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Design of a 28 GHz Transistor Microwave Amplifier for 5G Application

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Abstract:
5G wireless development is in constant activity. The performance of a radio input module is increasingly critical in the radio frequency signal path, especially those involving the amplifier. This article discusses the design of a transistor amplifier for 5G wireless applications The Transistor used for said amplifier is a FET designed by Alpha Industries named sp_aiiAF035P1_00_19941209 with voltage Vds = 5V, Ids = 70mA. The design of the amplifier is made with the ADS (Advanced Design System) software we used the micro-ribbon lines for the assembly of our amplifier they are printed on the Rogers Duriod 5880 substrate with a thickness of 0.127 mm and a relative permittivity of 2.2 . The technique of impedance adaptations is made by a stub favoring the transfer of maximum power from the input to the output. The simulation shows us that the amplifier has a Bandwidth greater than 2 GHz, the amplifier has a correct adaptation presenting a reflection coefficient at input S11 = -30.784dB and at output S22 = -16.978 dB with a gain of 7.68 dB. In order to improve the gain we made a transistor stage for our amplifier which allows us to obtain a gain of 15.31 dB. It is very important to notify to finish that the amplifier has an input and output impedance of 50 ohms which is the reference impedance thus facilitating the possibility of Co-Design Block Amplifier-Antenna is therefore at the output of the amplifier is added an antenna with an input impedance of 50 ohms.
***Key Word**: ADS; Amplifier; FET; Gain; Transistor.*

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I. Introduction

Mobile Generation Standards are developed to serve the current and future demands of mobile users. However, mobile traffic is growing exponentially every year and this increase is expected to continue in the future[1]. To better meet requirements and guarantee a good quality of service to users, a new communication standard, namely 5G, has been established. The primary objective of 5G technology is to increase transmission speeds, thereby providing better coverage at lower cost[2]. The 2015 World Radio communication Conference allocated the 24GHz to 86 Ghz bandwidth for future millimeter wave communications systems[3]. To any successful commercial 5G application, the output power (*P*out), linearity, reliability, cost, and form factors of an amplifier are all very important[4,5]

The high integration requirements of FEM integrated circuits and massive antenna systems may favor silicon-based technologies for 5G mobile products, even though GaAs or GaN FEMs generally perform better than their silicon counterparts [4,5.6,7.8], Nevertheless in this document we use in this document we model a transistor amplifier on microstrip line it should also be noted that our working frequency is 28GHz. Our manuscript is structured as follows: section II presents the selected transistor, section III presents the mathematical modeling and architecture of a microwave amplifier, section IV elaborates the design of the transistor amplifier section V lists the results obtained and section VI concludes our work

II. Presentation of the Transistor

The transistor amplifier are very recurrent microwave amplifiers their characteristics depend on the properties of the Transistor for the design in our work we looked at the FET transistor sp_aiiAF035P1_00_19941209 manufactured by Alpha Industries so we will first illustrate the characteristics of our transistor namely the input and output reflection coefficients S_{11}, S_{22} the transmission coefficient S_{21} which represents the transmission from the input to the output or the own gain of the transistor and of the future amplifier S_{12}, represents the isolation or the reverse transmission from the output to the input the drain source voltage Vds = 5V and the current Ids = 70 mA. We will therefore presently illustrate the parameters listed below with the figures below.

