UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Posgrados

Detection of non-analytic non-linearities and intermodulation in MOS based passive mixers

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I would also like to thank my colleagues in the team MOST, they have been a great help during my internship and stance in Toulouse, they have been very skilled tutors of the French language.

Finally, I want to express my deep gratitude to my parents, they were a great support during this year of Master's.

RESUMEN

El objetivo de este proyecto es caracterizar la linealidad de un mezclador pasivo que utiliza Mosfet sin polarización. Los rendimientos de los circuitos de microondas en términos de linealidad no siempre son precisos en programas de simulacion microondas CAD. La primera parte del trabajo se centra en el desarrollo de un banco de pruebas con un gran rango dinámico capaz de extraer intermodulación por bajo condiciones de señales de muy baja potencia. Para esta tarea es necesario agregar un filtro para atenuar los tonos de entrada, transmitiendo solo un tono de intermodulación. Después se utiliza un amplificador de bajo ruido especialmente diseñado para esta aplicación. Dos filtros se diseñaron con sus los respectivos amplificadores, sus simulaciones y pruebas fueron correctas, respectivamente. Las mediciones del tercer producto de intermodulación del mezclador muestran que la pendiente no es exactamente 3 dB / dB. La segunda parte está dedicada al desarrollo de un modelo de simulación con los datos de voltaje y corrientes extraidos de los Mosfets del mezclador. Esta tarea fue dirigida por el co-supervisor Jacques Sombrin, quien ha publicado varios documentos sobre intermodulación. El resultado de esta parte muestra que la corriente se puede describir como una adición de una función asimétrico con una contribución muy pequeña de una función simétrica

Palabras clave— Mezcladores pasivos, Intermodulation, Amplificador de bajo ruido, Mosfet, Filtro Pasivo

ABSTRACT

This project is intended to characterize the linearity of a passive mixer using cold MOS devices. The performances of microwave circuits in terms of linearity are not always accurately estimated in currents microwave CAD softwares. The first part of the work is focused on the development of a high-dynamic range test bench capable of extracting intermodulation performance under very small-signal operating conditions. For this task is necessary to add a filter for attenuate the input tones, transmitting just one intermodulation tone. After it is amplified with a low noise amplifier specially designed for this application. Two filters with their respective amplifier were designed, their corresponding simulations and tests were correct. The measurements of the third intermodulation product from the mixer show that the slope is not exactly 3 dB/dB. The second part is dedicated to the development of a simulation model with the voltage and currents data from the mixer's Mosfets. This task was directed by the co-supervisor Jacques Sombrin, who has published several documents about intermodulation. The result of this part shows that the current can be described as an addition of an asymmetric function with a very small contribution of a symmetric function.

Keywords— Passive Mixers, Intermodulation, Low Noise Amplifier, Mosfet, Passive Filter

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CHAPTER 1 INTRODUCTION

1.1 Context and presentation of the project

1.1.1 Laboratories

This project is a collaboration between LAAS (Laboratory of Analysis and Architecture of Systems) and the laboratory TeSA (Telecommunications for Space and Aeronautics). LAAS is one of the biggest from the French National Center of Research Scientific (CNRS). My co-supervisor Jacques Sombrin is from TeSA and is author of some publications in passive and active intermodulation.

1.1.2 Project

This project is intended to characterize the linearity of a passive mixer using cold MOS devices. The performances of microwave circuits in terms of linearity are not always accurately estimated in currents microwave CAD softwares.

The first part of the work is focused on the development of a high-dynamic range test bench capable of extracting intermodulation performance under very small-signal operating conditions.

The second part is dedicated to the development of a model using the theory developed by Jacques Sombrin [1],[2].

Based on the previous measurements, we will be able to verify if this new modeling strategy improves the accuracy of linearity simulations of the circuit compared to the usual analytical models.

1.2 State of the art

1.2.1 Non-linearities for frequency generation

This concept is really important to be defined because in the end all electronic devices are nonlinear and depending on their application, these effects are desirable or not. So, this is the case for frequency mixers where the non-linearities are involved in the frequency translation.

New frequencies are generated in non-linear circuits described by a power serie of the input voltage Eq. 1.1.

$$I = A_1V + A_2V^2 + A_3V^3 \tag{1.1}$$

The polynomial modeling of the non-linearity will appear new frequencies generated from the signal input V. All the mixing frequencies produced that are linear combinations of two or more tones are often called intermodulation (IM) [3]. Then can be extracted that the nth-degree term in the series generates n^{th} order mixing products of the frequencies in its control voltage or current.

Now can be defined the intermodulation distortion(IMD), that is produced by the intermodulation products generated in an amplifier or communications receiver.[3] These often present a serious problem, because they represent spurious signals that interfere with, and can be mistaken for, desired signals.

1.2.2 FET and MOS Passive Mixers

A mixer is fundamentally a linear device because shifting a signal from one frequency to another obeys the superposition theorem which is a linear operation performed by a time-varying resistor. Such a resistor can be approximated by using the channel of a FET or MOS device at low drain to source voltages. [3]

The resistance of this linear channel can be modulated by applying a LO voltage between gate and source pins. When the V_{GS} drops below its threshold voltage, the channel becomes an open circuit; when the V_{GS} reaches its maximum value (close to 0.5 V) the channel resistance drops to few ohms. This range of resistances is adequate to achieve good conversion performance in a resistive mixer.

The advantages of such mixers are very low distortion, low 1/f noise, and no shot noise; since the high-frequency noise is virtually entirely thermal, the noise figure equals the conversion losses [3].

1.2.3 Other works

The test bench described in Figure 1.1 is inspired by the one presented in [4][5]. These authors made simulations and measurements of the intermodulation products after filtering the output of the mixer. They found an excellent agreements between measurements, theory and simulations. They concluded by the validity of the slope of 3 dB/dB for the third intermodulation products. But we do not see very well that this 3 dB/dB is respected in any power range. In addition, the poor 18 dB isolation of the coupler makes each source sensitive to the other one.

Figure 1.1 displays the main blocks of this test. The goal of this is to corroborate his results and see if can be increased the range of measurements, especially for low power levels.

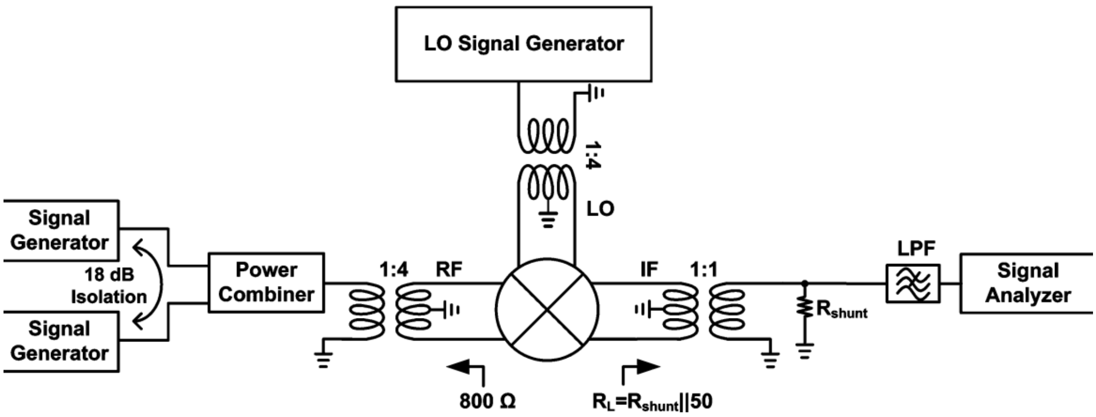


Figure 1.1: Passive mixer measurement setup[4]

Then these results in Figure 1.2 show that the range of mixer's input power is from -15 to 5 dBm and the power output is at a simple view between -125 and -65 dBm for the 500kHz intermodulation product obtained with an Local oscillator (LO) frequency of 500Mhz.

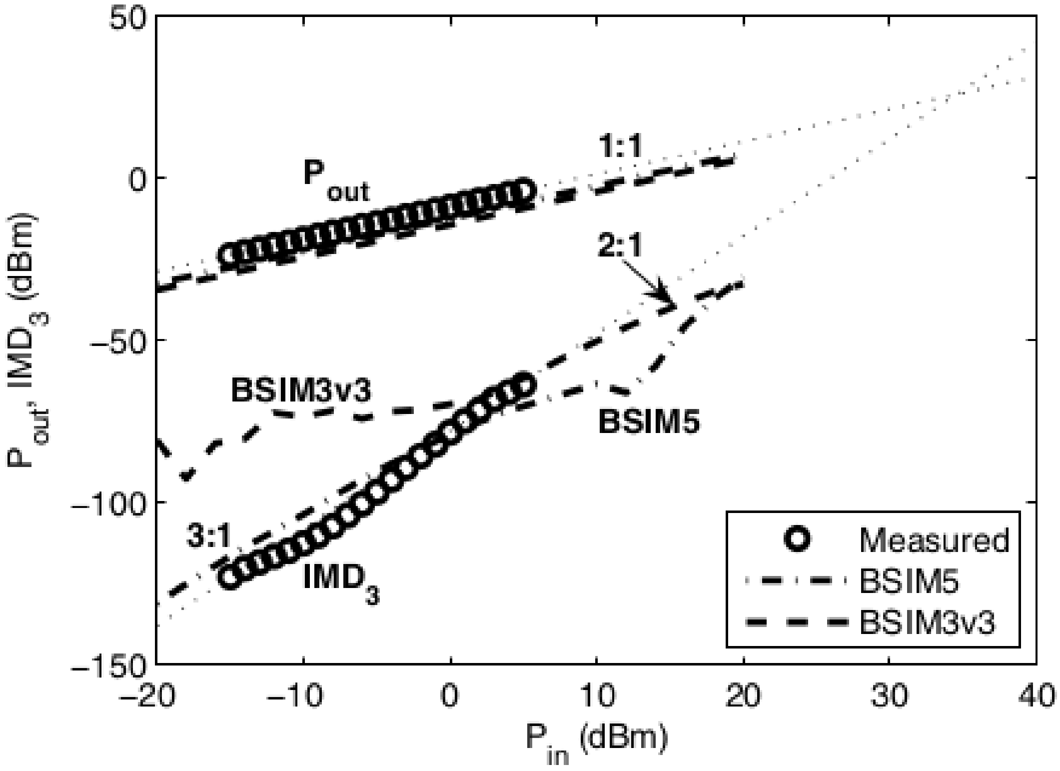


Figure 1.2: Intermodulation measurements from [4]

CHAPTER 2 INTERMODULATION MEASUREMENTS

2.1 Test Bench

For measure, only the third order intermodulation product is necessary to filter the mixer output. Figure 2.1 exhibits the schematic of test bench to measure the intermodulation products. At the each output of the signal generators f_1 and f_2 are located attenuators of 20dB, to avoid that intermodulation distortion products could be generated by the mix of these two signals. Combiner has isolation between its two input ports, then this device will reduce the creation of intermodulation products.

A variable attenuator is placed at the output of the combiner for control the carriers levels. The splitter is employed to measure the mixer's total input power at its RF port. Table 2.1 lists the frequencies used to perform the intermodulation measurements. A low-pass filter is added at the mixer's input for isolate the lower intermodulation frequency f_6 from the rest of the signals to avoid intermodulation produced inside the measuring instrument. This filter integrates an amplifier to lower the level of the noise floor of the spectrum analyzer and increase the level of the measured tone.

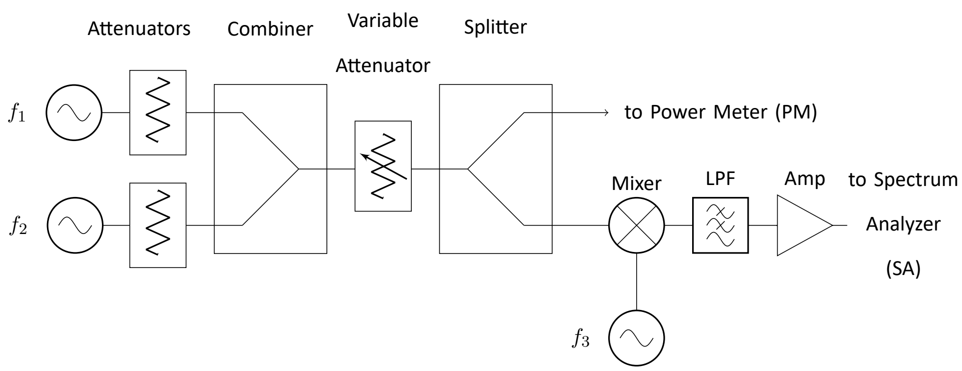


Figure 2.1: Intermodulation test bench

Carriers	Frequency (MHz)	Description
f_1	520	Carrier 1
f_2	539.5	Carrier 2
f_3	500	Local Oscillator (LO) with +15dBm
f_4	20	$f_1 - f_3$ (Intermediate Frequency)
f_5	39.5	$f_2 - f_3$ (Intermediate Frequency)
f_6	0.5	$2f_4 - f_5$ (IMD3-Low)
f_7	59	$2f_5 - f_4$ (IMD3-High)

Table 2.1: Frequencies and RF sources used in the test bench

2.1.1 Devices and Instruments of the Test Bench

In Table 2.2 are detailed all the components and instruments used in the test bench.

Device	Model	Description
VNA	OMICRON BODE 100	1Hz to 40MHz
Power Meter (PM)	ANRITSU ML2437A	10Mhz-40GHz, -70 to 20 dBm
Spectrum Analyzer (SA)	Keysight Field Fox N9951A	44GHz 25dBm Max
Signal Generator (f_1)	MARCONI INSTRUMENTS 2023	10 kHz-1.2 GHz
Signal Generator (f_2)	Hewlet Packard 8648C	100kHz- 3200MHz
Signal Generator (f_3)	ROHDE & SCHWARZ SMY02	9 kHz - 2.08 GHz
Mixer	PE4140	DC to 6 GHz LO -7 to +20dBm
Low-pass filter	Designed in this internship	Two gain modes
Amplifier (Amp)	Amplifier	36.64 dB Gain
Attenuators	SMA 10dB	20dB each source
Combiner	Mini circuits ZN2PD2-63-S+	350 to 6000 MHz 20dB isolation
Splitter	ANAREN 40264	500 to 1000MHz 20dB isolation
Variable Attenuator	SA1101SMA	1.5 to 11 dB
Power Supplies	TTi PL330	32Volt 3 Amp Max

Table 2.2: Instruments and devices used for the test bench

2.1.2 Combiner and Splitter

The main purpose of Combiner and Splitter are add or split the two carriers, respectively. Combiner Isolation between input ports helps to reduce the signal level that enters from one input to the other. So is desirable to have a good isolation in order to reduce the IM between the sources. In Table 2.3 are shown the isolation characteristics of each device at the respective frequency. Mini circuit isolation is greater than Anaren.

Frequency	Isolation (dB) Combiner Anaren	Isolation (dB) Splitter Minicircuits
f_1	24,141	43,36
f_2	25,85	34,81

Table 2.3: Measured values from the isolation of the passive devices

Some test were made for assure for minimize the IM between sources. The best device for test bench setup will be shown in the next sections.

2.1.3 Mixer Conversion Loss

The passive mixer down-converts the carriers f_1 and f_2 into the tones f_4 and f_5, respectively. These signals have lower power levels than the original carriers and depend on the LO power lower and their carrier frequency. In the Table 2.4 is presented the down-conversion losses obtained with same test bench schematic but with some changes. Just one signal source was enabled and without the filter and amplifiers, then the SA was connected directly to the mixers output.

One IMD3 product from the original carriers was obtained inside the signal sources $f_8 = 2f_1 - f_2$ with a Frequency of 500.5MHz was considered. If this frequency is down-converted with the same LO it will contribute to our final measure of 500 kHz IMD3 signal.

Down-converted signals	$f_1 \rightarrow f_4$	$f_2 \rightarrow f_5$	$f_8 \rightarrow f_6$
Frequency(MHz)	$520 \rightarrow 20$	$539.5 \rightarrow 39.5$	$500.5 \rightarrow 0.5$
Conversion Losses (dB)	17,56	17,97	16,05

Table 2.4: Down-conversion losses, with LO power of -15 dBm.

The losses are lower for the sources IMD3 than the two tone carriers, then It is necessary to check if the power levels at the mixer input to ensure that the contribution of this tone will not disturb the measurement of the desired signal.

2.1.4 Low Pass Filter

Design

This application requires an additional amplifier in order to measure the intermodulation products over a wide range of power levels without being annoyed by the noise floor of the measuring instrument.

