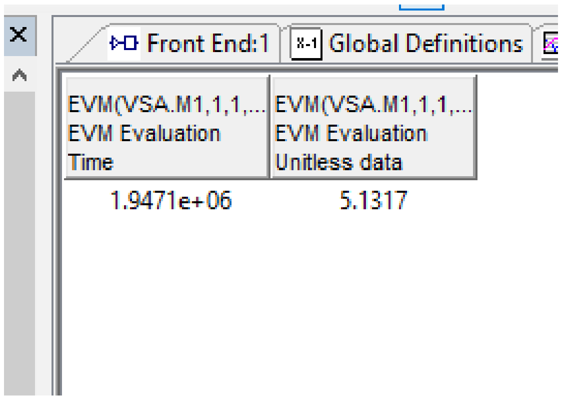


(c) Constellation

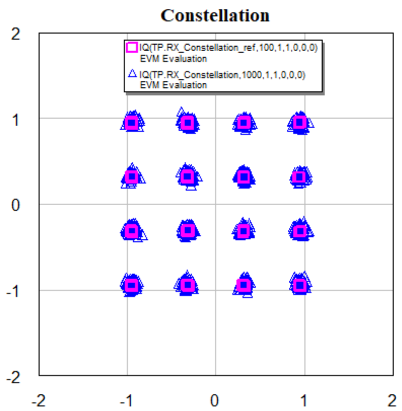
Figure 20: Phase mask 2



(a) Phase mask 3

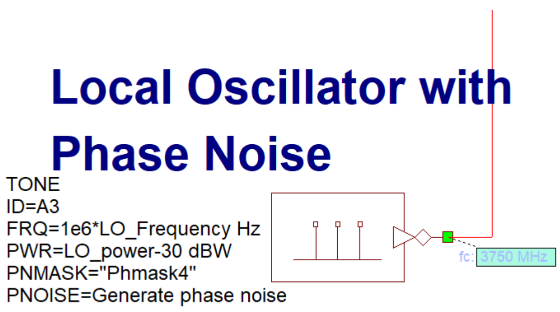


(b) EVM Evaluation

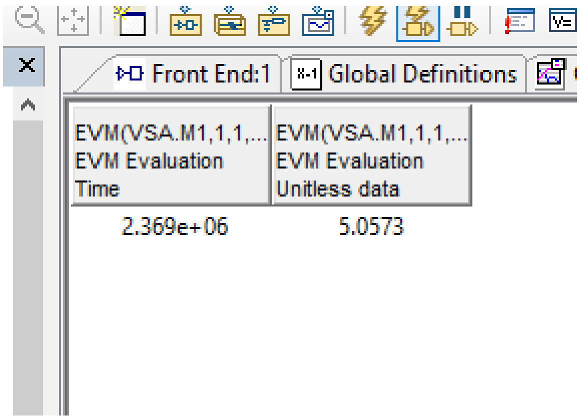


(c) Constellation

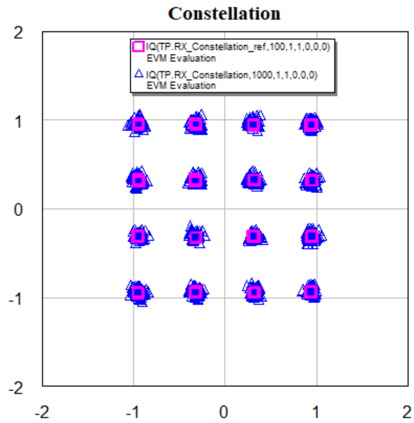