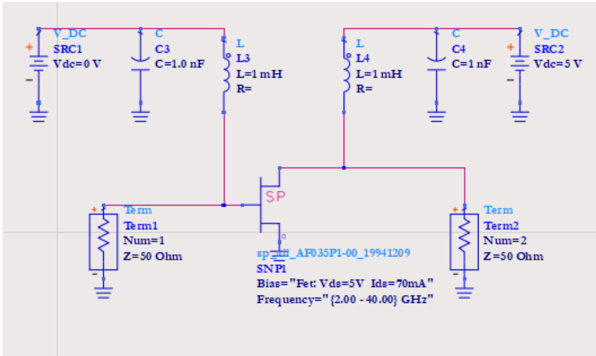

Figure 1: Schematic of the Transistor and Simulation of S parameters

The S parameters of the Transistor are shown in the following figure

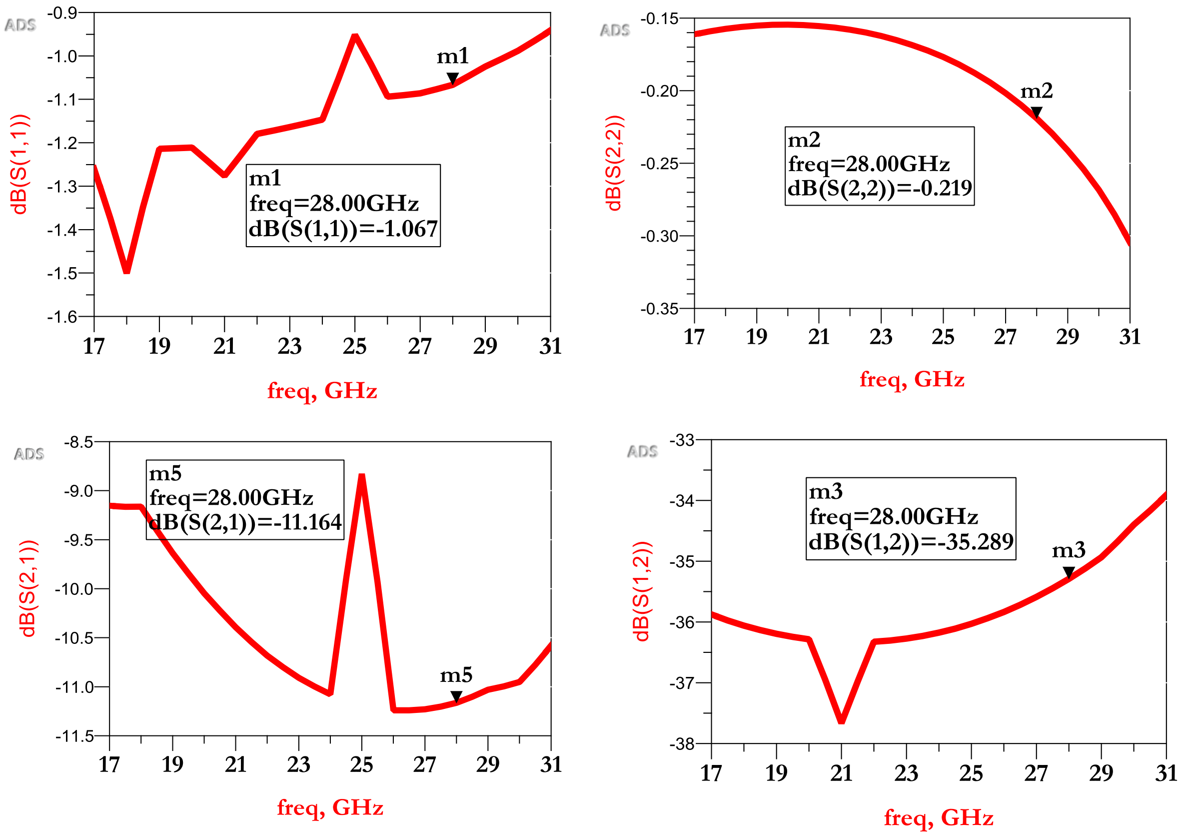

Figure 2: S parameters of the transistor

The table below summarizes the values of these parameters at the working frequency

Table no 1: Parameter S of the transistor

Parameter	Value
Frequency (GHz)	28
S_{11} (dB)	-1.067
S_{22} (dB)	-0.219
S_{21} (dB)	-11.164
S_{12} (dB)	-35.289

We realize that the inherent gain of the transistor is very low, it is imperative for us to improve this gain as well as the characteristics of the amplifier in order to produce an amplifier that meets the constraints imposed by 5G technology.

III. Mathematical and Architecture Modeling of a Microwave Amplifier

An Amplifier is an electronic device whose role is to increase the power of a signal introduced at its input

1. Mathematical Model of a Microwave Amplifier

To simplify our study we will admit that our amplifier is a quadrupole whose matrix is [S] and connected to a voltage source E with an internal impedance and it is loaded by an impedance

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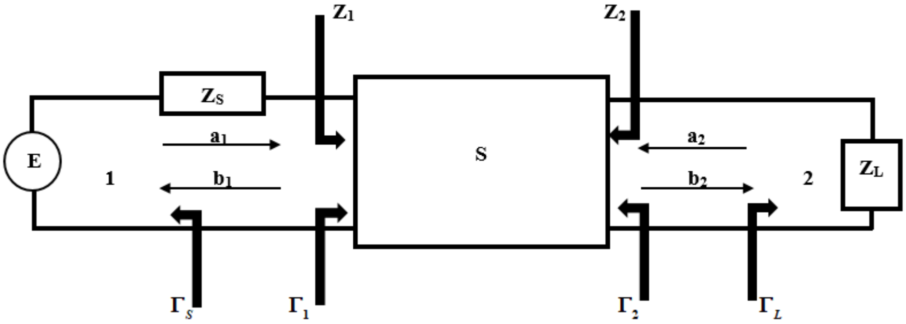


Figure 3: Distribution waves and reflection coefficients at the entry and exit of the quadrupole

The matrix [S] of distribution of this linear quadrupole is such that [9]:

$$[b] = [S][a] \Rightarrow \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} S_{12} \\ S_{21} S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \qquad (1.1)$$

$$\Rightarrow \begin{cases} b_1 = S_{11} a_1 + S_{12} a_2 & (1) \\ b_2 = S_{21} a_1 + S_{22} a_2 & (2) \end{cases} \qquad (1.2)$$

Z_2: is the output impedance of the quadrupole fed by the Zs impedance source.

a_1: is the incident wave at port 1;

b_1: is the wave reflected at the access;

a_2: is the incident wave at port 2;

b_2 :is the wave reflected at port 2.