The input impedance also needs to be kept as close to 50 Ω over all the frequency range to avoid new tones coming from the reflected waves getting back to the mixer and being mixed once again.

For getting better noise response without adding additional distortion a passive second-order filter was chosen with a cut of frequency close to 1 MHz to obtain a flat response around 500kHz. A resistor is placed at the output to calibrate the filter's quality factor.

Two filters were designed:

1. This Board has a similar attenuation of the two tones f_4 and f_5, the inductance's value was fixed by its self-resonance frequency that is located between 20 and 39.5 MHz. Then this design provides a good attenuation for high frequencies carriers and obtains a lower chance of intermodulation from the reflected downconverted signals.

2. The second board has a a better noise figure, so this means that the sensibility is improved. Also the cut-off frequency was increased, then the matching is better thatn the previous board.

The schematics for Board 1 and Board 2 done with KiCad are shown in Figures 2.2 and 2.3, respectively. Low noise low distortion operational amplifier (AD797) has been selected to provide the required gain. For the first board, we decided to implement two gain modes: High Gain mode with 28 dB and Low Gain mode with 14 dB. Board 2 has also two gain modes of: 37 dB and 24 dB.

The low noise design is obtained by following the manufacturer's recommendations. An additional filter with a cut off frequency 3.12MHz is placed at the end of the amplifier.

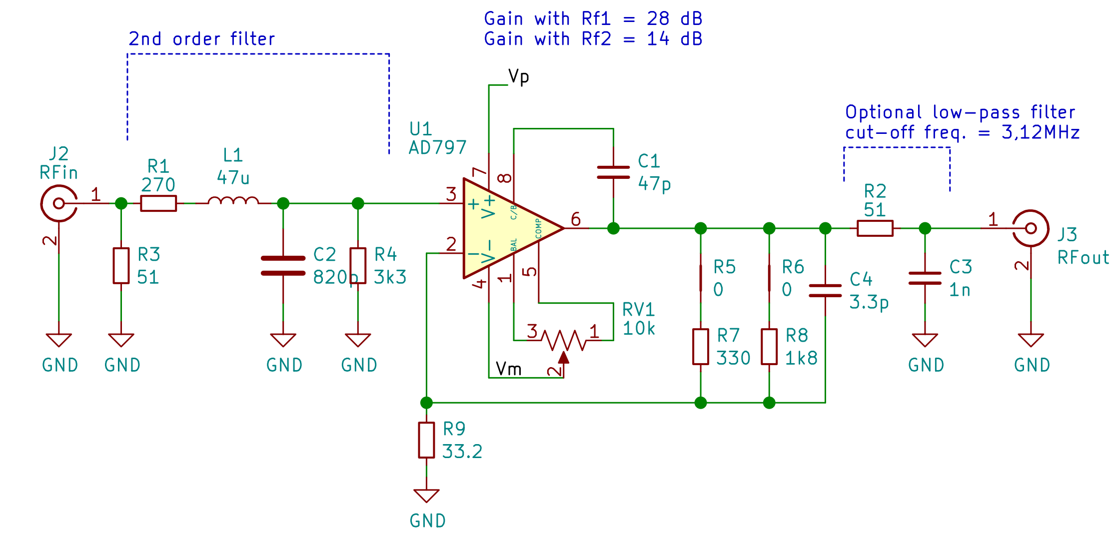


Figure 2.2: Board 1 schematic

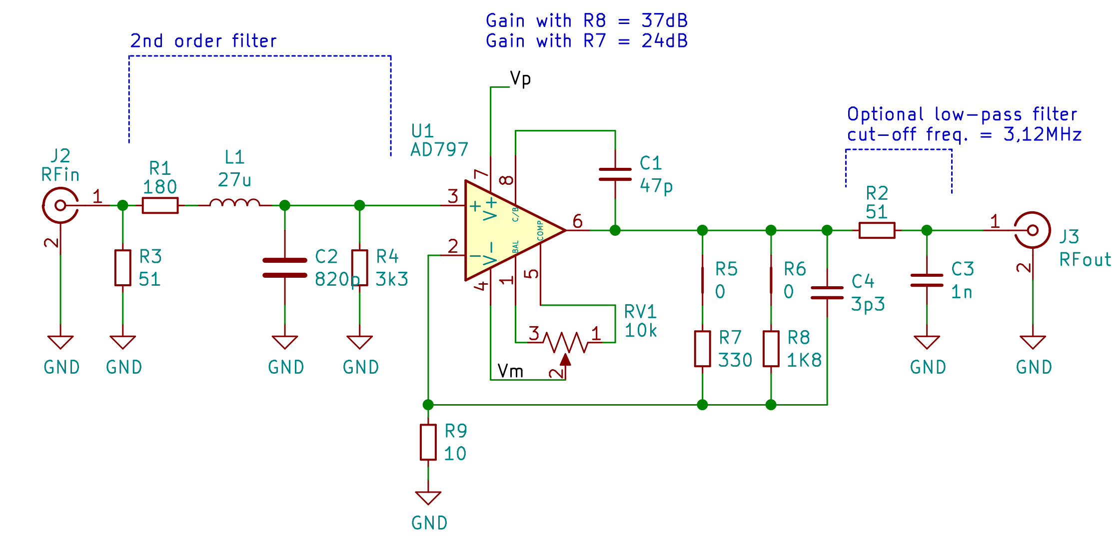


Figure 2.3: Board 2 schematic

Simulations and measurements results

The manufacturer's exact models of capacitors and inductances were used to simulate as close to the real circuit. The attenuation for both boars are greater than 60 dB for the frequencies above 20 MHz. Then this filter has an appropriate selectivity that provides a good response for the range of measurements and frequencies out of this bandwidth are highly attenuated.

A drawback of this filter is that it creates a region where its input impedance changes so this will generate a mismatch and could create a strong enough reflected wave that can go back to the mixer and create new intermodulation products.

The noise figure was estimated. The gain, and it's input impedance at 500kHz for 50 Ω, are shown in Table 2.5. As seen the values of impedance are close to 50 Ω, and the gains also has a good match. Finally, this design has been validated correctly for the application.

The response of all the board was measured with the VNA BODE100, this instrument characterizes and then generate the bode diagram of the device under test and extract the data directly to the PC. The Figure 2.4 shows the results got from the boards and in Figure 2.5 are presented the input impedances measured.

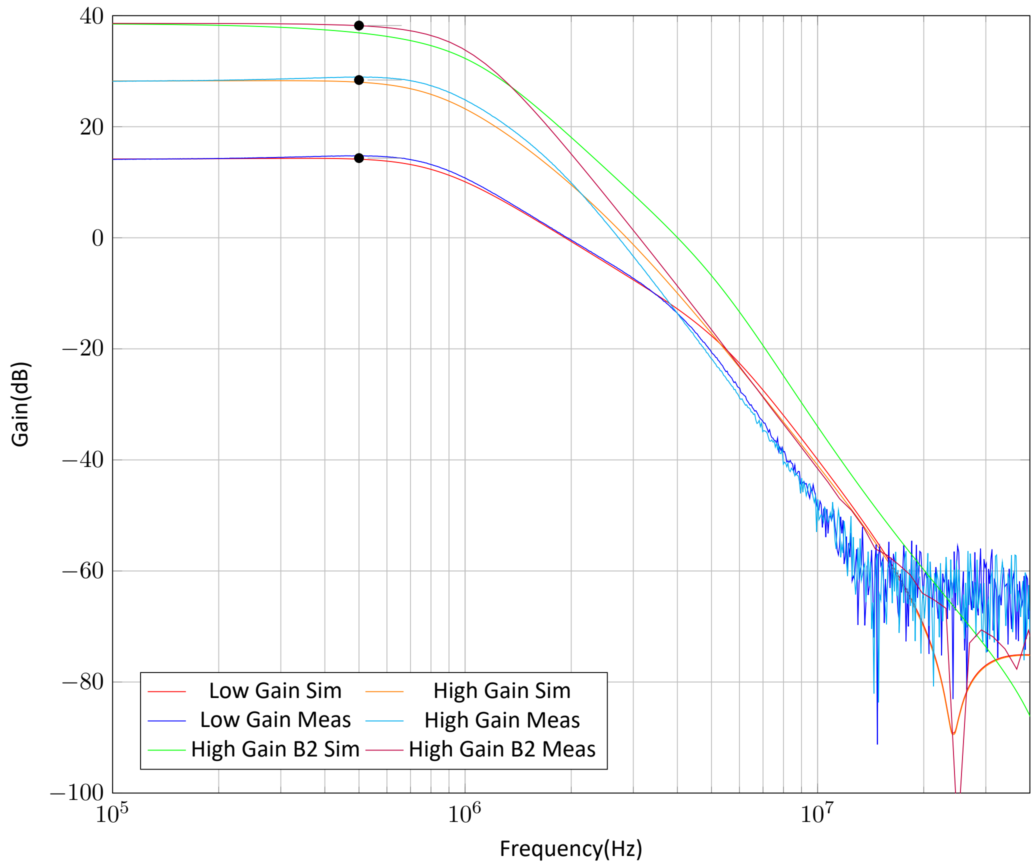


Figure 2.4: Gain Comparison between simulations and measurements

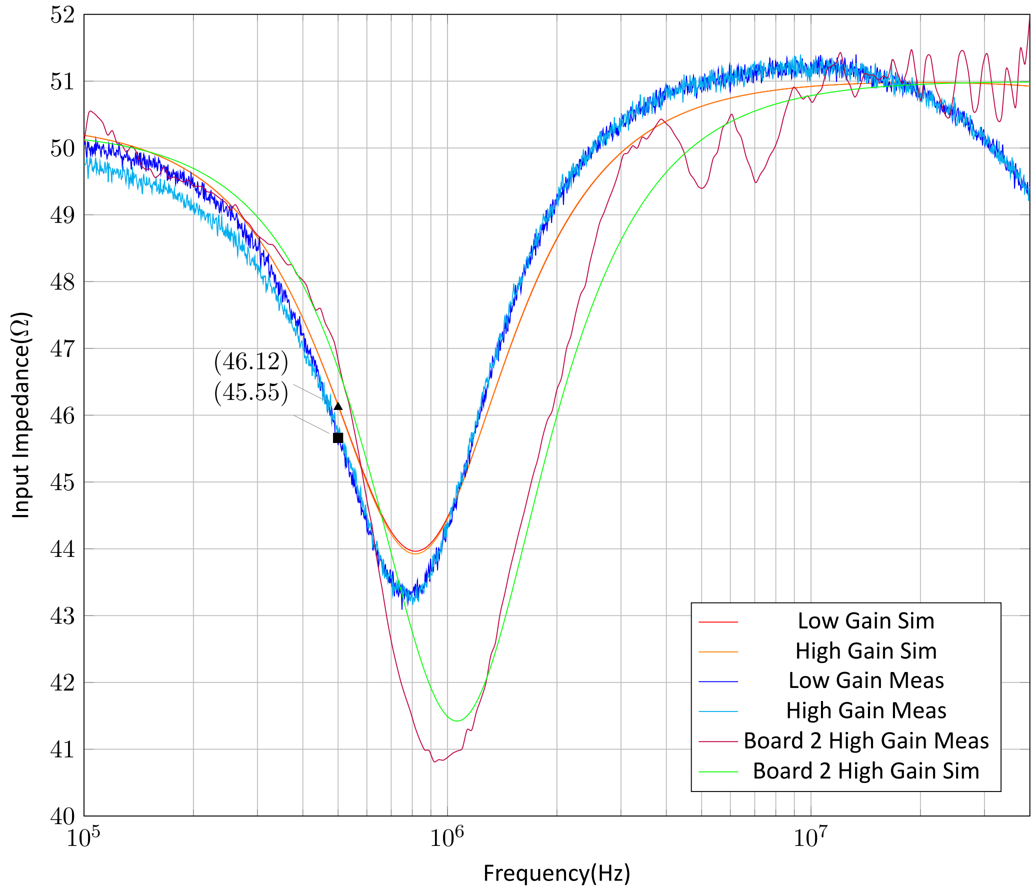


Figure 2.5: Input Impedance comparison between simulations and measurements

Board	Mode	Simulation		Measurements	
Number	Gain	Zin(Ω)	Gain(dB)	Zin(Ω)	Gain(dB)
1	Low	46.12	14.15	45.77	14.74
1	High	46.12	28.01	45.56	28.92
2	High	46.68	36.89	46.73	38.22

Table 2.5: Resume of the tests and simulations

In general, these results are close to the values obtained by the simulations for a high impedance load. Also was added the characterization of an additional amplifier with a higher gain (36.64 dB) will be used for the first board during these experiments.

2.1.5 Mixer input power calibration

It is necessary to measure the total power at the mixer's input to ensure the correct power level and check that all down-converted signals are produced by the carrier's power. If there are other intermodulation products and their harmonics with high power levels it may contribute to the final measure at the output of the board.

For measure, the source's intermodulation products in Figure 2.6 displays the schematic for this test and uses both ports of the Splitter to measure with the two instruments: the Power Meter(PM) and the Spectrum Analyzer(SA).

This procedure showed that the power measured with the Spectrum Analyzer at each Tone F_1 and F_2 varies linearly but comparing this result of the Power Meter with both carries, this last instrument at high levels reveals a non-linear response that can be seen in Figure 2.7. In it can be found the data from each tone, the pure tones sum, and both tones at the same time. The sum is equal to the measure of both tones at low power levels but at the top values can be found a small difference. The power levels difference between the ports of the Minicircuits as Splitter is 0.01 dB, where port1 power is greater than the other.

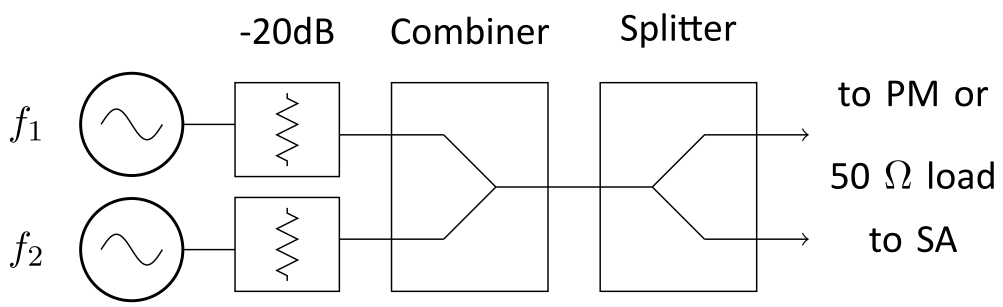


Figure 2.6: Sources intermodulation test

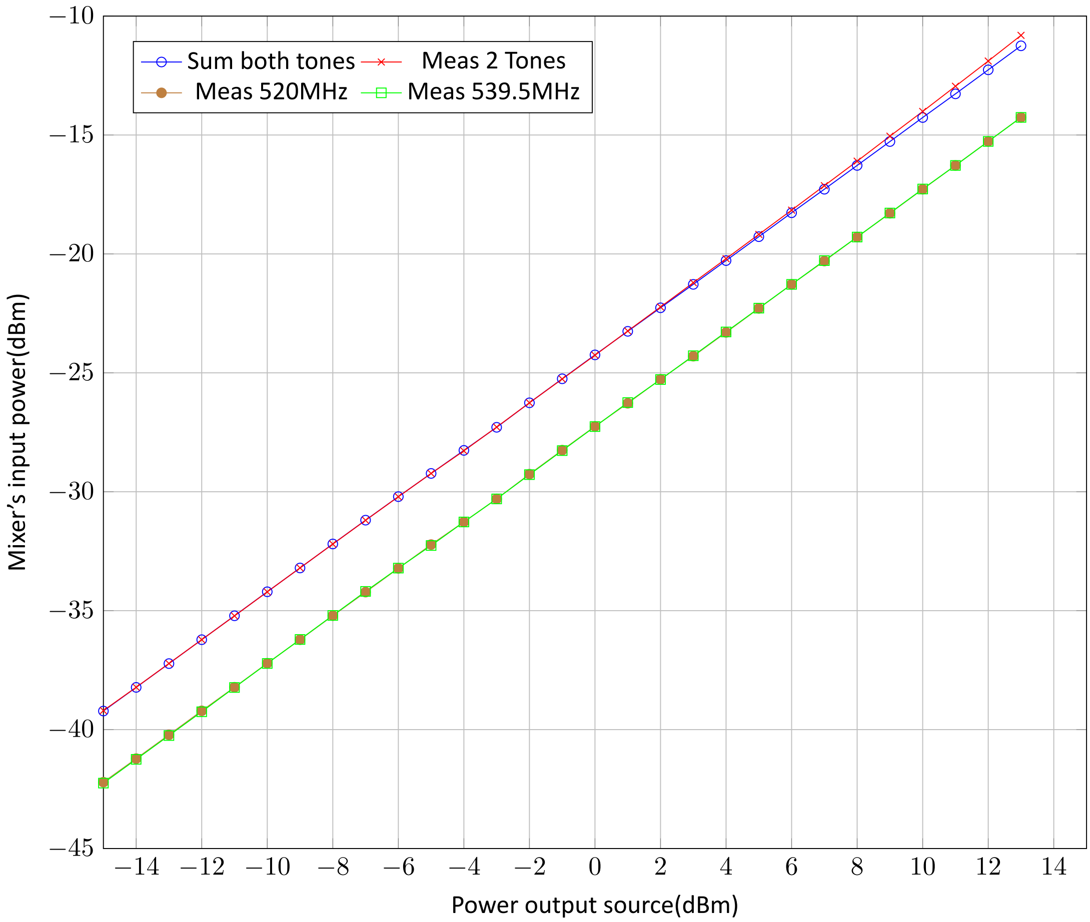


Figure 2.7: Mixer's input power calibration

For a better view of the intermodulation effects, in Figure 2.8 shows the difference between the 2 tones sum and measures, where at source's power levels higher than 0 dBm exist and increasing difference.