Figure 21: Phase mask 3



(a) Phase mask 4



(b) EVM Evaluation



(c) Constellation

Figure 22: Phase mask 4

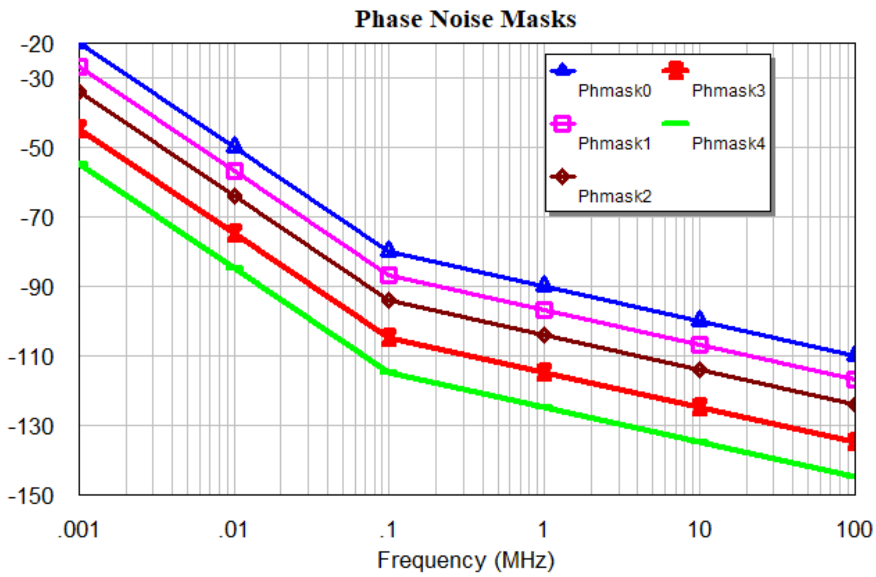


Figure 23: Phase Noise Masks

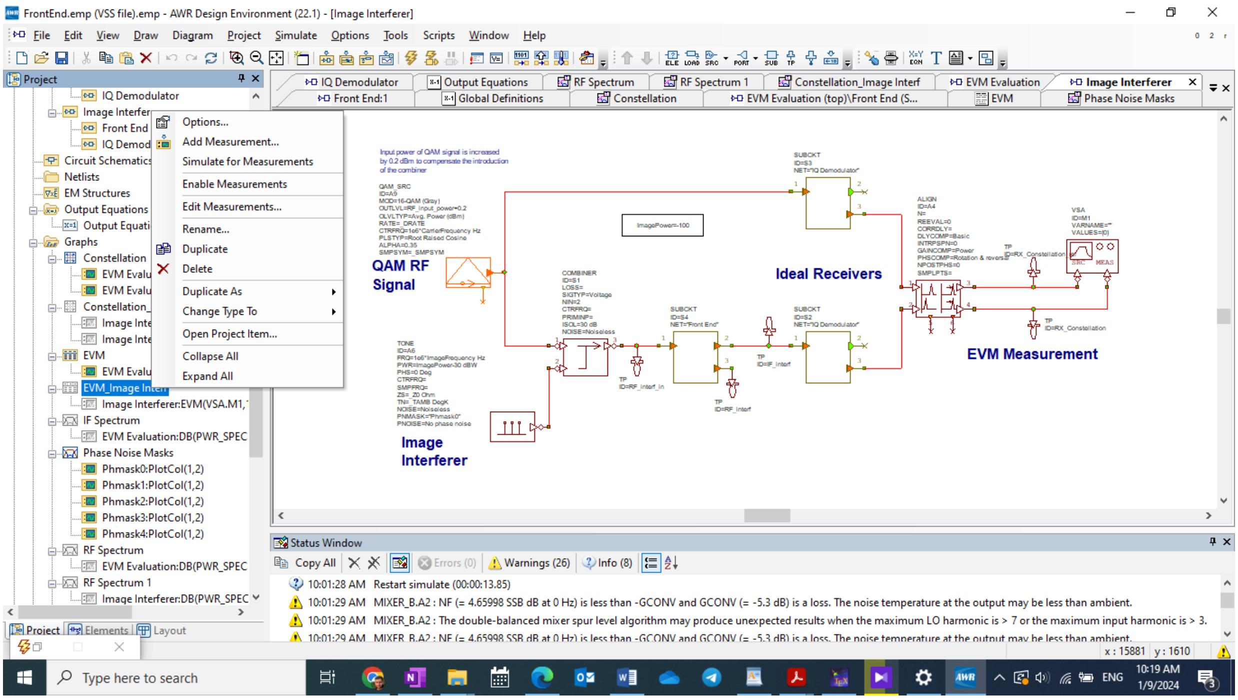
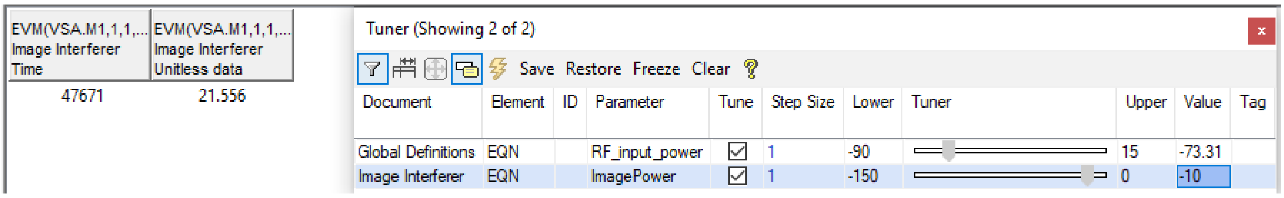
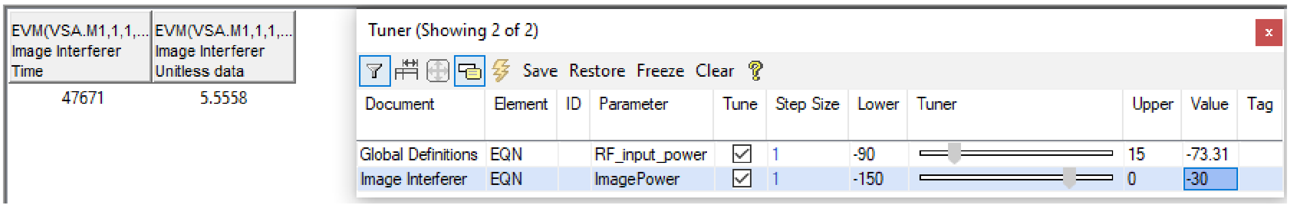