When making the amplifier, we try to have maximum gain. In other words, it is necessary to perform the adaptation at the input of the transistor and the source simultaneously with the adaptation between the transistor output and the load.

1.1 Study of the stability of the transistor

By definition:

- ✓ the reflection coefficient with respect to the source is written

$$\Gamma_S = \frac{Z_s - Z_0}{Z_s + Z_0} = \frac{a_1}{b_1} \qquad (1.3)$$

- ✓ the reflection coefficient with respect to the load is written

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{a_2}{b_2} \qquad (1.4)$$

- ✓ Based on the S parameters of the transistor, we will determine the input reflection coefficient.

By dividing equation (1) by a_1 we have:

$$\frac{b_1}{a_1} = S_{11} + S_{12}\frac{a_2}{a_1} \Rightarrow \Gamma_1 = S_{11} + S_{12}\frac{a_2}{a_1} \qquad (1.5)$$

Recall that by definition $\Gamma_1 = \frac{Z_1 - Z_0}{Z_1 + Z_0} = \frac{a_1}{a_2} \qquad (1.6)$

Z_1 is the input impedance of the transistor loaded by Z_L. Similarly by dividing equation (2) by a_2 we have:

$$\frac{b_2}{a_2} = S_{22} + S_{21}\frac{a_1}{a_2} \text{ or } \frac{1}{\Gamma_L} = \frac{b_2}{a_2} \Rightarrow \frac{1}{\Gamma_L} = S_{22} + S_{21}\frac{a_1}{a_2}$$

$$\Rightarrow \frac{a_1}{a_2} = \frac{1 - S_{22}\Gamma_L}{S_{21}\Gamma_L}$$

$$\Rightarrow \frac{1}{\frac{a_1}{a_2}} = \frac{1}{\frac{1 - S_{22}\Gamma_L}{S_{21}\Gamma_L}}$$

$$\Rightarrow \frac{a_2}{a_1} = \frac{S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \qquad (1.7)$$

(1.7) in (1.5) we have :

$$\Gamma_1 = S_{11} + S_{12}\frac{S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \qquad (1.8)$$

- ✓ Likewise from the parameters S we will determine the reflection coefficient at the exit. By dividing equation (2) by a2 we have:

$$\frac{b_2}{a_2} = S_{21}\frac{a_1}{a_2} + S_{22} = \Gamma_2 \qquad (1.9)$$

By definition $\Gamma_2 = \frac{Z_2 - Z_0}{Z_2 + Z_0} = \frac{b_2}{a_2} \qquad (1.10)$

Z_2 is the output impedance of the transistor supplied by the source.

Similarly by dividing equation (1) by a_1 we have:

$$\frac{b_1}{a_1} = S_{11} + S_{12}\frac{a_2}{a_1} = \frac{1}{\Gamma_S} \Rightarrow \frac{a_2}{a_1} = \frac{1 - S_{11}\Gamma_S}{S_{12}\Gamma_S} \qquad (1.11)$$

$$\frac{1}{\frac{a_2}{a_1}} = \frac{1}{\frac{1 - S_{11}\Gamma_S}{S_{12}\Gamma_S}} \Rightarrow \frac{a_1}{a_2} = \frac{S_{12}\Gamma_S}{1 - S_{11}\Gamma_S} \qquad (1.12)$$

(1.12) in (1.9) we find :

$$\Gamma_2 = S_{21}\frac{S_{12}\Gamma_S}{1 - S_{11}\Gamma_S} + S_{22} \tag{1.13}$$

For the system to be stable at entry, it is necessary that:

$$|\Gamma_1| < 1 \tag{1.14}$$

For the system to be stable at the output, it is necessary that:

$$|\Gamma_2| < 1 \tag{1.15}$$

Considering K as the stability factor, the expression of the stability factor is given by the following formula:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$ and if $|\Delta| < 1$ and if K>1 then the transistor is unconditionally stable [9] Δ : The determinant of the matrix S

$$\Delta = S_{11}S_{22} - S_{21}S_{12} \tag{1.16}$$

1.2 Simultaneous adaptation

To achieve simultaneous adaptation, it suffices only to take K> 1. From the previous equations we can determine the reflection coefficients which ensure the simultaneous adaptation to the input and to the output[9].The maximum transducic gain is written: $G_{T\max} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right)$

(1.17)

if |Δ |>1 then stability is conditional, but simultaneous adaptation is possible. The maximum transducic gain is written: $G_{T\max} = \frac{|S_{21}|}{|S_{12}|}\left(K + \sqrt{K^2 + 1}\right)$ (1.18)