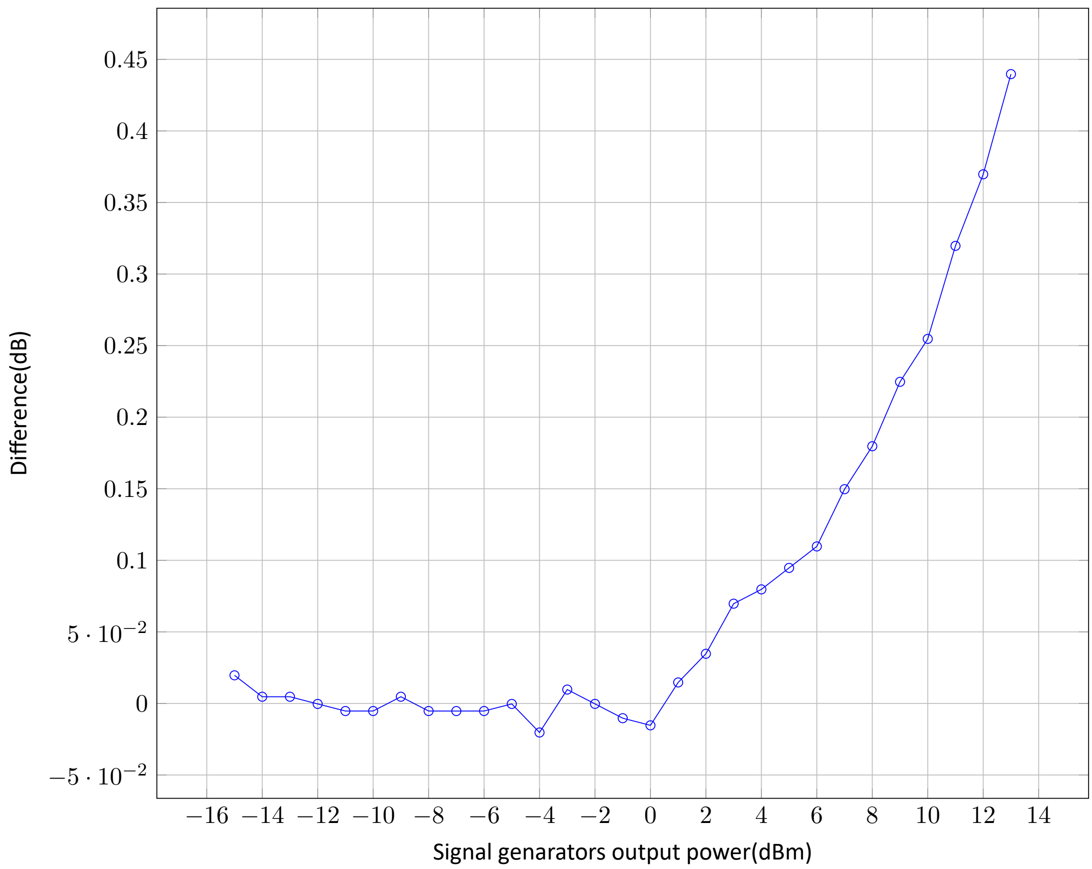


Figure 2.8: Intermodulation inside signal generators

Finally, the Spectrum Analyzer was used to measure the f_8 intermodulation power levels. These are lower than -87.13 dBm so if they enter to the mixer the contribution will be -103.16 dBm. The lowest IM power levels are achieved using ANAREN as Combiner and Mini circuits as Splitter.

Pin (dBm)	Power 500.5 Mhz (dBm)			Power 0.5 MHz(dBm)
	50 Ω	PM	12dB Attenuator	Downconverded
13	-89,14	-87,13	-89,24	-103.16

Table 2.6: 500.5 MHz carrier level power at splitter with differents loads

This result also shows that the original test setup from [4] in Figure 1.1, it has not been taken into account the intermodulation products generated by the signal sources and by the lack of attenuation, the test's results are not only produced by the mixer.

2.1.6 Intermodulation measurements

The intermodulation measurements from the test bench are presented in this section. The spectrum analyzer has an internal pre-amplifier that was enabled to lower the noise floor for increase the range of measurements. The results in Figure 2.9 shows the data with the use of this option. The curves correspond to the measured done with both boards.

Figure 2.9 shows the results from the measure of the power from the lowest frequency intermodulation distortion product at the output from the mixer. All the data values were threaded and as seen in the four cases the power levels are overlapped after the subtraction of the gain provided by the amplifiers.

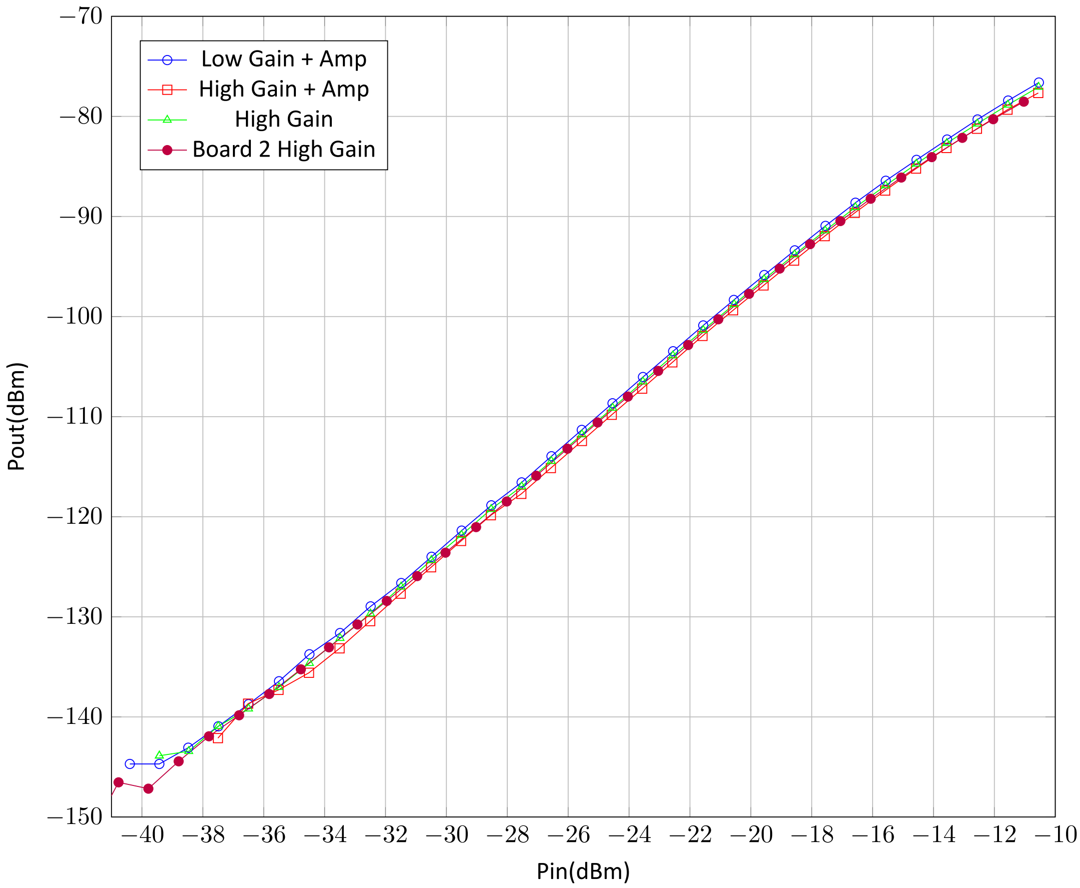


Figure 2.9: Intermodulation measurements with pre-amplifier enabled

From the reference test [4] in Figure 1.2. The mixer's input measurement power range with the board was increased from 20 to 50 dBm, also the intermodulation distortion products were measured at lower power levels.

These results displayed in Figure 2.10 show that the slope for the third-order intermodulation distortion product is not 3 or even a fixed integer. In the three cases can be seen that at low power levels the slope has an average value close to 2.6. At higher power levels than -23 dBm, the slope magnitudes decrease from the average.

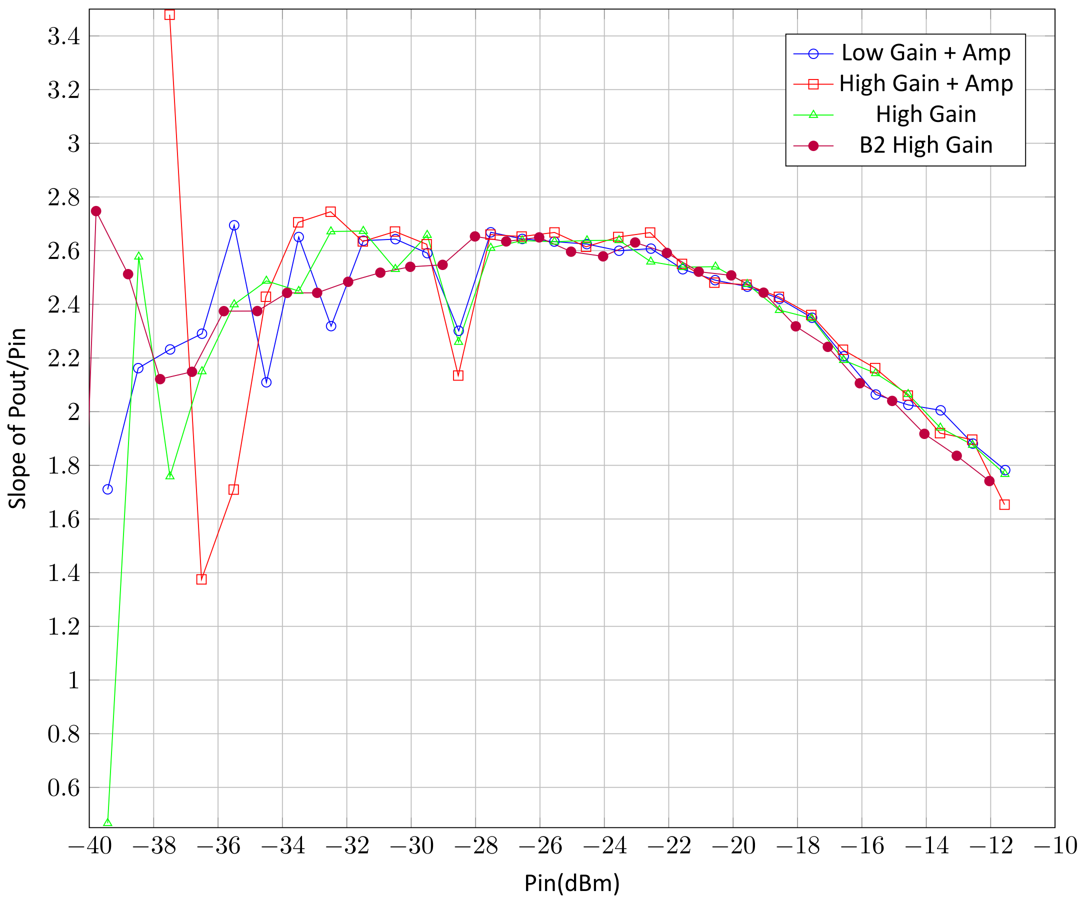


Figure 2.10: Slopes obtained from the measurements with the pre-amplifier enabled

In the area around -27 dBm the negative peak is due to the change of the internal attenuators from the signal sources. The option of hold the attenuators was used for the second board, but the range was only increased by some dBm. So the variable attenuator was used to decrease the input power to the mixer.

CHAPTER 3 DATA MODELING

3.1 Device modeling

The first part is related to the characterization of the mixer that will be used during this study. The current data obtained from the MOSFET's inside the device was translated to a floating configuration as seen in Figure 3.1, so the reference of the gate voltage is defined as the half of the voltage between drain and source. This expression is presented in Eq. (3.1).

$$V_{GG} = V_{GS} - \frac{V_{DS}}{2} \tag{3.1}$$

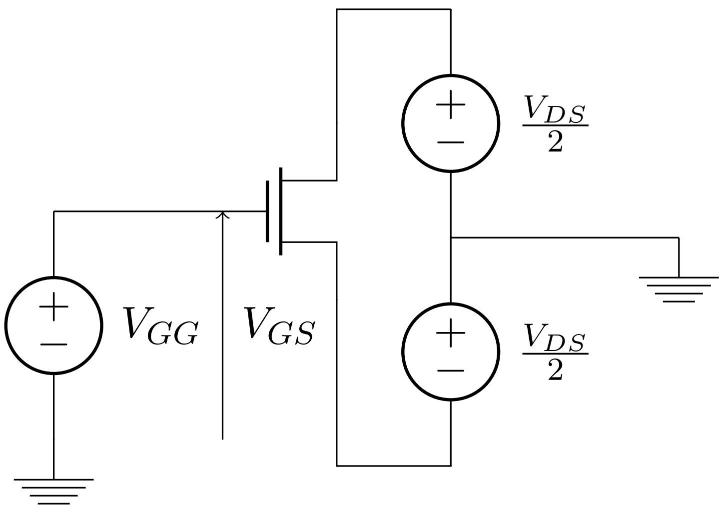


Figure 3.1: Schematic for DC analysis of a NMOS transistor

From the original data set provided were extracted the current values for one MOSFET, the result is showed in Figure 3.2. As seen each color represents I_{DS}current in function of V_{DS} at a specific V_{GG}, then all the data is in function of these two variables, $I_{DS} = f(V_{DS}, V_{GG})$. Also, all the curves pass through the origin and then go to each side linearly until reach +/- 0.6 V_{DS}.

