Co Design PA-Antenna for automotive radars with 79 GHz frequency

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Abstract— This document proposes a transmitter block consisting of an antenna and an amplifier for automotive radar application. As part of our research work, we chose to design a rectangular printed patch antenna. We proceeded to the result of the pre-sizing formulas and the techniques of impedance adaptation to the modeling of the patch antenna printed on a Rogers Duriod 5880 substrate of relative permittivity 2.2 and thickness 0.127mm with the theory of transmission lines. Then after finishing the design of the antenna we proceeded to the design of a field effect type transistor amplifier (FET). The amplifier design is also made with the same substrate used for the antenna design, to ensure the maximum power transfer between the antenna and the amplifier, we have designed a matching network. We use the following software for the implementation: CST-Microwave 2018 for the design of the antenna and ADS 2020 for the modeling of the amplifier and the Antenna-Amplifier block.

Keywords- *Amplifier, Antenna, micro-ribbon, Radar, FET Transistor*

I. INTRODUCTION

Improving road safety can now be considered through the implementation of systems providing new functionalities to current equipment, in particular through inter-vehicle communications. In this perspective, radar systems appear as devices capable of establishing, in addition to location, communication with the vehicle detected if the latter obviously has such a device, or with any other vehicle making it possible to relay a signal in the event of an emergency. The idea is obviously to route to the driver information before he can himself visualize the danger or event, and thus allow him to reduce his reaction time, or even allow the system to autonomously activate the vehicle's controls (braking, warning, horn, ..) [1-2].

In recent decades, millimeter wave radar sensor technology has brought new challenges to the automotive radar markets. It is becoming the most promising technology due to its performance and multi-domain applications. The 77-81GHz band has recently authorized for medium-range (MRR) and short-range (SRR) automotive radars in order to ensure the comfort and safety of the operation of the system, it is proving more interesting and increasingly replacing the current solutions to 24 GHz, which is polluting in the electromagnetic sense for certain sensitive sectors (radio astronomy in particular [3]. Based on the foregoing, the constraints imposed by Radar systems are very severe, so Radar transmitters, namely antennas and amplifiers, should provide good characteristics. This document proposes a block formed by the antenna and the amplifier operating in the 79GHz band, thus meeting the various constraints imposed by such systems. Our work is summarized as follows: in section II we present the modeling of the patch antenna, in section III we proceed to the modeling of the amplifier and in section IV we represent the Antenna-Amplifier block then section V close the work with a conclusion.

II. PATCH ANTENNA

In this document we propose a patch antenna operating at the 79 GHz frequency band for Automotive Radar application. This antenna is essential when building our transmitter unit.

II.1. patch design

The objective of this part is to design a single micro-ribbon patch antenna composed of a patch and a coaxial cable for the power supply. To determine the dimensions of a patch antenna rectangular, the operating frequency, dielectric constants and substrate thickness must be known. The analysis method used for the determination of the physical dimensions is that of transmission line theory and is presented in several steps as follows [4]:

Step 1: Calculation of the width W of the patch antenna La width W of the rectangular patch antenna given by equation (1)

$$W = \frac{C}{2 f_o \sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{1}$$

where f_o is the resonant or operating frequency of the antenna, ε_r is the relative permittivity of the substrate.

Step 2: calculation of the effective dielectric constant of the patch antenna

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

Step 3: calculate the effective length of the patch antenna

$$L_{eff} = \frac{C}{2 f_o \sqrt{\varepsilon_{reff}}} \tag{3}$$

Step 4: calculation of ΔL

$$\Delta L = 0.412h \frac{(\varepsilon_{eff} + 0,3)\left(\frac{W}{h} + 0,264\right)}{(\varepsilon_{eff} - 0,258)\left(\frac{W}{h} + 0,813\right)} \quad (4)$$

Step 5: calculate the length L of the patch antenna

$$L = L_{eff} - 2\Delta L \quad (5)$$

Step 6: calculation of the dimension of the ground plane (L_g, w_g).

The transmission line model is applicable only for an infinite ground plane. But practically we uses a finished ground plane with precise values. Let show that:

$$L_g = 6h + L$$
$$w_g = 6h + W \quad (6)$$

- Power supply managment

Two feeding techniques are widely used for feeding patch antennas, contact feeding and proximity feeding. In contact power supply technology, a distinction is made between microstrip line power supply and coaxial cable power supply. In the proximity coupling power supply, a distinction is made between electromagnetic coupling power supply and open coupling power supply [5]. In this document we have chosen the contact power supply because of its ease of manufacture and its better reliability according to [6].