The figure below shows Rollet's stability constant and the mod_delta determinant to deduce
On the stability of the transistor

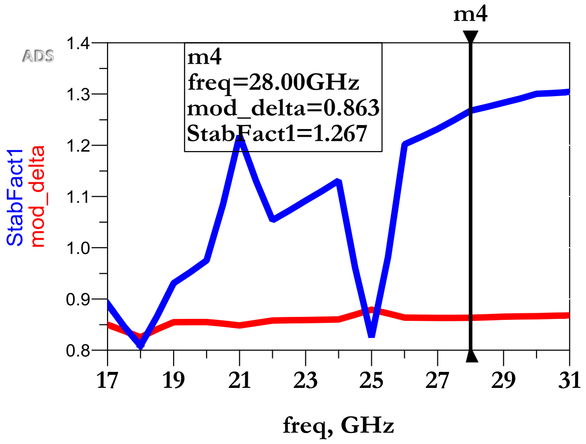


Figure 4: Parameter defining the stability of the transistor

The table below summarizes these parameters and their interpretation

Table no 2 : Summary of Parameters defining the stability of the transistor

Parameter	Value	Interpretation
Frequency (GHz)	28	Working frequency
Rollet's stability K	1.267	The transistor is unconditionally stable
Mod_delta	0.861	

Rollet's stability constant K> 1 and mod_delta (Δ) <1 the transistor is unconditionally stable so simultaneous adaptation is possible[9]

2. Architecture of a Microwave Amplifier

The architecture of a Microwave Amplifier is shown as follows:

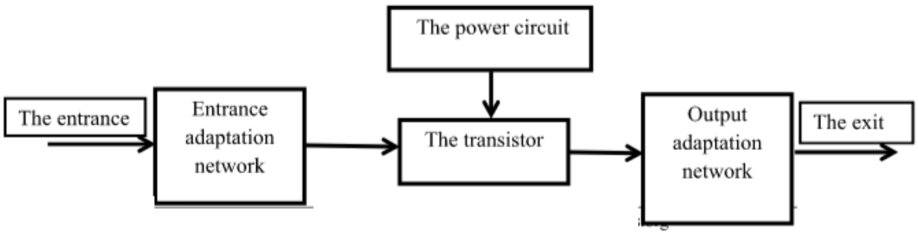


Figure 5: Microwave amplifier

IV Design of the Transistor Amplifier

For the design of the amplifier we will first start with impedance matching. The adaptation with Stub has been opted for by this document. The structure of the stub is shown below