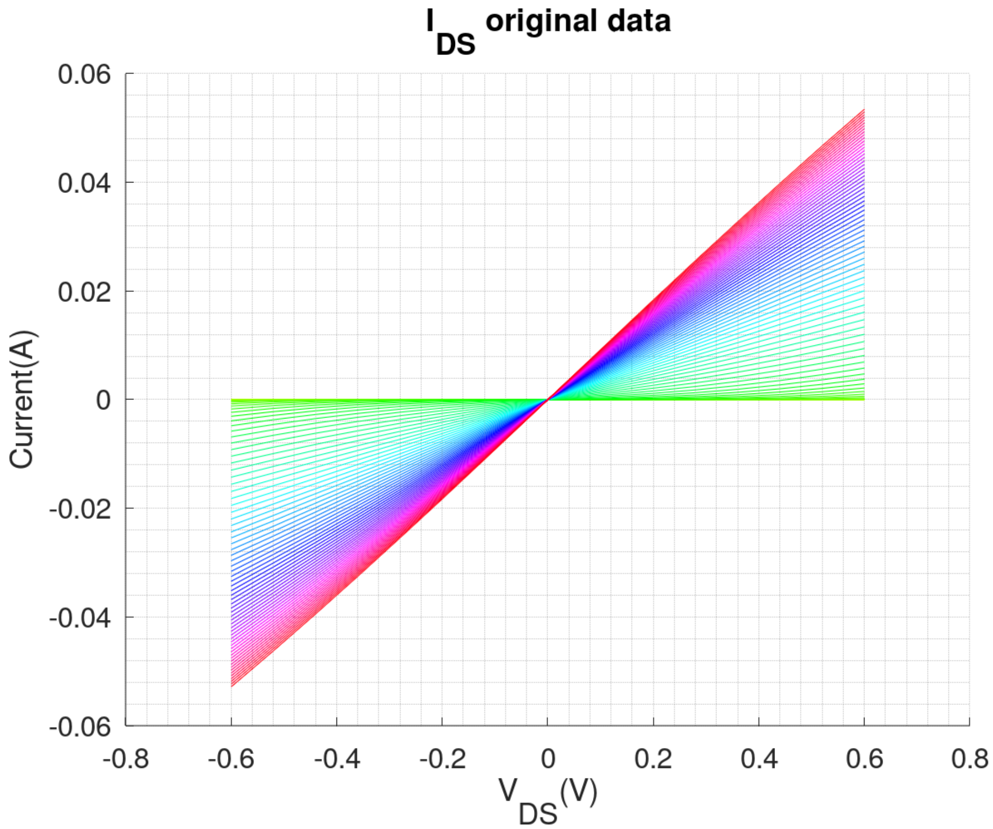


Figure 3.2: Mosfets currents measured

As seen all current curves follow behave close as an asymmetric function, because the magnitudes in the left side, in negative V_{DS} part, are at a first look the same value than in the positive V_{DS} for the same voltage magnitude. To fit with a polynomial function this data, each current will be split into two types of functions: asymmetric and symmetric functions as showed in Eq. (3.2).

$$I(V_{DS}) = I_{symmetric}(V_{DS}) + I_{asymmectric}(V_{DS}) \tag{3.2}$$

Asymmetric part is defined with the following expression :

$$I_{asymmetric} = \begin{cases} C_{asymmetric} & V_{DS} > 0 \\ -C_{asymmetric} & V_{DS} < 0 \end{cases}$$

Where $C_{asymmetric}$ can be obtained with the Eq. (3.3). This is the half difference between the positive and negative V_{DS} .

$$C_{asymmetric}(|V_{DS}|) = \frac{I(V_{DS+}) - I(V_{DS-})}{2} \tag{3.3}$$

Now, for the symmetric part is needed to find the difference between the original and the asymmetrical part. I_{diff} is defined in Eq (3.4) and is equal to this subtraction.

$$I_{diff} = I(V_{DS}) - I_{asymmetric}(V_{DS}) \tag{3.4}$$

Symmetric part is defined with the following expression :

$$I_{symmetric} = \begin{cases} C_{symmetric} & V_{DS} > 0 \\ C_{symmetric} & V_{DS} < 0 \end{cases}$$

In contrast to an asymmetric function, the symmetric is defined as the half sum for each positive and negative V_{DS} as seen in Eq (3.5).

$$C_{symmetric}(|V_{DS}|) = \frac{I_{diff}(V_{DS+}) + I_{diff}(V_{DS-})}{2} \tag{3.5}$$

In Figures 3.3 and 3.4 are shown the asymmetric and symmetric parts, respectively. The maximum amplitude in the total current is almost the same as the Asymmetric part, and it can be proved by the low magnitude for the symmetric part.

Another thing found in this graph is that there is a non-equal shape in some currents at the symmetric part, at low current values (green and cyan) the shape is different and probably is due to errors from the instrument of measure.

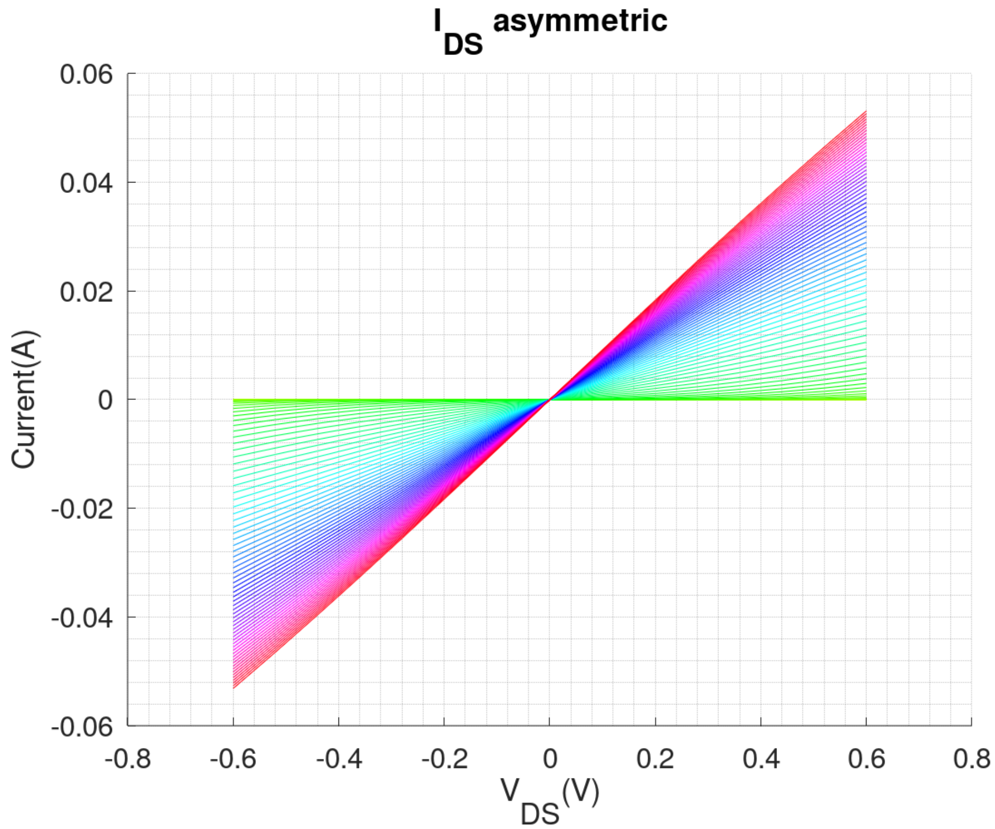


Figure 3.3: Asymmetric part

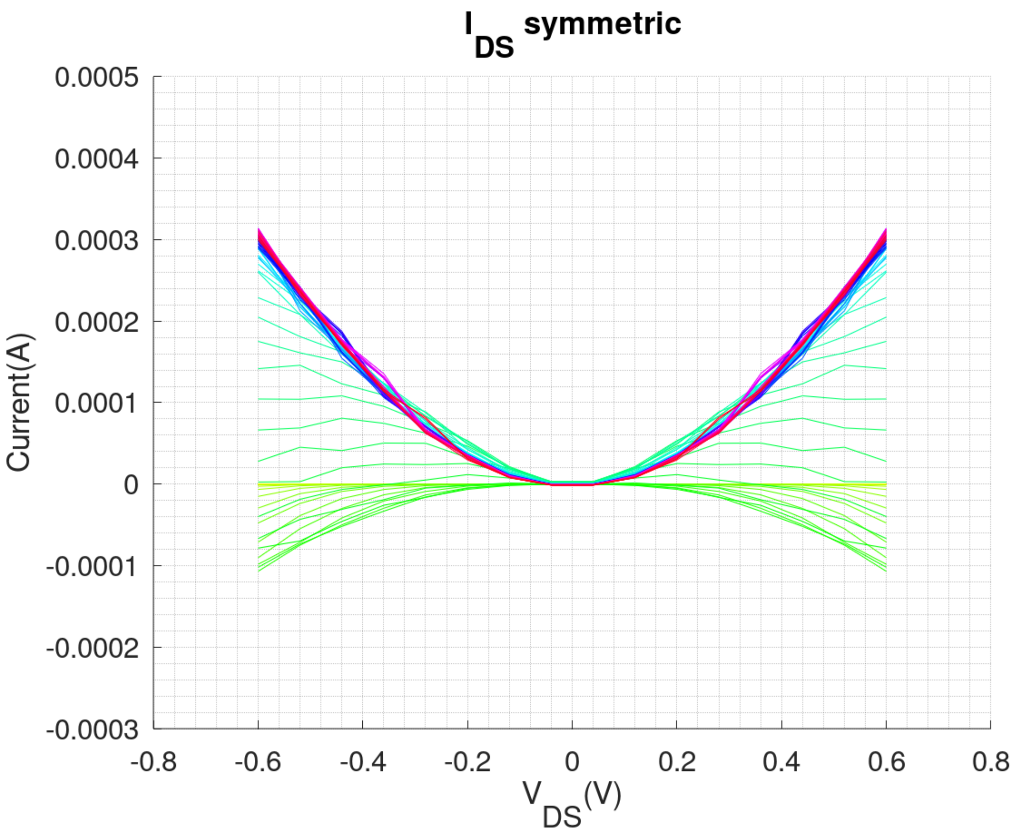


Figure 3.4: Symmetric part

3.1.1 Polynomial Modeling

Both parts of the current, asymmetric and symmetric will be fitted with a polynomial model of the third degree. This restriction is due to the creation of the third intermodulation product that is required for the theory to exist at least the same degree in the model.

Asymmetric Model

The asymmetric model fitting is the main work because these currents are the most representative in magnitude. So for this case, there must exist coefficients of odd degree, in Eq. (3.6) these are denoted A_{1a} and A_{3a}, the subindex (1a) denotes that is the first coefficient for the asymmetric part.

$$I_{asymmetric} = A_{1a}V_{DS} + A_{2a}V_{DS}^2 + A_{3a}V_{DS}^3 \tag{3.6}$$

The least mean square method was selected as the procedure for fitting these curves, but this method only ensures that the error will be the lowest. This not means that the coefficients will have a physical meaning so it is needed to find another solution to set the values of the coefficients. The software used for this task is Octave and has its own function.

To extract the first coefficient, the method used is to divide $I_{asymmetric}$ for V_{DS}, this result is in Eq.(3.7) where now is defined the Conductance of the asymmetric model $G_{asymmetric}$ with the coefficient A_{1a} as a constant so it could get at the origin of V_{DS} when it is 0V.

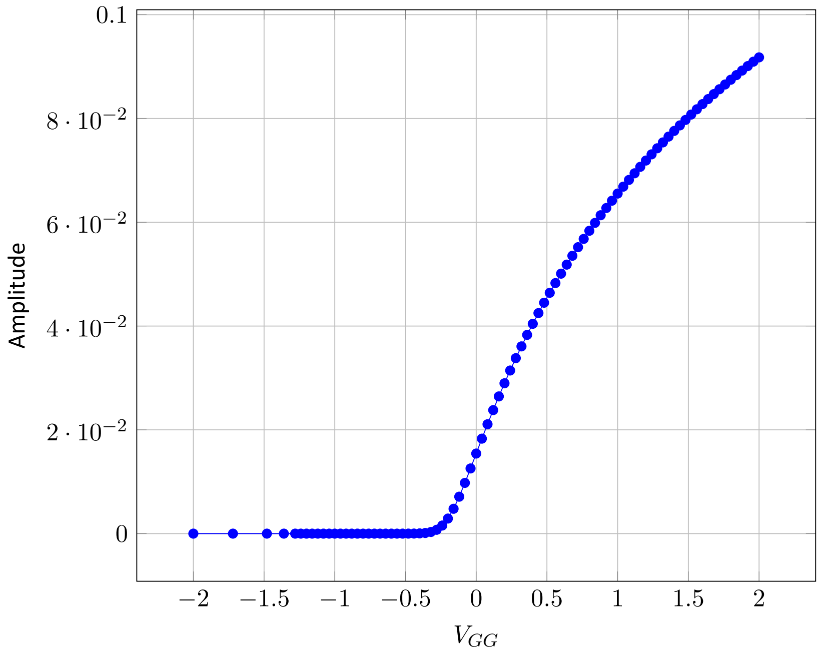
$$G_{asymmetric} = A_{1a} + A_{2a}V_{DS} + A_{3a}V_{DS}^2 \tag{3.7}$$

If in $G_{asymmetric}$ expression is subtracted the value of the new constant, this at the end can be used to create a new polynomial equation with one degree less and then this new expression can be fitted with the least mean square method. This procedure was used especially in this part and the constant-coefficient value is currently set.

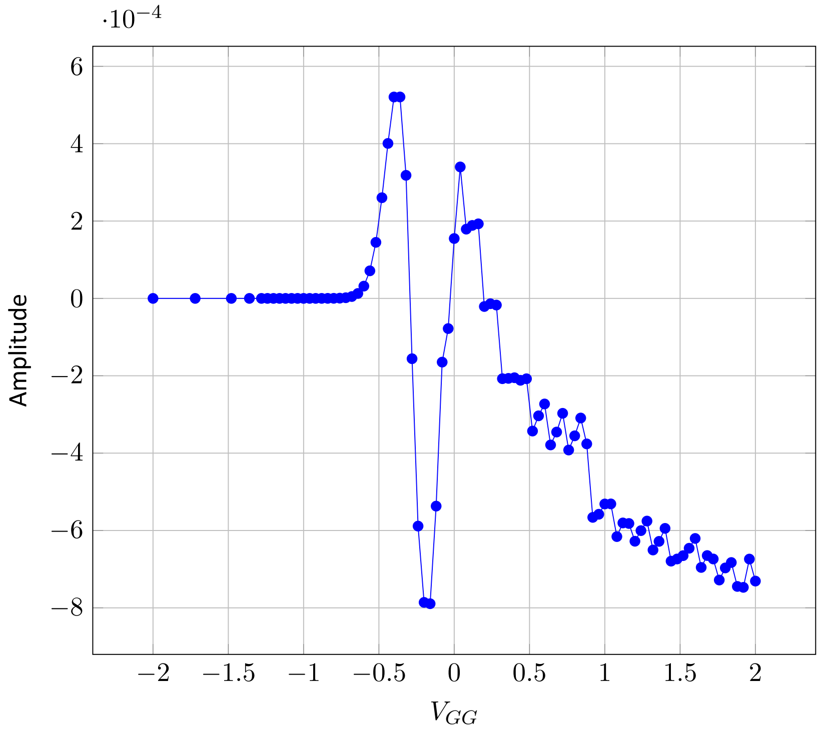
The final fitting with one of the lowest relative error showed in Figures 3.5a,3.5b and 3.5c of the coefficients A_{1a}, A_{2a} and A_{3a} respectively.

After viewing the result can be established that the coefficient with the biggest influence is the A_{1a} where its maximum amplitude is close to 0.1 and in all the positive V_{GG} it is located. Then the third term A_{3a} is who has also an important contribution to the model but in this case, is negative in all the positive V_{GG} so it presents restriction to avoid the magnitude of the current increase at high levels.

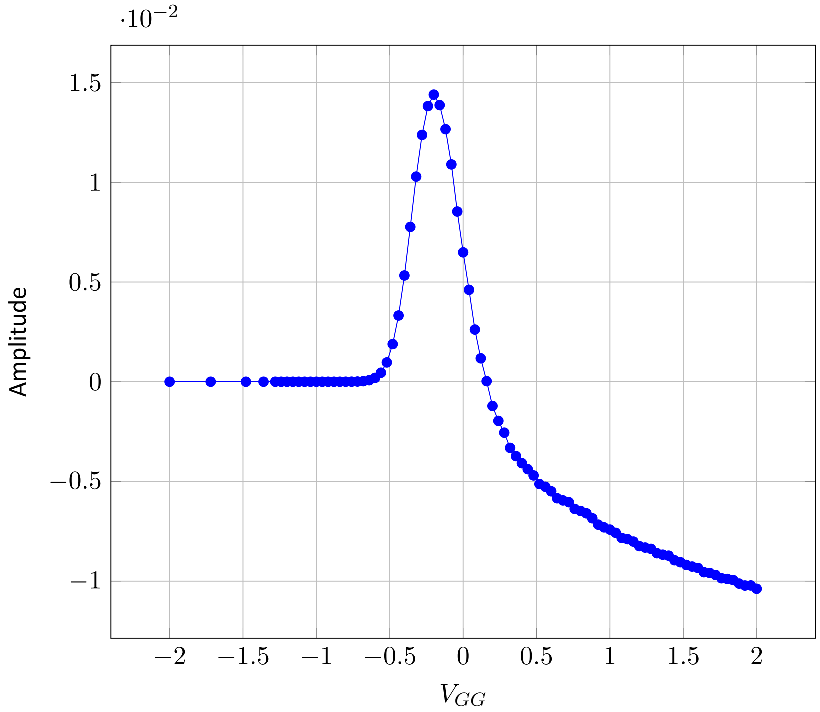
Finally can be said that the second term does not have a very smooth response as the others so probably this is just a way to reduce the error by the fitting algorithm.