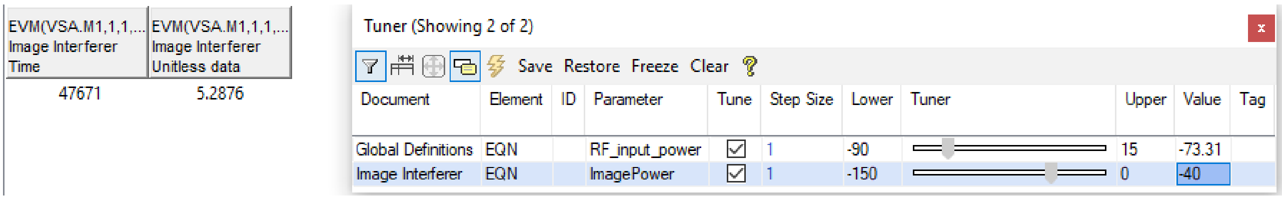
Figure 24: Enable Measurements



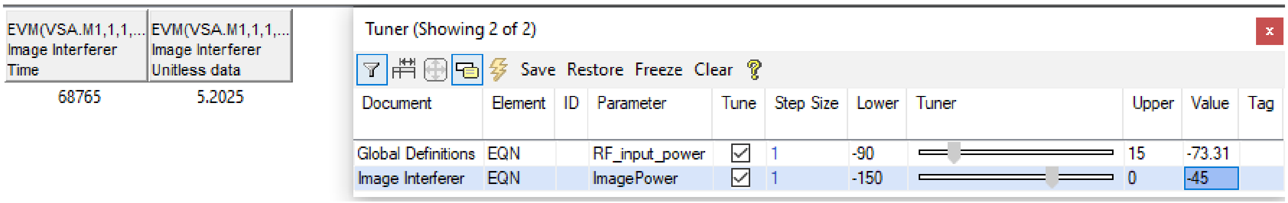
(a) -10 dB Image Power and it's EVM



(b) -30 dB Image Power and it's EVM

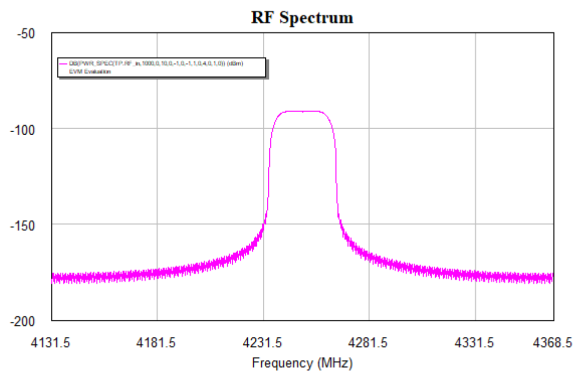


(c) -40 dB Image Power and it's EVM

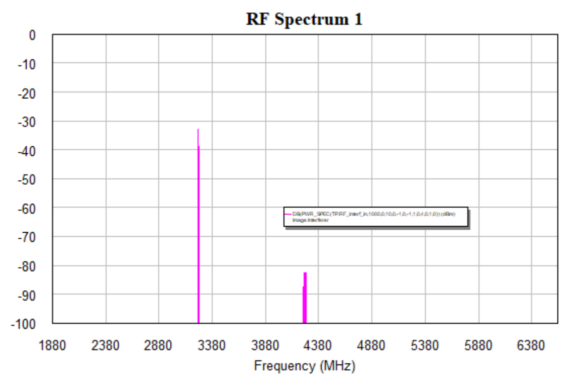


(d) -45 dB Image Power and it's EVM

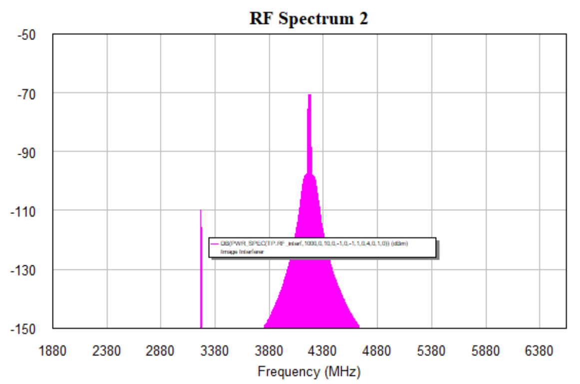
Figure 25: Different Image Power Values and their EVM for Phase Mask 3