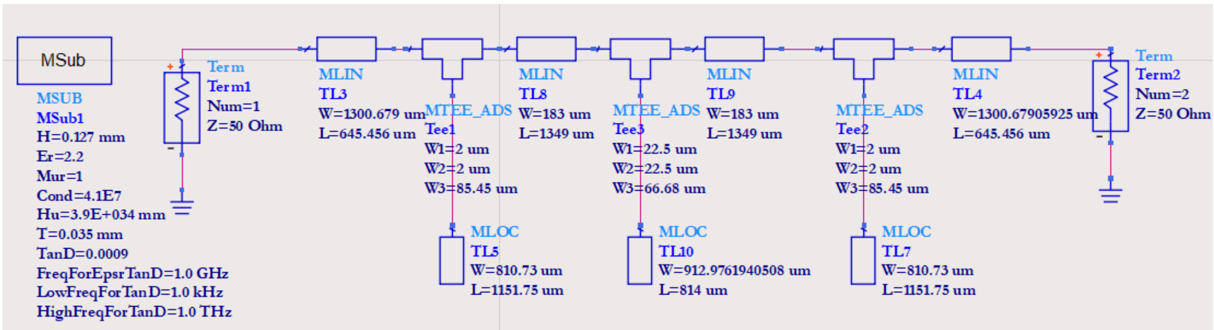


Figure 6: Stub structure

The figure below shows the S parameters of the Stub

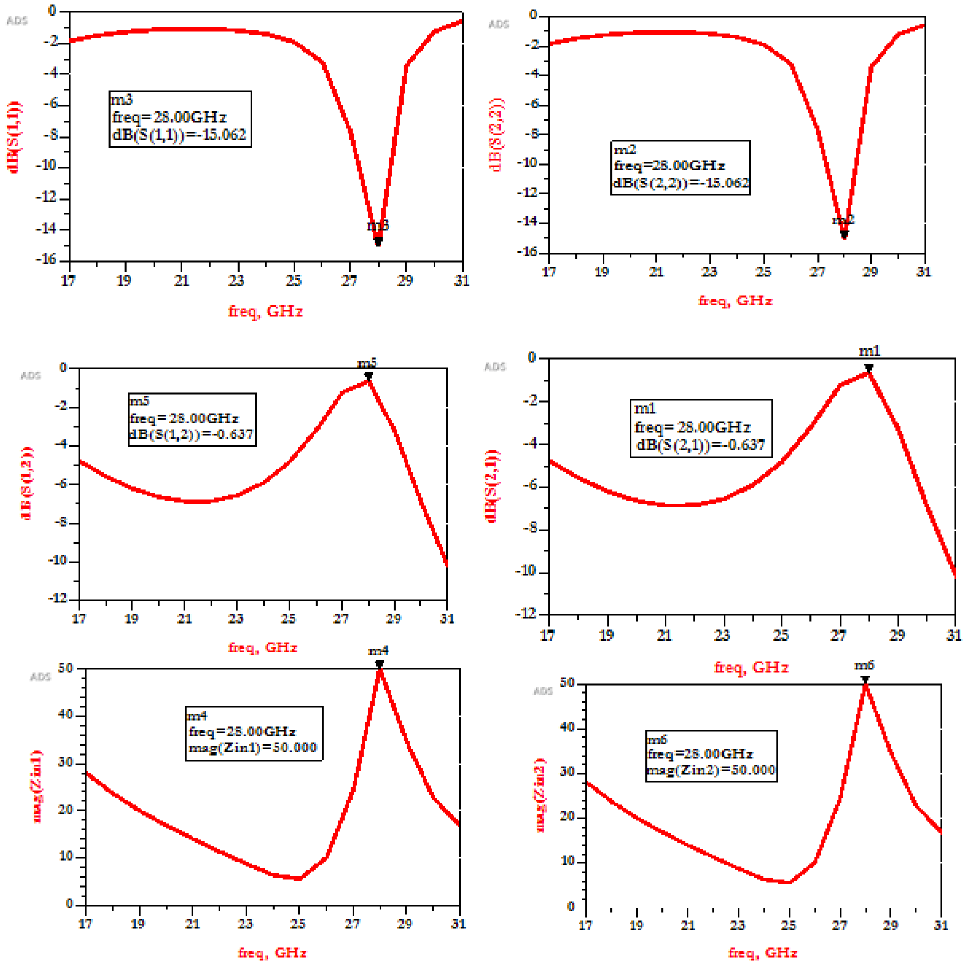


Figure 7: Stub S parameters

The validation of our Stub is confirmed by an impedance adaptation to 50 ohms at the input and at the output the table below summarizes the result obtained

Table no 3: Stub S parameters

Parameters	Value
S_{11} (dB)	-15.062
S_{22} (dB)	-15.062
S_{12} (dB)	-0.637
S_{21} (dB)	-0.637

The above table presents the results of synthesis of the parameters S of the stub at the resonant frequency of the transistor. From these results, it can be seen that: $S_{11} = S_{22}$; $S_{12} = S_{21}$ Hence, the matching of the impedance is good, because the waves leaving the source and passing through the line are not partly reflected when they arrive on the load.