After choosing the feeding technique. As in all microwave work, we proceeded with the study of impedance matching. The adaptation technique used in his work consists of inserting notches in order to bring the impedance of the antenna back to that of the power line. Figure 1 shows equivalent circuit of notches with slit, each notch is equivalent to a parallel admittance Y with a conductance G and a susceptance B [7]. The conductance is expressed as follows:

$$G_1 = \frac{1}{120\pi^2} \int \left[\frac{\sin(\frac{K_0 W_p}{2} \cos\theta)}{\cos\theta} \right]^2 \sin^3\theta \, d\theta \quad (7)$$

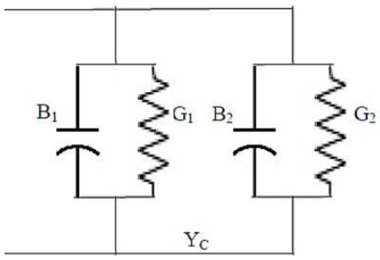


Figure 1: Equivalent circuit of notches with slot.

The mutual conductance is expressed as follows:

$$G_2 = \frac{1}{120\pi^2} \int \left[\frac{\sin\left(\frac{K_0 W_p}{2}\cos\theta\right)}{\cos\theta} \right]^2 \times j_0(K_0 L_p \sin\theta) \sin^3\theta \, d\theta \tag{8}$$

Where j_o represents the Bessel function of order 0. The resistance of the antenna is:

$$R_{in} = \frac{1}{G_1 + G_2} \tag{9}$$

After having developed all the theoretical analysis that allows us to find, using mathematical relations, the various parameters for the design of the antenna, we will now proceed to the modeling of the antenna.

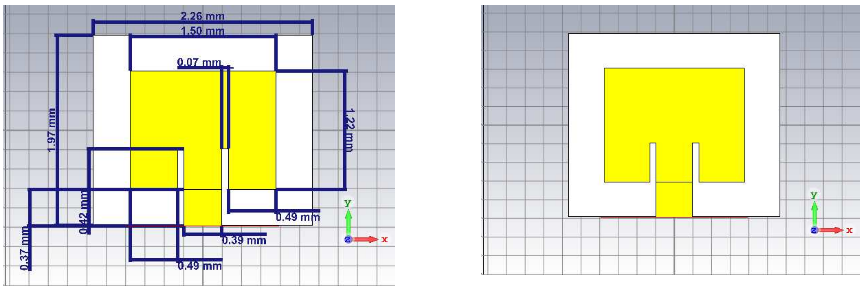
II.2 Modeling of the Patch antenna

II.2.1 Rectangular Patch

The previous section allowed us to show how to obtain the different antenna dimensions of a rectangular patch antenna. Table 1 below illustrates these dimensions.

TABLE 1 : ANTENNA DIMENSION

Dimension	Valeur (mm)
W_p	1.5
L_p	1.22
W_g	2.26
L_g	1.97
W_f	0.3912
L_f	0.37
Fi	0.42
gap	0.07



a) b)

Figure 2: Rectangular patch antenna: a) with dimension, b) without dimension.

The simulation of this antenna gives us the following results:

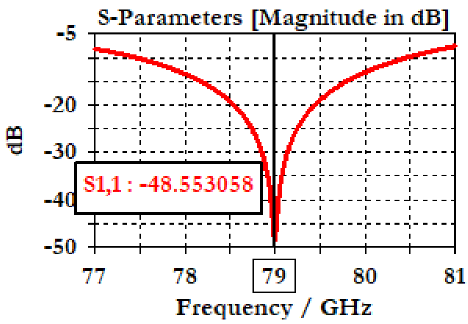


Figure 3: Return losses S11 (dB)

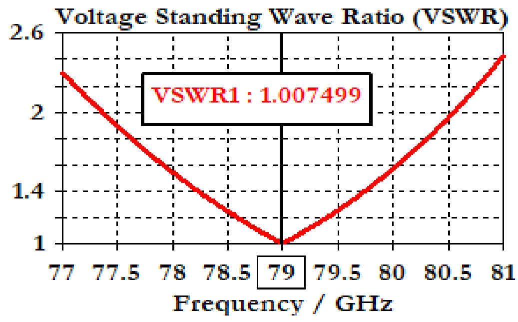


Figure 4: Standing wave ratio

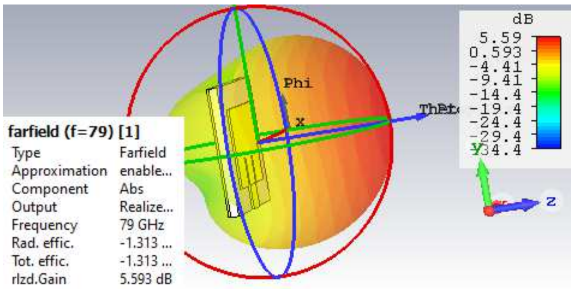


Figure 5: 3D radiation pattern of the antenna.

The results obtained above show that our antenna is suitable for the Transmission line because it presents return losses S11 = -48 dB <-10 dB and a near-perfect standing wave ratio VSWR = 1 ≤2 but the gain of the antenna is 5.593 dB which is very insufficient for our application, which is why we are going to model an antenna network to improve this gain.