(a) $A_1 a$ coefficient



(b) A_2a coefficient



(c) A_3a coefficient

Figure 3.5: Coefficients of Asymmetric Model

Figure 3.6 shows the relative error of the asymmetric model, where are displayed the curves of some V_{GG}. As seen the error in all the cases is close to being null but at the limits, their values are greater than in the other voltage range of V_{DS}.

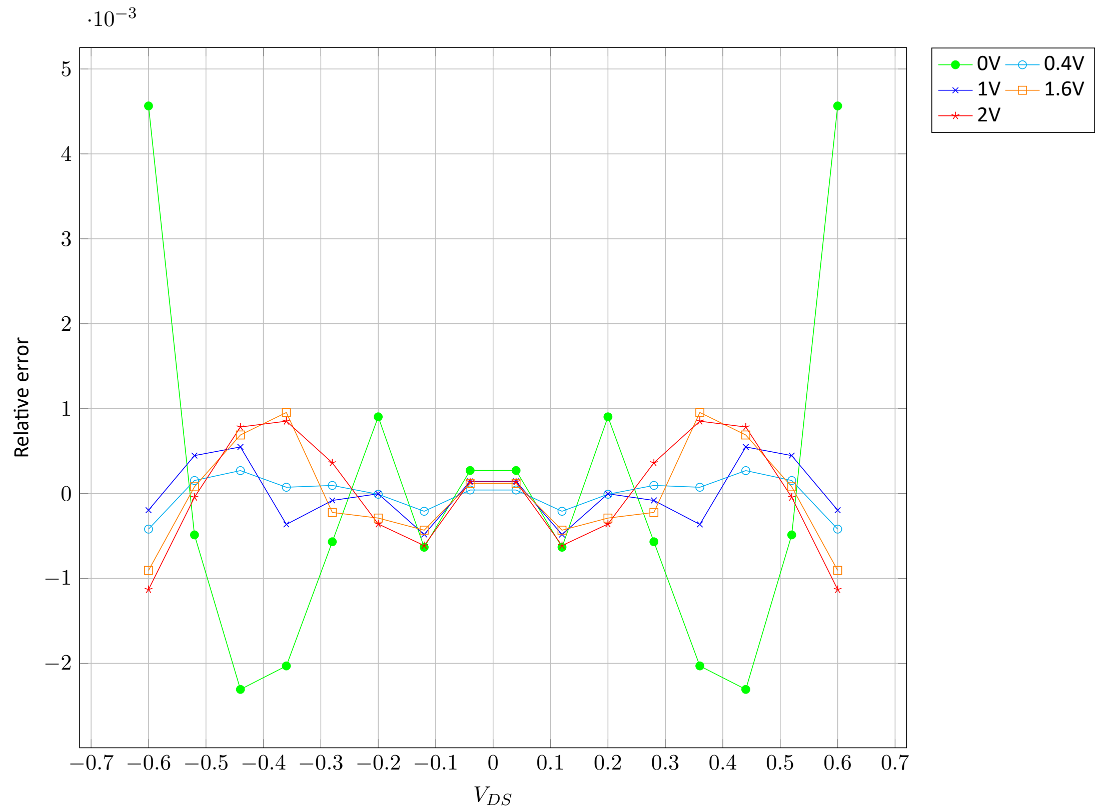


Figure 3.6: Relative error of Asymmetric model for some V_{GG}

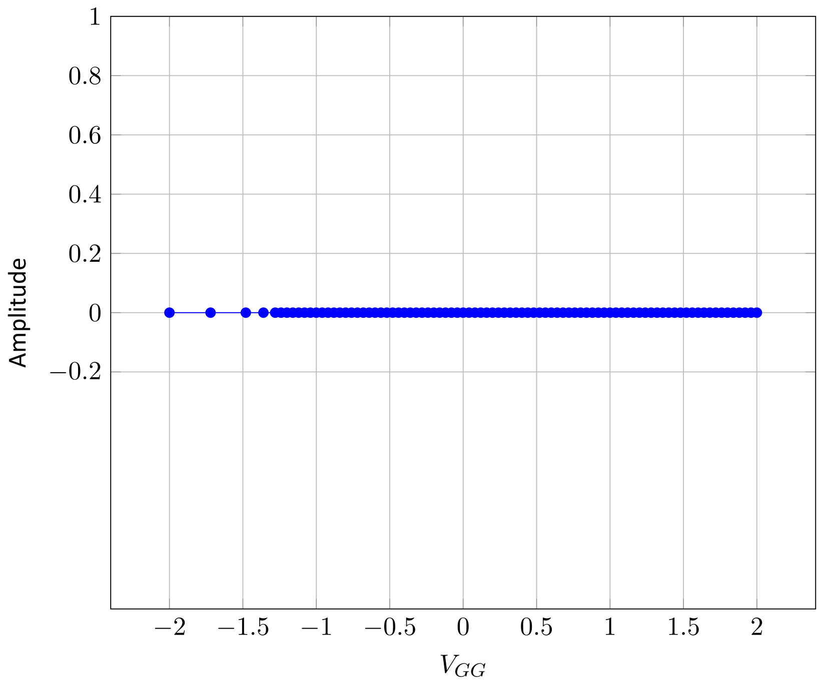
Symmetric Model

In this part, since the beginning was added a new coefficient that is attributed to constant term and it corresponds to a symmetric function. Eq(3.8) shows the new element added A_0 to the original expression to test if it would be important to be considered for the error calculation. The coefficients for these models are denoted with (A_{Xs}) where the 'X' is the number of the corresponding coefficient for the symmetric part.

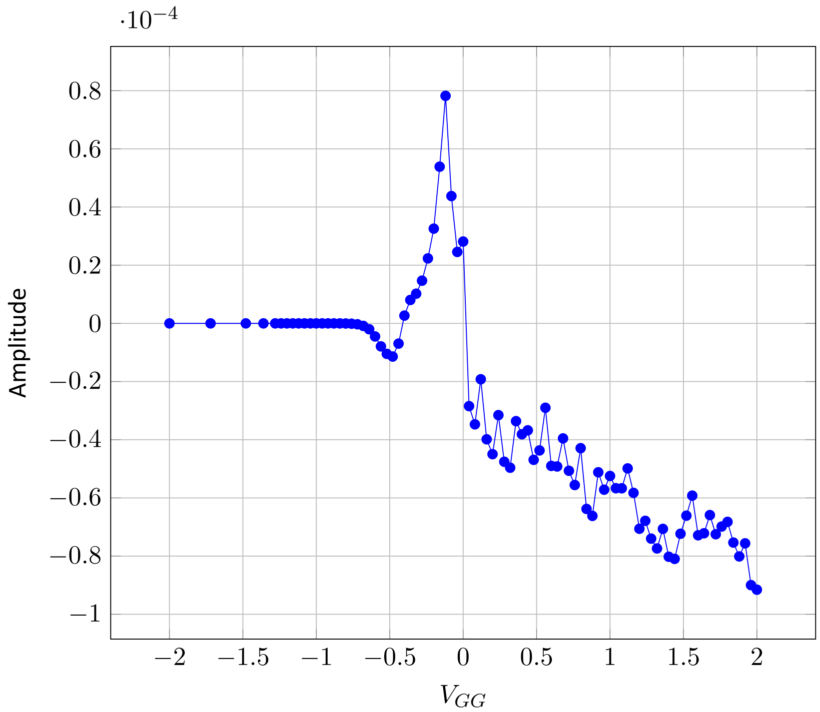
$$I_{symmetric} = A_0 + A_{1S}V_{DS} + A_{2S}V_{DS}^2 + A_{3S}V_{DS}^3 \tag{3.8}$$

Then in Figures 3.7a,3.7b, 3.7c and 3.7d are displayed the values of the A_0, A_{1S},A_{2S} and A_{3S}. After all the development was concluded that the value of the constant term introduced for this model the A_0 can be neglected, the error values obtained were the same as for the model that takes into account this, so for more simplicity, the value of this is set to 0.

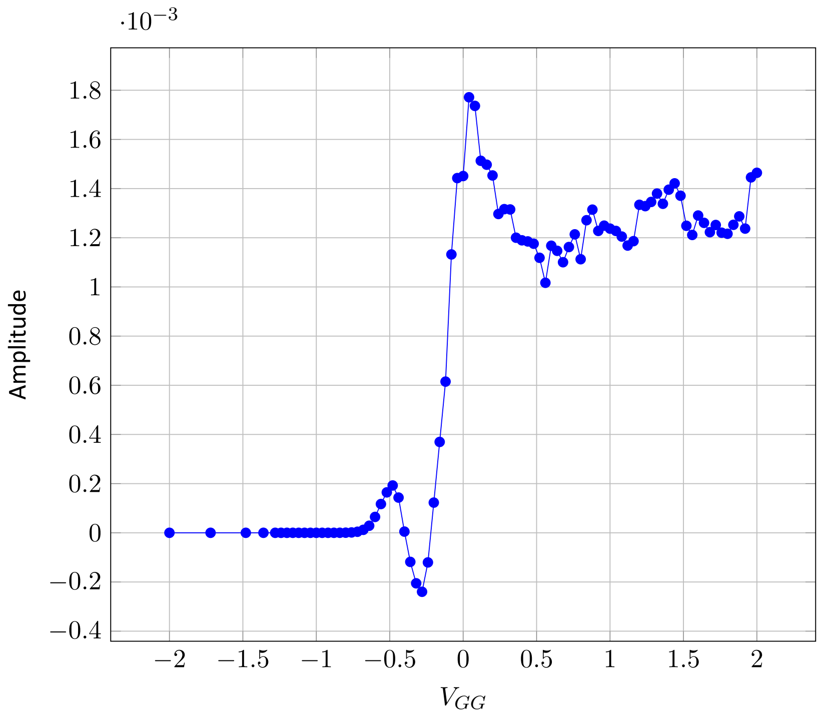
Then the element with more influence is the second as expected due to that corresponds to the symmetric model but it can be approached like a step response because at low V_{GG} is very small and after it's value remains close to a constant value. For the other coefficients, the second with more influence is the corresponding to the third degree, at low V_{GG} the amplitude, is greater but once in the upper limit the value is almost constant. Finally, the last coefficient is like 10 times smaller than the previous and it is always negative from 0V.



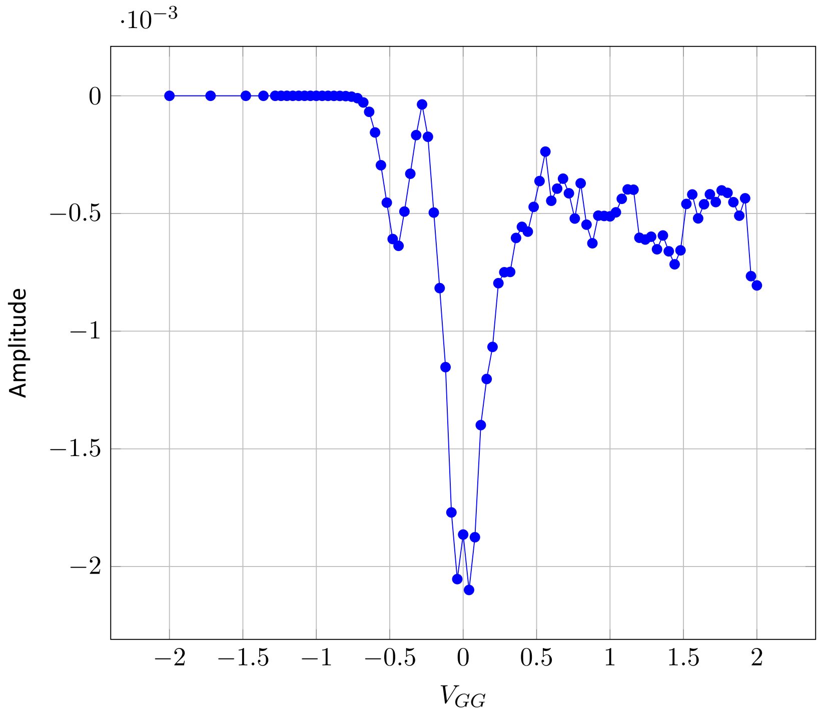
(a) A_0s coefficient



(b) A_1s coefficient



(c) A_2s coefficient



(d) A_3s coefficient

Figure 3.7: Coefficients of Symmetric Model

Figure 3.8 shows the graph of the relative error for the symmetric model, here can be found that just for values between the 0.6 to 1V the error is big, but due to this part of the symmetric current is smaller than to the asymmetric, this model has a good fit and low error for the values over 0V of V_{GG}

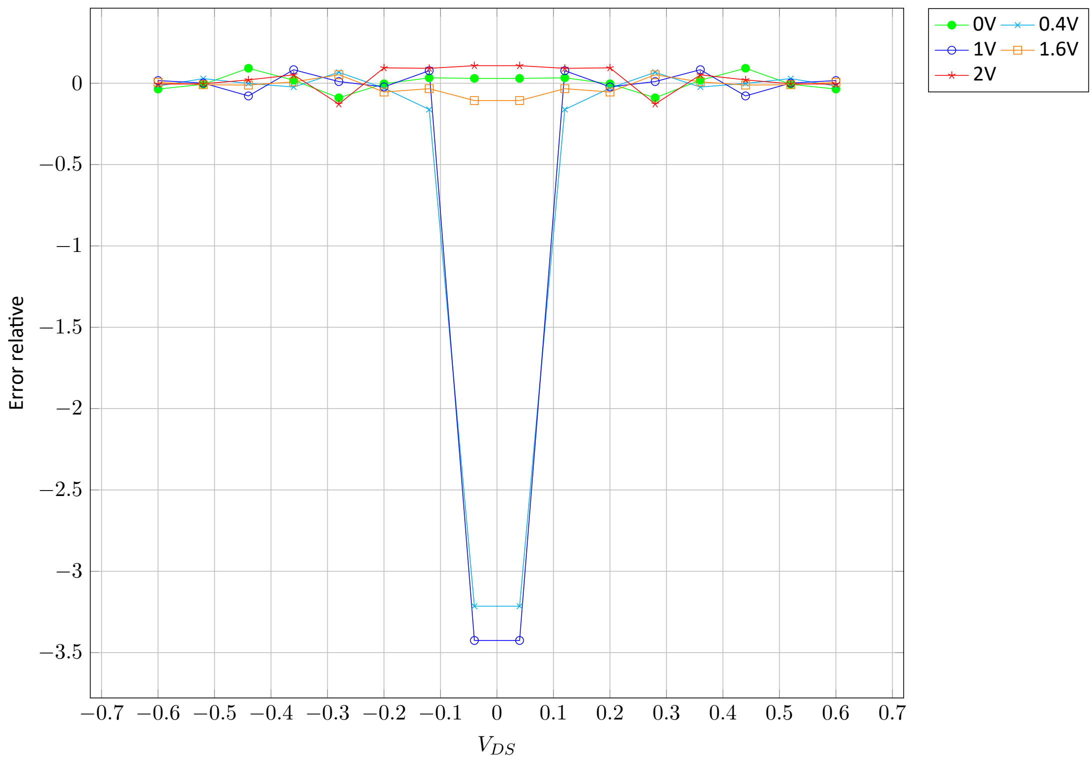


Figure 3.8: Relative error of Symmetric model for some V_{GG}

3.2 Device Simulation

In this section is going to be presented the simulation of the mixer over ADS software. The main goal is to simulate the total mixer behavior and get the intermodulation distortion products with a local oscillator generated by the software. First is needed to describe the mixer like a ring of MOSFETs where the local oscillator is connected to the gates as seen in Figure 3.9.

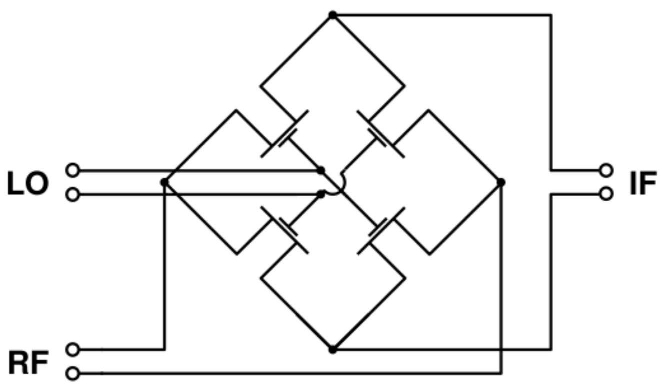


Figure 3.9: Internal schematic of mixer's mosfets

The basic device for the simulation is a non-linear voltage-controlled current source (NonlinVCCS), the main feature of this components permits to the current at the output being controlled by a voltage and its current expression is a polynomial like the developed model in the previous section, then only is required to load the coefficients into a data file to be simulated in a sequence.