The design of the transistor amplifier is shown in the figure below

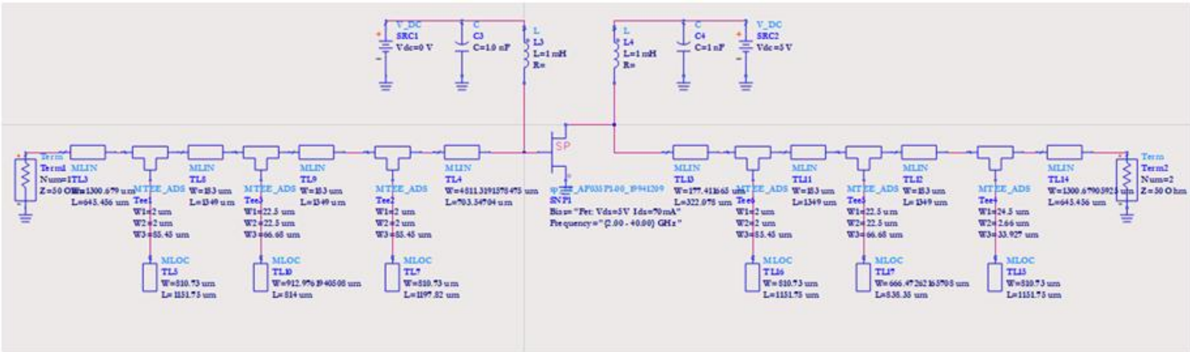


Figure 8: Microwave amplifier

The simulation of our amplifier gives the following results

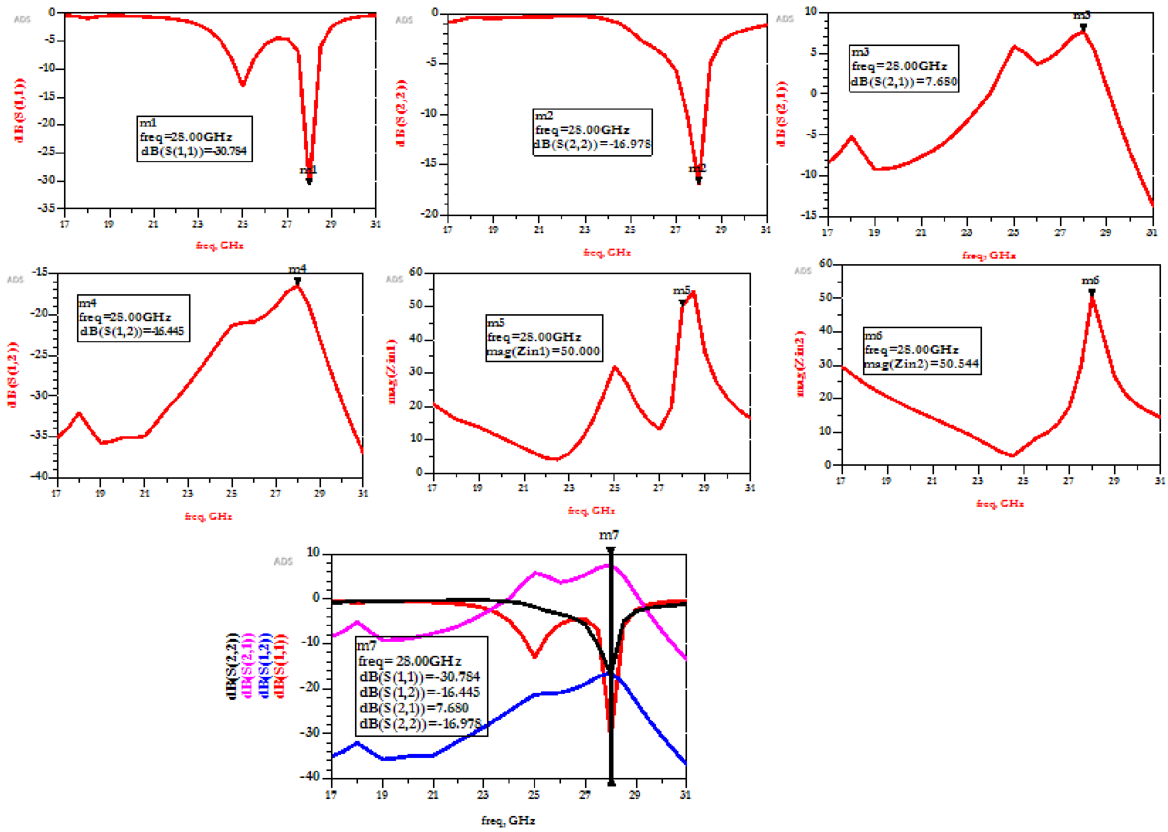


Figure 9: Parameter S of the Amplifier

The table below presents a summary of the results obtained

Table no 4: Summary of the characteristics of the amplifier

Parameters	Value
S_{11} (dB)	-30.784
S_{22} (dB)	-16.978
S_{12} (dB)	-16.445
S_{21} or Power Gain (dB)	7.68
Input impedance (ohms)	50
Output impedance (ohms)	50.544

The input and output impedance of the amplifier has an impedance of 50 ohms which confirms the validity of our results. To do this, the gain in power being obviously insufficient for 5G applications, we solve this problem by making transistor stages. The figure below illustrates the new amplifier configuration.

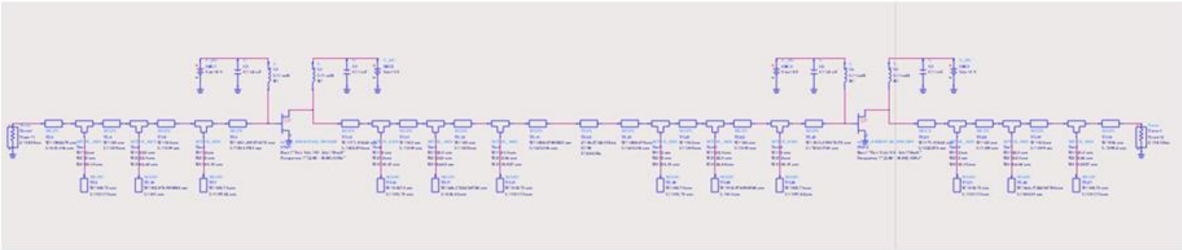


Figure 10: Microwave amplifier with stages

The simulation of our amplifier gives the following results:

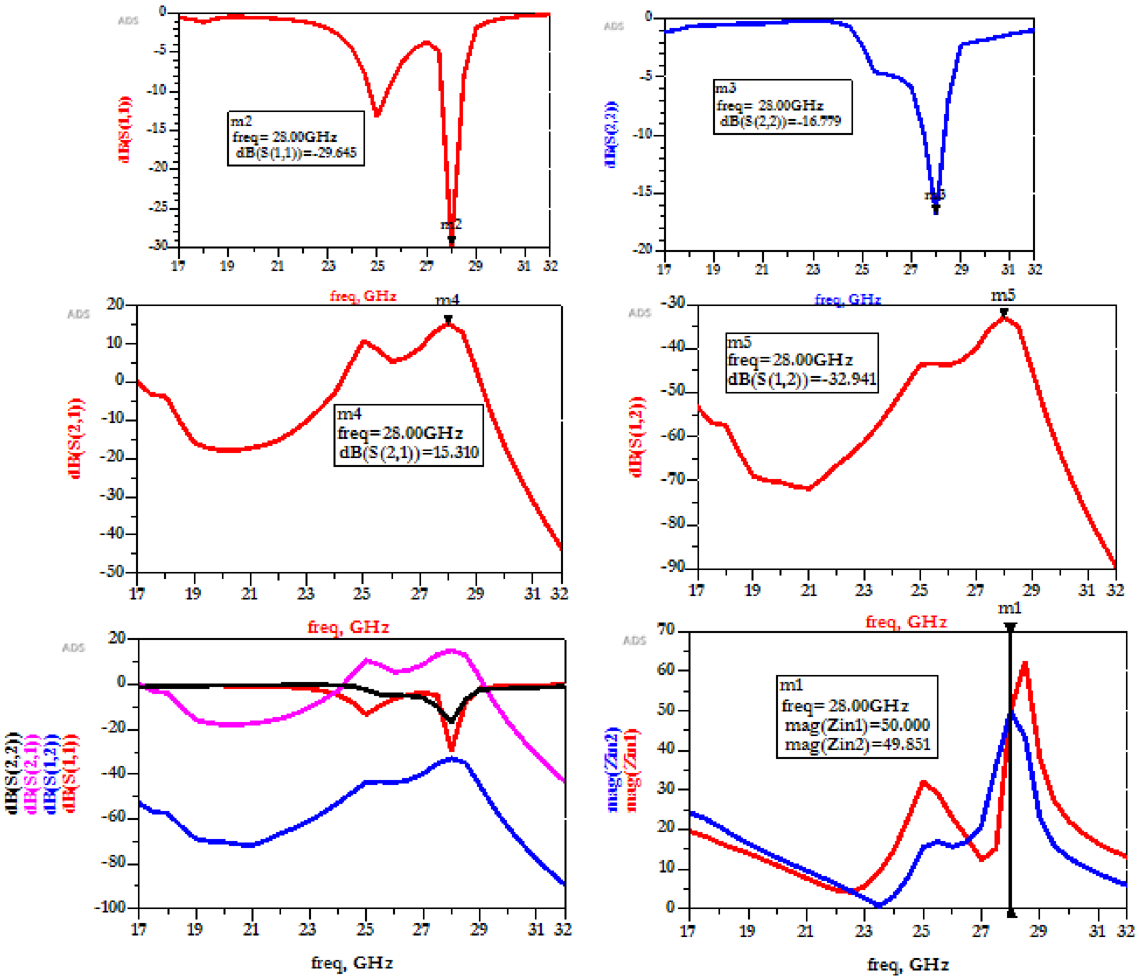


Figure 11: S Parameters and Impedance of the Amplifier with Stage

The table below summarizes the results obtained

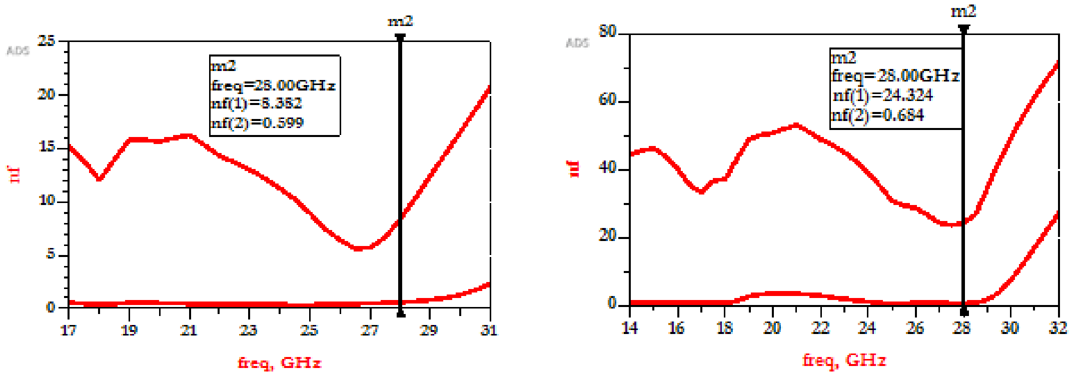
Table no 5: Summary of Obtained Parameters

Parameters	Value
Frequency (GHz)	28
S_{11} (dB)	-29.645
S_{22} (dB)	-16.779
S_{21} (dB)	15.31
S_{12} (dB)	-32.941
Input impedance (ohms)	50
Output impedance (ohms)	49.851

The input and output impedance of the stage amplifier is correct so we can confirm the validity of our results. We will therefore discuss and explain the different results obtained.