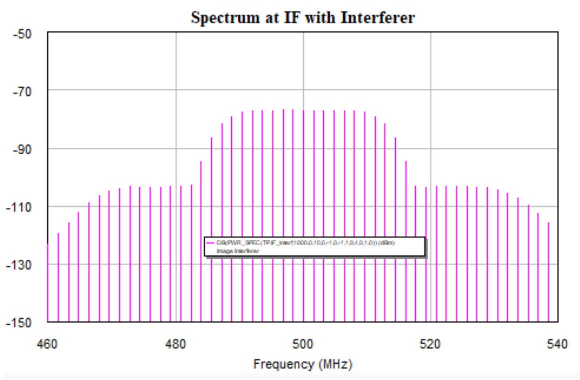
(a) RF Spectrum



(b) RF Spectrum 1



(c) RF Spectrum 2



(d) Spectrum at IF with Interferer

Figure 26: IF and RF Spectrum Plots with Phase Mask3

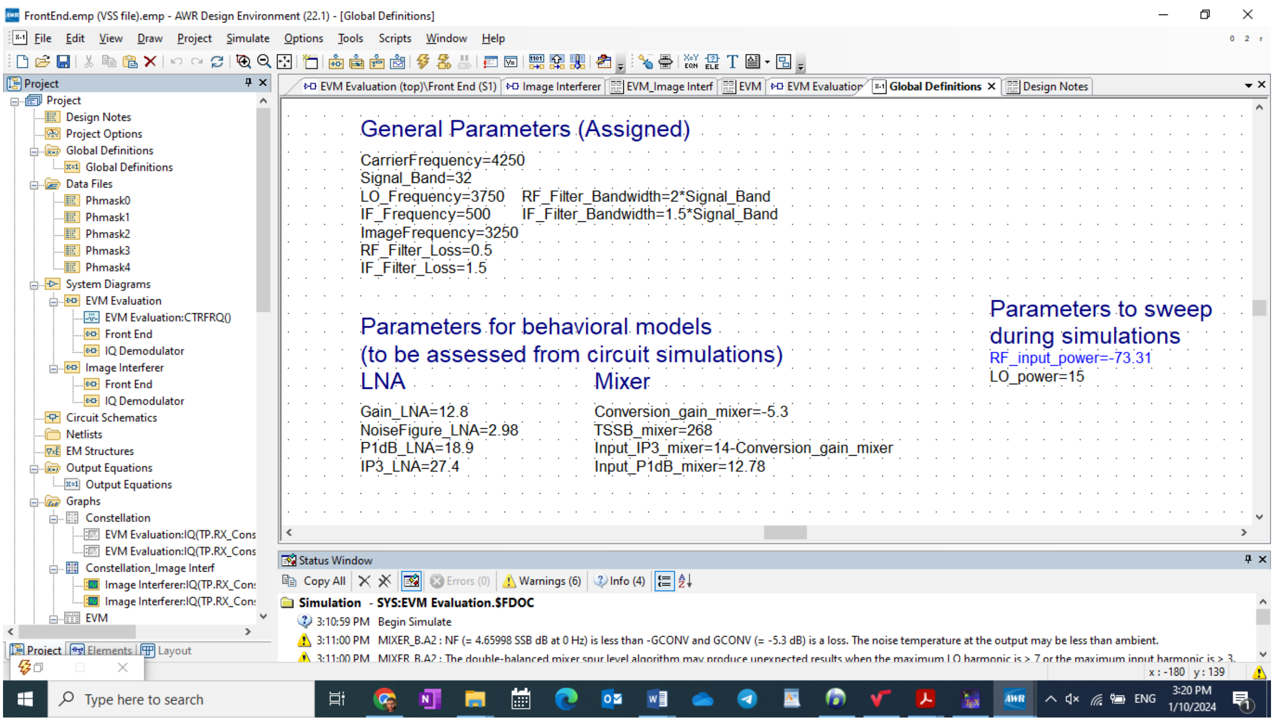


Figure 27: Final Values for all Parameters