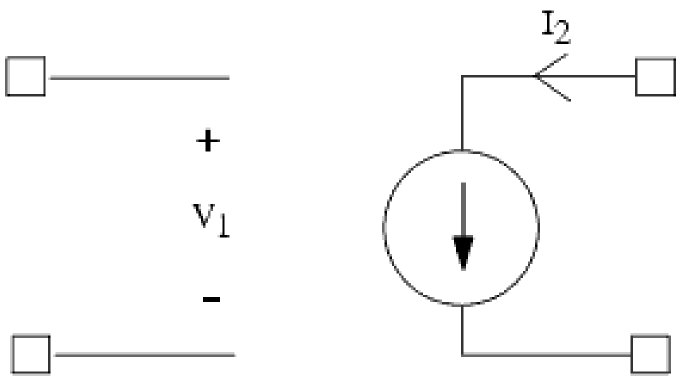


Figure 3.10: Symbol of the Nonlinear voltage controlled current source

Now in the next Figure, 3.11 is presented all the schematic done in ADS for the simulation. As seen it is a basic model that takes into account just the MOSFETs and the software's local oscillators blocks for the signals required.

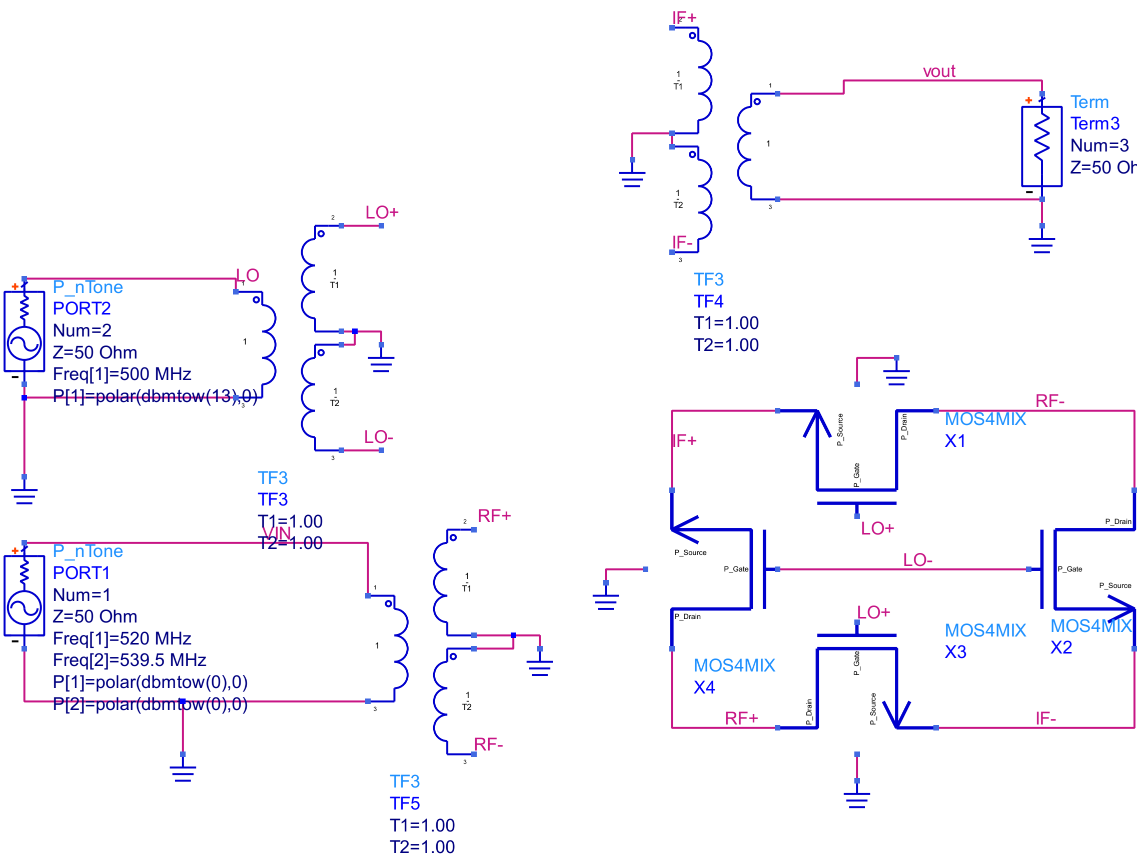


Figure 3.11: Mixer schematic in ADS

The simulation software didn't allowed to change the variables required for the test. Just one variable can be set. So will be required to ask help from the software creators for implement all the model.

CHAPTER 4 CONCLUSIONS

The characterization of the board showed that the results from the detailed simulation that took into account the exact models of the elements provided by the manufactures were almost accurate. The gain provided for an impedance of 50 Ω is almost equal for both modes of gain with their simulations.

Intermodulation distortion products found by the combination of both the signal generators can affect the final test because if these are not properly attenuated or managed can influence the mixer and generate higher power level signals of the intermodulation product. In the test setup from Khatri [4] shown in Figure 1.1 the isolation of 18 dB between ports is not enough for avoid the creation of these products and his results can be influenced by the intermodulation from the source. Another solution that could be applied is filter the input of the mixer[6].

The slope of the third intermodulation product is not equal to 3 dB/dB. The result found is that the for mixer under test it is close to 2.6 and at the top of the range it was decreasing to almost reaching 1.7. In this part, it is still something to look because there is one point close to the middle of the range that in the three tests it does not follow this value. But in the end, the results range was increased from the base test.

From the modeling part, the drain-source current can be described almost as an asymmetric function with a small contribution of a parabolic function that is a symmetric function. The coefficient in the asymmetric part with more influence is the fist, due to the linear behavior of the MOSFET at this region.

From the symmetric part was found that the contribution of the second term and can be seen as a step function. The model is still in development up to the current date to validate it and continue to the next step that is the simulation.

BIBLIOGRAPHY

[1] Jacques Sombrin. Non-analytic at the origin, behavioral models for active or passive non-linearity. *International Journal of Microwave and Wireless Technologies*, 5(2):133–140, 2013.

[2] Jacques Sombrin, Geoffroy Soubercaze-Pun, and Isabelle Albert. New models for passive non linearities generating intermodulation products with non-integer slopes. In *2013 7th European Conference on Antennas and Propagation (EuCAP)*, pages 25–28. IEEE, 2013.

[3] Stephen A Maas. *Nonlinear microwave and RF circuits*. Artech house, 2003.

[4] Himanshu Khatri, Prasad S. Gudem, and Lawrence E. Larson. In *Simulation of Intermodulation Distortion in Passive CMOS FET Mixers*, pages 1593 – 1596, 07 2009.

[5] Himanshu Khatri, Prasad S Gudem, and Lawrence E Larson. Distortion in current commutating passive cmos downconversion mixers. *IEEE Transactions on Microwave Theory and Techniques*, 57(11):2671–2681, 2009.

[6] *Intermodulation Distortion Measurements on Modern Spectrum Analyzers, Rohde & Schwarz, Application Note*.

APPENDIX A LTSPICE-OCTAVE

A.0.1 Code for Extract the curves

The following code reads the real and imaginary data in from the simulation file. The data saved is Frequency, Gain in dB, Input Impedance in Z as .dat file the first value correspond for 50 Ω and the next for 1 $k\Omega$ loads,.

```
#code for read and plot ltspice to octave
# 1) format the file extracted from ltspice in excel
clc
clear all
close all
%graphics_toolkit (”gnuplot”)
K=180/pi;
points=701;
#ids=csvread('mesures/currents.csv');

%data = dlmread ('LPF_V3_f1_Rg2H.csv',””,2,0);% read the file csv from 2nd row,
%data = dlmread ('LPF_V3_f1_Rg2L.csv',””,2,0);
%data = dlmread ('LPF_V3_f1_Rg1H.csv',””,2,0);
%data = dlmread ('LPF_V3_f1_Rg1L.csv',””,2,0);

%data = dlmread ('LPF_V3_f3_Rg2H.csv',””,2,0);% read the file csv from 2nd row,
%data = dlmread ('LPF_V3_f3_Rg2L.csv',””,2,0);
%data = dlmread ('LPF_V3_f3_Rg1H.csv',””,2,0);
```

```
data = dlmread ('LPF_V3_f1_september.csv',"",2,0);

    F=data(1:points,1); % Frequency
%data for 50ohm
       Gain_A=data(1:points,2)+j.*data(1:points,3);     % V(out3)/V(in2)
%Amplifier_A=data(1:points,4)+j.*data(1:points,5);  % V(filter)/V(in2)
  %Filter_A=data(1:points,6)+j.*data(1:points,7);
           Z_A=data(1:points,4)+j.*data(1:points,5);          % -V(in2)/I(V3)
%data for 1kohm
       Gain_B=data(points+2:1+2*points,2)+j.*data(points+2:1+2*points,3);     % V(out3)/V(in2)
%Amplifier_B=data(points+2:1+2*points,4)+j.*data(points+2:1+2*points,5)
   %Filter_B=data(points+2:1+2*points,6)+j.*data(points+2:1+2*points,7);  % V(filter)/V(in2)
           Z_B=data(points+2:1+2*points,4)+j.*data(points+2:1+2*points,5);          % -V(in2)/I(V3)
%------------------------------------------
%% log data A
Gmag_A=20.*log10(abs(Gain_A)); %OK
Gphase_A=K*angle(Gain_A);
%Fil_mag_A=20.*log10(abs(Filter_A))
Zin_A=abs(Z_A);
%% log data B
Gmag_B=20.*log10(abs(Gain_B)); %OK
```

```
Gphase_B=K*angle(Gain_B);
%Fil_mag_B=20.*log10(abs(Filter_B))
Zin_B=abs(Z_B);
%%MATRIX DATA

F1RG1L =[F Gmag_A Gmag_B Zin_A Zin_B Gphase_A Gphase_B];


save F1_SEPTEMBER_HG.dat F1RG1L


%%

%%plot
figure 1

subplot(2,2,1)
  semilogx(F,Gmag_A)
  %legend("real","ideal");
  grid on
  title('50 Ohm');
subplot(2,2,2)
  %semilogx(F,Gphase_A)
  semilogx(F,Zin_A)
    title('50 Ohm Z');
  %legend("real","ideal");
  grid on
subplot(2,2,3)
  semilogx(F,Gmag_B)
  %legend("real","ideal");
```

```
    grid on
    title('1 kOhm');
subplot(2,2,4)
    %semilogx(F,Gphase_B)
    semilogx(F,Zin_B)
    title('1 kohm Z');
    %legend("real","ideal");
    grid on
```