V. Results and Discussions

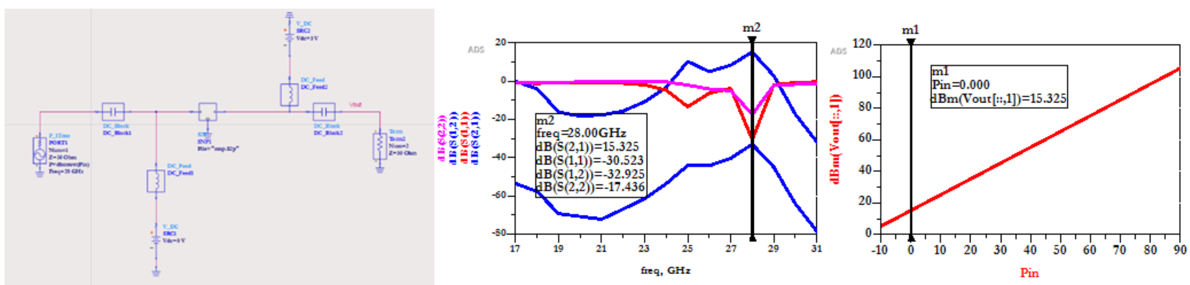
The amplifier designed below presents several results to us so it is a question for us in this part to explain them for a better understanding of the public. The figure below shows the noise figure of the amplifier



a) b)

Figure 12: Microwave Amplifier Noise Factor: a) without stage, b) with stage

The figures illustrated below each show us two curves, the curve nf (1) which represents the input noise factor and nf (2) the output noise factor we realize that the input noise factor is much higher has that of the output those which shows us that the impedance matching is good and that the amplifiers are low noise. The most striking fact in our design is at the level of the compression point a -1db which represents the linear character of the amplifier as well as its dynamic range so we carry out a test or we ingest low power at the input of the amplifier in order to observe the output power



a) b) c)

Figure 13: Linearity of the amplifier: a) linearity diagram, b) Parameter S obtained, c) Linearity curve

First, it is important to note that the amplifier under test is the amplifier with a stage. To better understand the notion of linearity, we can say that we speak of linearity when:

$$P_{out} = Gain \times P_{in} \qquad (1.19)$$

When this relation is no longer valid for an input power then we notice a distortion when we observe figure 13 c) we do not notice any distortion despite having pushed the input power scale we see that for an input power of 0 dBm we obtain at output a power of 15.325 dBm the gain of our amplifier is 15.325 dB so we realize that the input signal has been amplified. The fact for us not to observe distortion is incredible because it means that our amplifier has absolute linearity and very large dynamic range. The summary of the results obtained and interpreted are illustrated in the table below

Table no 6 : Summary of Findings and Interpretations

Working frequency is 28 GHz				
Parameter	Transistor	Amplifier		Interpretation
		Amplifier without stages	Amplifier with stage	
Input impedance (ohms)	Nothing	**50**	**50**	The input and output impedances are correct and comply with the reference impedance those which makes the results more practical and realistic
Ouput impedance (ohms)	Nothing	**50.544**	**49.851**	
S_{11} (dB)	**-1.067**	**-30.784**	**-29.645**	The input and output reflection coefficients are correct because they are less than -10 dB those which define the simultaneous adaptation and these coefficients are very low compared to that of the transistor
S_{22} (dB)	**-0.219**	**-16.978**	**-16.445**	
S_{21} (dB)	**-11.164**	**7.68**	**15.31**	The transmission coefficients meanwhile increase compared to that of the transistor, but we note that the coefficient S21 is particularly very large because in microwave it represents the power gain of the amplifier. The transmission coefficient S12 is always small because it represents the inverse gain or the isolation.It should also be noted the improvement of the power gain when we decide to make the stages those which shows that the technique opted for the improvement of the gain is valid
S_{12} (dB)	**-35.289**	**-16.445**	**-32.941**	
Bandwidth (GHz)	Nothing	**Greater than 2 GHz**		The Bandwidth is good those who confirm that the designed amplifier meets the requirements imposed by 5G Applications good

VI. Conclusion

Ultimately in this paper we have designed a transistor amplifier with a gain of 15.31 dB and therefore the linearity curve does not present any distortion. The amplifier presented is, in view of these characteristics, able to meet the constraints imposed by 5G applications. What is quite remarkable in this work is that the chosen transistor does not present a particular gain specific to it interesting so we were able with the help of our stub to produce a transistor amplifier presenting a conforming gain imposed by the 5G Applications This amplifier presents an input and output impedance of 50 ohms which is the reference impedance which allows us to plan in perspective to join at the output of the amplifier an antenna with an input impedance of 50 ohms for the design of an Amplifier-Antenna Unit for 5G Application.

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