APPENDIX B MODEL-OCTAVE

The following code reads the voltages and currents data from the passive Mixer and after is applied the procedure for obtain the coefficients of the polynomial expression

```
#CODE DONE FOR OCTAVE
clc
clear all
close all
%graphics_toolkit('gnuplot')
ids=csvread('mesures/ids_4.csv');
vds=csvread('mesures/Vds.csv');
vdsc=vds(6:21); # create the new vds vector
vgg=csvread('mesures/vgg.csv');
#correct the value for 1 transistor
#ids=ids/4;
#poly grade
#matrix lengths
lvds=length(vds); #length of vds vector
lvgg=length(vgg); #length of vgg vector
lvdsc=length(vdsc); #length of new vds vector
#EXAMPLE, do not enable!
#for x1=1:1:lvds (x1 for row, x2 for columns)
#   for x2=1:1:lvgg
#     Mf(x1,x2)=ids(x1,x2);
#    end
#end
```

```
#Vector for 0 to 0.6 VDS
vdsc_up=vdsc(9:16);
#Vector for -0.6 to 0 VDS
vdsc_down=vdsc(1:8);
lvds_half=length(vdsc_up);% length of the half original vector of vdsc
In=ids(6:21,:); % currents values from -0.6 to 0.6 VDS
#Current vectors
In_up=In(9:16,:);  % 0 to 0.6 VDS
In_down=In(1:8,:); % -0.6 to 0 VDS
% loop for find the asymmetric value, half sum of the abs between the positive and negative VDS
for x1=1:1:lvds_half
A_val(x1,:)=0.5*(abs(In_up(x1,:))+abs(In_down(1+lvds_half-x1,:)));
end

for x1=1:1:lvds_half
   In_asymmetric_up(x1,:)=A_val(x1,:);
In_asymmetric_down(x1,:)=-A_val(1+lvds_half-x1,:);
end
In_asymmetric=[In_asymmetric_down ;In_asymmetric_up]; % Asimetric vector
%substraction from the original data
            In_D=In-In_asymmetric;
            %creation of the upper and lower vectors of the current for the symmetrical case
        In_D_up=In_D(9:16,:);
     In_D_down=In_D(1:8,:);
%loop for calculate symmetric with the half sum between the positive and negative current values
```

```
for x1=1:1:lvds_half
S_val(x1,:)= 0.5*(In_D_up(x1,:) +In_D_down(1+lvds_half-x1,:));
S_val_neg(1+lvds_half-x1,:)=S_val(x1,:);
end
%Current Symmetrical
In_symmetric_up=S_val;
In_symmetric_down=S_val_neg;
%Ids-a0 for the symmetrical case
In_symmetric_up_dc=In_symmetric_up%-In_symmetric_up(1,:);
In_symmetric_down_dc=In_symmetric_down%-In_symmetric_down(lvds_half,:);
In_symmetric=[In_symmetric_down; In_symmetric_up]; %up and down current
In_symmetric_dc=[In_symmetric_down_dc; In_symmetric_up_dc];
%error of the symmetrical and asymmetric part separation
In_err=abs(In-In_asymmetric-In_symmetric);
% G calculation asymmetric
% rdivide is the function for divide each element with the respective element in the other vector
G_asymmetric_up=rdivide(In_asymmetric_up,vdsc_up);
G_asymmetric_down=rdivide(In_asymmetric_down,vdsc_down);
%Coefficients A1 for asymmetric
A1as_up=G_asymmetric_up(1,:);
A1as_down=G_asymmetric_down(lvds_half,:);
%G2 ASYMETRIC, first substract the A1 coefficent
G_asy_up=G_asymmetric_up-A1as_up;
G_asy_down=G_asymmetric_down-A1as_up;
G2_asymmetric_up=rdivide(G_asy_up,vdsc_up);
G2_asymmetric_down=rdivide(G_asy_down,vdsc_down);
G2_asymmetric=[G2_asymmetric_down; G2_asymmetric_up];
```

```
%A2=0 for asymmetric
G3_asymmetric_up=rdivide(G2_asymmetric_up,vdsc_up);
G3_asymmetric_down=rdivide(G2_asymmetric_down,vdsc_down);
G3_asymmetric=[G3_asymmetric_down;G3_asymmetric_up];
%SYMMETRICAL
%Gcalculation with A0 not zero
G_symmetric_up=rdivide(In_symmetric_up_dc,vdsc_up);
G_symmetric_down=rdivide(In_symmetric_down_dc,vdsc_down);
%Gcalculation with A0 zero
G_symmetric_up_zero=rdivide(In_symmetric_up,vdsc_up);
G_symmetric_down_zero=rdivide(In_symmetric_down,vdsc_down);
%G2calculation with A0 not zero
G2_symmetric_up=rdivide(G_symmetric_up,vdsc_up);
G2_symmetric_down=rdivide(G_symmetric_down,vdsc_down);
%G2 calculation with A0 zero
G2_symmetric_up_zero=rdivide(G_symmetric_up_zero,vdsc_up);
G2_symmetric_down_zero=rdivide(G_symmetric_down_zero,vdsc_down);
%VECTORs CREATION
G_asymmetric=[G_asymmetric_down; G_asymmetric_up];
G_symmetric=[G_symmetric_down; G_symmetric_up];
G_symmetric_zero=[G_symmetric_down_zero; G_symmetric_up_zero];
G2_symmetric=[G2_symmetric_down; G2_symmetric_up];
G2_symmetric_zero=[G2_symmetric_down_zero; G2_symmetric_up_zero];


%ORDER OF COEFFICIENTS [A3 A2 A1 A0]
%UP COEFF
%All coefficients calculated with the octave function
Co_asymmetric_up=[ACo_up; zeros(1,lvgg) ];
%Asymmetric with all fixed coef
```

```
Co_asymmetric_up_fixed=[A3Co_up;zeros(1,lvgg);A1as_up;zeros(1,lvgg)];
%Asymmetric with A1 fixed
Co_asymmetric_up_fixed_a1=[A23Co_up;A1as_up;zeros(1,lvgg)];

% SYMETRIC A0 A1
Co_symmetric_up=[zeros(1,lvgg);SCo_up;S_val(1,:)];
% SYMETRIC  A1
Co_symmetric_up_zerof=[SCo_up_zerof;zeros(1,lvgg)];
Co_symmetric_up_zero=[zeros(1,lvgg);SCo_up_zero;zeros(1,lvgg)];
% SYMETRIC A2
Co_symmetric_up_zero2=[zeros(1,lvgg);S2Co_up_zero;zeros(1,lvgg);zeros
    (1,lvgg)];
% SYMETRIC A2 A0
Co_symmetric_up2=[zeros(1,lvgg);S2Co_up;zeros(1,lvgg);S_val(1,:)];
% SYMMETRIC A3 A2 A1 with A0 fixed
Co_symmetric_up_a0_fixed=[SCo_up_a0;S_val(1,:)];

%DOWN COEFF
%ASYMMETRIC A3 A1 both fixed
Co_asymmetric_down_fixed=[A3Co_down;zeros(1,lvgg);A1as_down;zeros(1,
    lvgg)];
%ASYMMETRIC  A1 fixed
Co_asymmetric_down_fixed_a1=[A23Co_down;A1as_down;zeros(1,lvgg)];
% ASYMMETRIC A1 A2 A3
Co_asymmetric_down=[ACo_down;  zeros(1,lvgg)  ];
%SYMMETRICAL A3=0 A2 A1 A0
Co_symmetric_down=[zeros(1,lvgg);SCo_down;S_val_neg(lvds_half,:)];
%SYMMETRICAL A3 A2 A1 A0=0
Co_symmetric_down_zerof=[SCo_down_zerof;zeros(1,lvgg)];
%SYMMETRICAL A3=0 A2 A1 A0=0
```

```
Co_symmetric_down_zero=[zeros(1,lvgg);SCo_down_zero;zeros(1,lvgg)];
% Symmetrical down A1=0
Co_symmetric_down2=[zeros(1,lvgg);S2Co_down;zeros(1,lvgg);S_val_neg(lvds_half,:)];
% Symmetrical down A1=0 A0=0
Co_symmetric_down_zero2=[zeros(1,lvgg);S2Co_down_zero;zeros(1,lvgg);zeros(1,lvgg)];
% SYMMETRIC A3 A2 A1 with A0 fixed
Co_symmetric_down_a0_fixed=[SCo_down_a0;S_val(1,:)];

for z=1:1:lvgg
%SYMMETRIC
%up
Iev_symmetrical_up(:,z)=polyval(Co_symmetric_up(:,z),vdsc_up);
Iev_symmetrical_up_zero(:,z)=polyval(Co_symmetric_up_zero(:,z),vdsc_up);
Iev_symmetrical_up_zerof(:,z)=polyval(Co_symmetric_up_zerof(:,z),vdsc_up);
Iev_symmetrical_up2(:,z)=polyval(Co_symmetric_up2(:,z),vdsc_up);
Iev_symmetrical_up_zero2(:,z)=polyval(Co_symmetric_up_zero2(:,z),vdsc_up);
Iev_symmetrical_up_a0_fixed(:,z)=polyval(Co_symmetric_up_a0_fixed(:,z),vdsc_up);
%down
Iev_symmetrical_down(:,z)=polyval(Co_symmetric_down(:,z),vdsc_down);
Iev_symmetrical_down_zero(:,z)=polyval(Co_symmetric_down_zero(:,z),vdsc_down);
Iev_symmetrical_down_zerof(:,z)=polyval(Co_symmetric_down_zerof(:,z),vdsc_down);
```

```
lev_symmetrical_down2(:,z)=polyval(Co_symmetric_down2(:,z),vdsc_down);
lev_symmetrical_down_zero2(:,z)=polyval(Co_symmetric_down_zero2(:,z),vdsc_down);
lev_symmetrical_down_a0_fixed(:,z)=polyval(Co_symmetric_down_a0_fixed(:,z),vdsc_down);

%ASYMMETRIC
%up
lev_asymmetrical_up(:,z)=polyval(Co_asymmetric_up(:,z),vdsc_up);
lev_asymmetrical_up_fixed(:,z)=polyval(Co_asymmetric_up_fixed(:,z),vdsc_up);
lev_asymmetrical_up_fixed_a1(:,z)=polyval(Co_asymmetric_up_fixed_a1(:,z),vdsc_up);
%down do not use
lev_asymmetrical_down(:,z)=polyval(Co_asymmetric_down(:,z),vdsc_down);
lev_asymmetrical_down_fixed(:,z)=polyval(Co_asymmetric_down_fixed(:,z),vdsc_down);
lev_asymmetrical_down_fixed_a1(:,z)=polyval(Co_asymmetric_down_fixed_a1(:,z),vdsc_down);
%do not use
end
lev_symmetrical=[lev_symmetrical_down;lev_symmetrical_up];
lev_symmetrical_zero=[lev_symmetrical_down_zero;lev_symmetrical_up_zero];
lev_symmetrical_zerof=[lev_symmetrical_down_zerof;lev_symmetrical_up_zerof];
lev_symmetrical2=[lev_symmetrical_down2;lev_symmetrical_up2];
```

```
Iev_symmetrical_zero2=[Iev_symmetrical_down_zero2;
    Iev_symmetrical_up_zero2];
Iev_symmetrical_a0_fixed=[Iev_symmetrical_down_a0_fixed;
    Iev_symmetrical_up_a0_fixed];

Iev_asymmetrical=[Iev_asymmetrical_down;Iev_asymmetrical_up];
Iev_asymmetrical_fixed=[Iev_asymmetrical_down_fixed;
    Iev_asymmetrical_up_fixed];
Iev_asymmetrical_fixed_a1=[Iev_asymmetrical_down_fixed_a1;
    Iev_asymmetrical_up_fixed_a1];


%this models were selected after the coefficients comparison, then
    are placed here for extract the graps
Imodel=Iev_symmetrical2+Iev_asymmetrical_fixed;
Imodel2=Iev_symmetrical_zero2+Iev_asymmetrical_fixed;

%%error calculation
  Ierror_symmetric=Iev_symmetrical-In_symmetric;
  Ierror_symmetric_zero=Iev_symmetrical_zero-In_symmetric;
  Ierror_symmetric_zerof=Iev_symmetrical_zerof-In_symmetric;
  Ierror_symmetric2=Iev_symmetrical2-In_symmetric;
  Ierror_symmetric_zero2=Iev_symmetrical_zero2-In_symmetric;
  Ierror_symmetric_a0_fixed=Iev_symmetrical_a0_fixed-In_symmetric;
 %
  Ierror_asymmetric=Iev_asymmetrical-In_asymmetric;
  Ierror_asymmetric_fixed=Iev_asymmetrical_fixed-In_asymmetric;
  Ierror_asymmetric_fixed_a1=Iev_asymmetrical_fixed_a1-In_asymmetric;
 %
  Ierror_model=Ierror_symmetric2+Ierror_asymmetric_fixed;
```

```
Ierror_model2=Ierror_symmetric_zero2+Ierror_asymmetric_fixed;
%Relative error
Ierror_asymmetric_p=rdivide(Ierror_asymmetric,In_asymmetric);
Ierror_asymmetric_p_fixed=rdivide(Ierror_asymmetric_fixed,
    In_asymmetric);
Ierror_asymmetric_p_fixed_a1=rdivide(Ierror_asymmetric_fixed_a1,
    In_asymmetric);
%
Ierror_symmetric_p=rdivide(Ierror_symmetric,In_symmetric);
Ierror_symmetric_p_zero=rdivide(Ierror_symmetric_zero,In_symmetric)
    ;
Ierror_symmetric_p_zerof=rdivide(Ierror_symmetric_zerof,
    In_symmetric);

Ierror_symmetric_p2=rdivide(Ierror_symmetric2,In_symmetric);
Ierror_symmetric_p_zero2=rdivide(Ierror_symmetric_zero2,
    In_symmetric);
Ierror_symmetric_p_a0_fixed=rdivide(Ierror_symmetric_a0_fixed,
    In_symmetric);
%
Ierror_model_p=rdivide(Ierror_model,In);
Ierror_model_p2=rdivide(Ierror_model2,In);
%miscellanious
%Averagging a2
%A2=mean(Co_symmetric2(2,43:87));
%Vector_A2=A2*ones(1,lvgg);
%New code for limited vgg values
plot_vgg=[37,52,62,77,87];
lplotvgg=length(plot_vgg);
```

```
%export coefficients in mat format for latex plot
CASY=[vgg.',Co_asymmetric_down_fixed_a1.'];
CSYM=[vgg.',Co_symmetric_up_zerof.'];
%export relative error for latex plot
ERRORASY=[vdsc,Ierror_asymmetric_p_fixed_a1];
ERRORSYM=[vdsc,Ierror_symmetric_p_zerof];
% Current
ALLCURRENTS=[vdsc,In];
%Symmetrical
IDSSYM=[vdsc, In_symmetric];
%Asymmetric
IDSASY=[vdsc, In_asymmetric];
%
save Coef_asy.mat CASY
save Coef_sy.mat  CSYM
save ERRORASY.mat ERRORASY
save ERRORSYM.mat ERRORSYM
save ALLCURRENTS.mat ALLCURRENTS
save IDSASY.mat IDSASY
save IDSSYM.mat IDSSYM
  %plotting
%color vector
colors=hsv(lvgg);
colors_plot=hsv(lplotvgg);
z0=1;%initial value
% figures list
figure(1)
set(gca,'FontSize',15)
hold all
```

```
for z=1:lvgg
plot(vdsc,In(:,z),'color',colors(z,:));
end
grid minor
title('I_{DS} original data'); xlabel('V_{DS}(V)');ylabel('Current(A)');
hold off

figure (2)
set(gca,'FontSize',15)
hold all
for z=1:lvgg
plot(vdsc,In_asymmetric(:,z),'color',colors(z,:));
end
grid minor
title('I_{DS} asymmetric'); xlabel('V_{DS}(V)');ylabel('Current(A)');
hold off

figure (3)
set(gca,'FontSize',15)
hold all
for z=1:lvgg
plot(vdsc,In_D(:,z),'color',colors(z,:));
end
grid minor
title('I_{DS} original-Asymmetric'); xlabel('V_{DS}(V)');ylabel('Current(A)');
hold off

figure (4)
```

```
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
plot(vdsc,In_symmetric(:,z),'color',colors(z,:));
end
grid minor
title('I_{DS} symmetric'); xlabel('V_{DS}(V)');ylabel('Current(A)');
hold off

figure (5)
set(gca,'FontSize',15)
hold all
for z=1:lvgg
plot(vdsc,In_err(:,z),'color',colors(z,:));
end
grid minor
title('I_{DS} -I_{asy}-I_{sy} '); xlabel('V_{DS}(V)');ylabel('Current
    (A)');
hold off

figure (6)
set(gca,'FontSize',15)
hold all
for z=1:1:lvgg
subplot(1,2,1)
plot(vdsc,Imodel(:,z),'color',colors(z,:));
title('I_{DS} MODEL 1'); xlabel('V_{DS}(V) ');ylabel('Current(A)');
grid minor
hold on
subplot(1,2,2)
```

```
plot(vdsc,Imodel2(:,z),'color',colors(z,:));
title('I_{DS}  MODEL 2 '); xlabel('V_{DS}(V)  ');ylabel('Current(A)');
grid minor
hold on
end
hold off

figure (61)
set(gca,'FontSize',15)
hold all
for z=43:1:lvgg
subplot(1,2,1)
plot(vdsc,Imodel(:,z),'color',colors(z,:));
title('I_{DS}  MODEL 1'); xlabel('V_{DS}(V)  ');ylabel('Current(A)');
grid minor
hold on
subplot(1,2,2)
plot(vdsc,Imodel2(:,z),'color',colors(z,:));
title('I_{DS}  MODEL 2 '); xlabel('V_{DS}(V)  ');ylabel('Current(A)');
grid minor
hold on
end
hold off

figure (7)
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
```

```
subplot(1,2,1)
plot(vdsc,Ierror_model_p(:,z),'color',colors(z,:));
title('Model 1 error '); xlabel('V_{DS}(V)');ylabel('Relative error');
grid minor
hold on
subplot(1,2,2)
plot(vdsc,Ierror_model_p2(:,z),'color',colors(z,:));
title('Model 2 error'); xlabel('V_{DS}(V)');ylabel('Relative error');
grid minor
hold on
end
hold off

figure (71)
set(gca,'FontSize',15)
hold all
for z=43:1:lvgg
plot(vdsc,Ierror_model_p(:,z),'color',colors(z,:));
end
grid minor
title('Model error'); xlabel('V_{DS}(V)');ylabel('Relative error');
hold off

figure (81)
set(gca,'FontSize',15)
hold on
for z=1:1:lvgg
subplot(2,3,1)
hold on
```

```
plot(vdsc,Ierror_symmetric_p(:,z),’color’,colors(z,:));
title(’A3=0 ’); xlabel(’V_{DS}(V) ’);ylabel(’Relative error’);
grid minor
subplot(2,3,2)
hold on
plot(vdsc, Ierror_symmetric_p_zero(:,z),’color’,colors(z,:));
title(’A0,A3=0 ’); xlabel(’V_{DS}(V) ’);ylabel(’Relative error’);
grid minor
subplot(2,3,3)
hold on
plot(vdsc,Ierror_symmetric_p2(:,z),’color’,colors(z,:));
title(’A3,A1,A0=0 ’); xlabel(’V_{DS}(V) ’);ylabel(’Relative error’);
grid minor
subplot(2,3,4)
hold on
plot(vdsc,Ierror_symmetric_p_zero2(:,z),’color’,colors(z,:));
title(’A3,A1=0’); xlabel(’V_{DS}(V) ’);ylabel(’Relative error’);
grid minor
subplot(2,3,5)
hold on
plot(vdsc,Ierror_symmetric_p_a0_fixed(:,z),’color’,colors(z,:));
title(’ All coefficents ’); xlabel(’V_{DS}(V) ’);ylabel(’Relative
    error’);
grid minor
subplot(2,3,6)
hold on
plot(vdsc,Ierror_symmetric_p_zerof(:,z),’color’,colors(z,:));
title(’ A0=0 ’); xlabel(’V_{DS}(V) ’);ylabel(’Relative error’);
grid minor
end
```

```
hold off

figure (82)
set(gca,'FontSize',15)
hold on
for z=43:1:lvgg
subplot(2,3,1)
hold on
plot(vdsc,Ierror_symmetric_p(:,z),'color',colors(z,:));
title('A3=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(2,3,2)
hold on
plot(vdsc, Ierror_symmetric_p_zero(:,z),'color',colors(z,:));
title(' A0,A3=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(2,3,3)
hold on
plot(vdsc,Ierror_symmetric_p2(:,z),'color',colors(z,:));
title(' A3,A1,A0=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(2,3,4)
hold on
plot(vdsc,Ierror_symmetric_p_zero2(:,z),'color',colors(z,:));
title('A3,A1=0'); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(2,3,5)
hold on
plot(vdsc,Ierror_symmetric_p_a0_fixed(:,z),'color',colors(z,:));
```

```
title('all coefficients'); xlabel('V_{DS}(V)');ylabel('Relative error');
grid minor
subplot(2,3,6)
hold on
plot(vdsc,Ierror_symmetric_p_zerof(:,z),'color',colors(z,:));
title('A0=0'); xlabel('V_{DS}(V)');ylabel('Relative error');
grid minor
end
hold off

figure (9)
set(gca,'FontSize',15)
hold on
for z=1:1:lvgg
subplot(1,3,1)
hold on
plot(vdsc,Ierror_asymmetric_p(:,z),'color',colors(z,:));
title('A0=0'); xlabel('V_{DS}(V)');ylabel('Relative error');
grid minor
subplot(1,3,2)
hold on
plot(vdsc,Ierror_asymmetric_p_fixed(:,z),'color',colors(z,:));
title('A0,A2=0'); xlabel('V_{DS}(V)');ylabel('Relative error');
grid minor
subplot(1,3,3)
hold on
plot(vdsc,Ierror_asymmetric_p_fixed_a1(:,z),'color',colors(z,:));
title('A0=0 and A1 set'); xlabel('V_{DS}(V)');ylabel('Relative error');
```

```
grid minor
end
hold off

figure (91)
set(gca,'FontSize',15)
hold on
for z=43:1:lvgg
subplot(1,3,1)
hold on
plot(vdsc,Ierror_asymmetric_p(:,z),'color',colors(z,:));
title('A0=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(1,3,2)
hold on
plot(vdsc,Ierror_asymmetric_p_fixed(:,z),'color',colors(z,:));
title('A0,A2=0 A1 set '); xlabel('V_{DS}(V) ');ylabel('Relative error
    ');
grid minor
subplot(1,3,3)
hold on
plot(vdsc,Ierror_asymmetric_p_fixed_a1(:,z),'color',colors(z,:));
title(' A0=0 and A1 set '); xlabel('V_{DS}(V) ');ylabel('Relative
    error');
grid minor
end
hold off
```

```
figure (92)
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
plot(vdsc,Ierror_asymmetric_p_fixed(:,z),'color',colors(z,:));
end
grid minor
title('Asymmetric A1 and A3 fixed model error '); xlabel('V_{DS}(V) ');ylabel('Relative error');
hold off

figure (93)
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
plot(vdsc,Ierror_asymmetric_p_fixed_a1(:,z),'color',colors(z,:));
end
grid minor
title('Asymmetric A1 fixed model error '); xlabel('V_{DS}(V) '); ylabel('Relative error');
hold off



figure (10)
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
plot(vdsc,G_asymmetric(:,z),'color',colors(z,:));
```

```
end
grid minor
title('GAsymmetric '); xlabel('V_{DS}(V) ');ylabel('Conductance(S)');
hold off

figure (11)
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
plot(vdsc,G_symmetric_zero(:,z),'color',colors(z,:));
end
grid minor
title('Gsymmetric zero a0=0 '); xlabel('V_{DS}(V) ');ylabel('Conductance(S)');
hold off


figure(12)
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
plot(vdsc,G_symmetric(:,z),'color',colors(z,:));
end
grid minor
title('Gsymmetric '); xlabel('V_{DS}(V) ');ylabel('Conductance(S)');
hold off

%Asymmetric down coefficients
figure(131)
set(gca,'FontSize',15)
```

```
subplot(2,2,1)
plot(vgg,Co_asymmetric_down(1,:),vgg,Co_asymmetric_down_fixed(1,:),
    vgg,Co_asymmetric_down_fixed_a1(1,:));
%legend('A0=0  ','A0,A2=0 A1',' A0=0 A1',"location",'Southwest');
grid minor
title('A3'); xlabel('Vgg  ');ylabel('Amplitude');
subplot(2,2,2)
plot(vgg,Co_asymmetric_down(2,:),vgg,Co_asymmetric_down_fixed(2,:),
    vgg,Co_asymmetric_down_fixed_a1(2,:));
%legend('A0=0  ','A0,A2=0 A1',' A0=0 A1',"location",'Southeast');
grid minor
title('A2'); xlabel('Vgg  ');ylabel('Amplitude');
subplot(2,2,3)
plot(vgg,Co_asymmetric_down(3,:),vgg,Co_asymmetric_down_fixed(3,:),
    vgg,Co_asymmetric_down_fixed_a1(3,:));
%legend('A0=0  ','A0,A2=0 A1',' A0=0 A1',"location",'Northwest');
grid minor
title('A1'); xlabel('Vgg  ');ylabel('Amplitude');
subplot(2,2,4)
plot(vgg,Co_asymmetric_down(4,:),vgg,Co_asymmetric_down_fixed(4,:),
    vgg,Co_asymmetric_down_fixed_a1(4,:));
legend('A0=0  ','A0,A2=0 A1','A0=0 A1',"location",'Eastoutside');
grid minor
title('A0'); xlabel('Vgg  ');ylabel('Amplitude');

%Asymmetric up coefficients
figure(132)
set(gca,'FontSize',15)
subplot(2,2,1)
```

```
plot(vgg,Co_asymmetric_up(1,:),vgg,Co_asymmetric_up_fixed(1,:),vgg,
    Co_asymmetric_up_fixed_a1(1,:));
%legend('A0=0  ','A0,A2=0 A1',' A0=0 A1',"location",'Southwest');
grid minor
title('A3'); xlabel('Vgg  ');ylabel('Amplitude');
subplot(2,2,2)
plot(vgg,Co_asymmetric_up(2,:),vgg,Co_asymmetric_up_fixed(2,:),vgg,
    Co_asymmetric_up_fixed_a1(2,:));
%legend('A0=0  ','A0,A2=0 A1',' A0=0 A1',"location",'Southeast');
grid minor
title('A2'); xlabel('Vgg  ');ylabel('Amplitude');
subplot(2,2,3)
plot(vgg,Co_asymmetric_up(3,:),vgg,Co_asymmetric_up_fixed(3,:),vgg,
    Co_asymmetric_up_fixed_a1(3,:));
%legend('A0=0  ','A0,A2=0 A1',' A0=0 A1',"location",'Northwest');
grid minor
title('A1'); xlabel('Vgg  ');ylabel('Amplitude');
subplot(2,2,4)
plot(vgg,Co_asymmetric_up(4,:),vgg,Co_asymmetric_up_fixed(4,:),vgg,
    Co_asymmetric_up_fixed_a1(4,:));
legend('A0=0  ','A0,A2=0 A1','A0=0 A1',"location",'Eastoutside');
grid minor
title('A0'); xlabel('Vgg  ');ylabel('Amplitude');

%Symmetrical down coefficients A0=!0
figure(141)
set(gca,'FontSize',15)
subplot(2,2,1)
plot(vgg,Co_symmetric_down(1,:),vgg,Co_symmetric_down2(1,:),vgg,
    Co_symmetric_down_a0_fixed(1,:));
```

```
%legend('A3=0','A3,A1=0','All',"location",'Northwest');
title('A3'); xlabel('Vgg '); ylabel('Amplitude');
grid minor
subplot(2,2,2)
plot(vgg,Co_symmetric_down(2,:),vgg,Co_symmetric_down2(2,:),vgg,
    Co_symmetric_down_a0_fixed(2,:));
%legend('A3=0','A3,A1=0','All',"location",'Northwest');
title('A2'); xlabel('Vgg '); ylabel('Amplitude');
grid minor
subplot(2,2,3)
plot(vgg,Co_symmetric_down(3,:),vgg,Co_symmetric_down2(3,:),vgg,
    Co_symmetric_down_a0_fixed(3,:));
%legend('A3=0','A3,A1=0','All',"location",'Southeast');
title('A1'); xlabel('Vgg '); ylabel('Amplitude');
grid minor
subplot(2,2,4)
plot(vgg,Co_symmetric_down(4,:),vgg,Co_symmetric_down2(4,:),vgg,
    Co_symmetric_down_a0_fixed(4,:));
legend('A3=0','A3,A1=0','All',"location",'Eastoutside');
title('A0'); xlabel('Vgg '); ylabel('Amplitude');
grid minor

%Symmetrical up coefficients A0=!0
figure(142)
set(gca,'FontSize',15)
subplot(2,2,1)
plot(vgg,Co_symmetric_up(1,:),vgg,Co_symmetric_up2(1,:),vgg,
    Co_symmetric_up_a0_fixed(1,:));
%legend('A3=0','A3,A1=0','All',"location",'Northwest');
title('A3'); xlabel('Vgg '); ylabel('Amplitude');
```

```
grid minor
subplot(2,2,2)
plot(vgg,Co_symmetric_up(2,:),vgg,Co_symmetric_up2(2,:),vgg,
    Co_symmetric_up_a0_fixed(2,:));
%legend('A3=0','A3,A1=0','All',"location",'Northwest');
title('A2'); xlabel('Vgg ');ylabel('Amplitude');
grid minor
subplot(2,2,3)
plot(vgg,Co_symmetric_up(3,:),vgg,Co_symmetric_up2(3,:),vgg,
    Co_symmetric_up_a0_fixed(3,:));
%legend('A3=0','A3,A1=0','All',"location",'Southeast');
title('A1'); xlabel('Vgg ');ylabel('Amplitude');
grid minor
subplot(2,2,4)
plot(vgg,Co_symmetric_up(4,:),vgg,Co_symmetric_up2(4,:),vgg,
    Co_symmetric_up_a0_fixed(4,:));
legend('A3=0','A3,A1=0','All',"location",'Eastoutside');
title('A0'); xlabel('Vgg ');ylabel('Amplitude');
grid minor


%Symmetrical down coefficients A0=0
figure(143)
set(gca,'FontSize',15)
subplot(2,2,1)
plot(vgg,Co_symmetric_down_zero(1,:),vgg,Co_symmetric_down_zerof(1,:)
    ,vgg,Co_symmetric_down_zero2(1,:));
%legend('A3 = 0','A3,A1=0',"location",'Southeast');
```

```
title('A3'); xlabel('Vgg '); ylabel('Amplitude');
grid minor
subplot(2,2,2)
plot(vgg,Co_symmetric_down_zero(2,:),vgg,Co_symmetric_down_zerof(2,:),vgg,Co_symmetric_down_zero2(2,:));
%legend('A3 = 0','A3,A1=0',"location",'Southeast');
title('A2'); xlabel('Vgg '); ylabel('Amplitude');
grid minor
subplot(2,2,3)
plot(vgg,Co_symmetric_down_zero(3,:),vgg,Co_symmetric_down_zerof(3,:),vgg,Co_symmetric_down_zero2(3,:));
%legend('A3 = 0','A3,A1=0',"location",'Southeast');
title('A1'); xlabel('Vgg '); ylabel('Amplitude');
grid minor
subplot(2,2,4)
plot(vgg,Co_symmetric_down_zero(4,:),vgg,Co_symmetric_down_zerof(4,:),vgg,Co_symmetric_down_zero2(4,:));
legend('A3 = 0','A0=0','A3,A1=0',"location",'Eastoutside');
title('A0'); xlabel('Vgg '); ylabel('Amplitude');
grid minor

%Symmetrical up coefficients A0=0
figure(144)
set(gca,'FontSize',15)
subplot(2,2,1)
plot(vgg,Co_symmetric_up_zero(1,:),vgg,Co_symmetric_up_zerof(1,:),vgg,Co_symmetric_up_zero2(1,:));
%legend('A3 = 0','A3,A1=0',"location",'Southeast');
title('A3'); xlabel('Vgg '); ylabel('Amplitude');
grid minor
```

```
subplot(2,2,2)
plot(vgg,Co_symmetric_up_zero(2,:),vgg,Co_symmetric_up_zerof(2,:),vgg
    ,Co_symmetric_up_zero2(2,:));
%legend('A3 = 0','A3,A1=0',"location",'Southeast');
title('A2'); xlabel('Vgg ');ylabel('Amplitude');
grid minor
subplot(2,2,3)
plot(vgg,Co_symmetric_up_zero(3,:),vgg,Co_symmetric_up_zerof(3,:),vgg
    ,Co_symmetric_up_zero2(3,:));
%legend('A3 = 0','A3,A1=0',"location",'Southeast');
title('A1'); xlabel('Vgg ');ylabel('Amplitude');
grid minor
subplot(2,2,4)
plot(vgg,Co_symmetric_up_zero(4,:),vgg,Co_symmetric_up_zerof(4,:),vgg
    ,Co_symmetric_up_zero2(4,:));
legend('A3 = 0','A0=0','A3,A1=0',"location",'Eastoutside');
title('A0'); xlabel('Vgg ');ylabel('Amplitude');
grid minor


figure (15)
set(gca,'FontSize',15)
hold all
for z=z0:lvgg
plot(vdsc,G2_asymmetric(:,z),'color',colors(z,:));
end
grid minor
title('G2Asymmetric test '); xlabel('V_{DS}(V) ');ylabel('Conductance
    (S)');
hold off
```

```

figure (16)
set(gca,’FontSize’,15)
hold all
for z=z0:lvgg
plot(vdsc,G3_asymmetric(:,z),’color’,colors(z,:));
end
grid minor
title(’G3Asymmetric test ’); xlabel(’V_{DS}(V) ’);ylabel(’Conductance (S)’);
hold off
%Plot for reports with less vgg values

figure (1000)
set(gca,’FontSize’,15)
for z=1:lplotvgg
plot(vdsc,In_asymmetric(:,plot_vgg));
end
grid minor
title(’I_{DS} asymmetric 4 Vgg’); xlabel(’V_{DS}(V)’);ylabel(’Current (A)’);
legend(’0V’,’0.6V’,’1V’,’1.6V’,’2V’,”location”,’Eastoutside’);
hold off



figure (2000)
set(gca,’FontSize’,15)
for z=1:lplotvgg
plot(vdsc,In_symmetric(:,plot_vgg));
```

```
end
grid minor
title('I_{DS} symmetric 4 Vgg'); xlabel('V_{DS}(V)');ylabel('Current(A)');
legend('0V','0.6V','1V','1.6V','2V',"location",'Eastoutside');
hold off

figure (810)
set(gca,'FontSize',15)
hold all
for z=1:1:lplotvgg
subplot(2,3,1)
hold on
plot(vdsc,Ierror_symmetric_p(:,plot_vgg));
title('A3=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(2,3,2)
hold on
plot(vdsc, Ierror_symmetric_p_zero(:,plot_vgg));
title('A0,A3=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(2,3,3)
hold on
plot(vdsc,Ierror_symmetric_p2(:,plot_vgg));
title('A3,A1,A0=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(2,3,4)
hold on
plot(vdsc,Ierror_symmetric_p_zero2(:,plot_vgg));
title('A3,A1=0'); xlabel('V_{DS}(V) ');ylabel('Relative error');
```

```
grid minor
subplot(2,3,5)
hold on
plot(vdsc,Ierror_symmetric_p_a0_fixed(:,plot_vgg));
title(' All coefficents '); xlabel('V_{DS}(V) ');ylabel('Relative
    error');
grid minor
subplot(2,3,6)
hold on
plot(vdsc,Ierror_symmetric_p_zerof(:,plot_vgg));
title(' A0=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
legend('0V','0.6V','1V','1.6V','2V',"location",'Eastoutside');
end

hold off

figure (910)
set(gca,'FontSize',15)
hold on
for z=1:1:lplotvgg
subplot(1,3,1)
hold on
plot(vdsc,Ierror_asymmetric_p(:,plot_vgg));
title('A0=0 '); xlabel('V_{DS}(V) ');ylabel('Relative error');
grid minor
subplot(1,3,2)
hold on
plot(vdsc,Ierror_asymmetric_p_fixed(:,plot_vgg));
```

```
title('A0,A2=0 A1 set '); xlabel('V_{DS}(V) ');ylabel('Relative error
    ');
grid minor
subplot(1,3,3)
hold on
plot(vdsc,Ierror_asymmetric_p_fixed_a1(:,plot_vgg));
title(' A0=0 and A1 set '); xlabel('V_{DS}(V) ');ylabel('Relative
    error');
grid minor
legend('0V','0.6V','1V','1.6V','2V',"location",'Eastoutside');
end
hold off

%enable figures loop
%1 png
ena=1;

if (ena==1)
saveas (1, "figures/sc7/report/fig1.png");
saveas (2, "figures/sc7/report/fig2.png");
saveas (3, "figures/sc7/report/fig3.png");
saveas (4, "figures/sc7/report/fig4.png");
saveas (5, "figures/sc7/report/fig5.png");

saveas (6, "figures/sc7/report/fig6.png");
saveas (61, "figures/sc7/report/fig61.png");
saveas (7, "figures/sc7/report/fig7.png");
%saveas (71, "figures/sc7/report/fig71.png");
saveas (81, "figures/sc7/report/fig81.png");
saveas (82, "figures/sc7/report/fig82.png");
```

```

saveas (9, ”figures/sc7/report/fig9.png”);
saveas (91, ”figures/sc7/report/fig91.png”);
%saveas (92, ”figures/sc7/report/fig92.png”);
%saveas (93, ”figures/sc7/report/fig93.png”);
saveas (10, ”figures/sc7/report/fig10.png”);
saveas (11, ”figures/sc7/report/fig11.png”);
saveas (12, ”figures/sc7/report/fig12.png”);
saveas (131, ”figures/sc7/report/fig131.png”);
saveas (132, ”figures/sc7/report/fig132.png”);
saveas (141, ”figures/sc7/report/fig141.png”);
saveas (142, ”figures/sc7/report/fig142.png”);
saveas (143, ”figures/sc7/report/fig143.png”);
saveas (144, ”figures/sc7/report/fig144.png”);
saveas (15, ”figures/sc7/report/fig15.png”);
saveas (16, ”figures/sc7/report/fig16.png”);

end
```