II.2.2. Modeling of linear antenna networks

An antenna network is the combination of several antennas of the same type to form a single antenna. The assembly must respect a certain distance between the radiating element, the standard pitch used in most cases is 0.25λ, for our work we will be interested in linear networks and we will make a modeling with 4 elements and the distance between each element will be 0.25λ.

Figure 7 below shows the modeling of the two antenna arrays, the step of value 0.25λ is equal to 1mm.

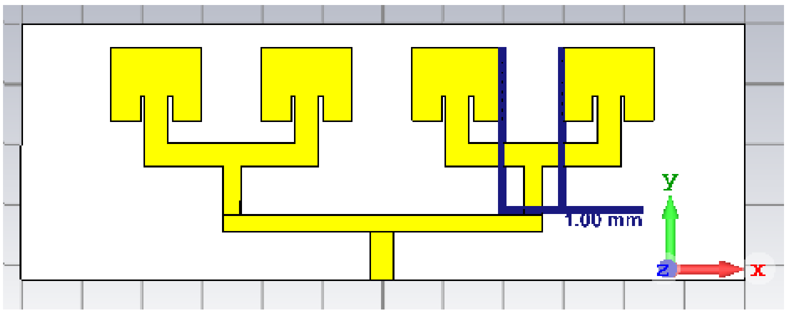


Figure 7: Linear 4-element antenna arrays.

We will then evaluate the different radio parameters of the proposed antenna networks.

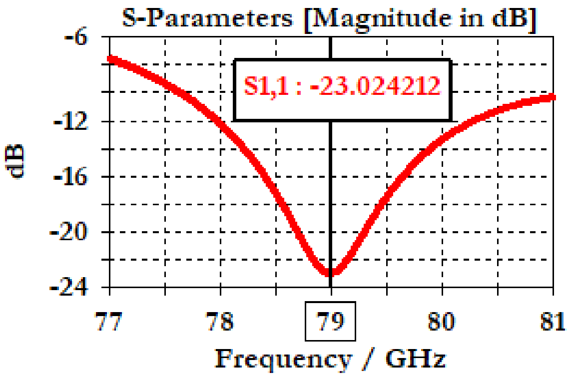


Figure 8: Reflection coefficients of antenna arrays.

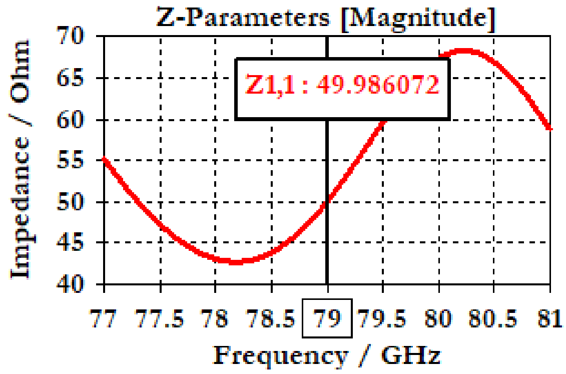


Figure 9: Input impedance of antenna networks

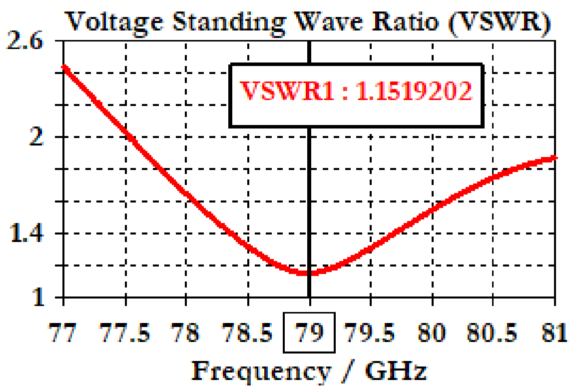


Figure 10: Standing wave ratio of the antenna network

Figures 8 to 10 show us that the antenna network is well suited to the transmission line, this means that the maximum power is transmitted and does not present a significant loss of adaptation. Indeed, figure 9 shows us that the input impedance of the antenna array is 49.98≈50ohms which shows that the antenna array is suitable because figure 8 a low reflection coefficient of the antenna array and we realize that the adaptation is correct because the network has reflection coefficients S11 <-10dB and a standing wave ratio SWR ≤2.

The 3D radiation pattern of the antenna array is shown below.

- 3D radiation from the antenna array

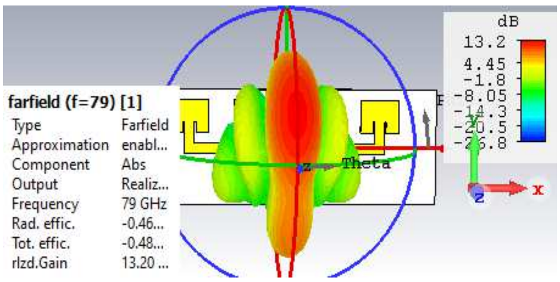
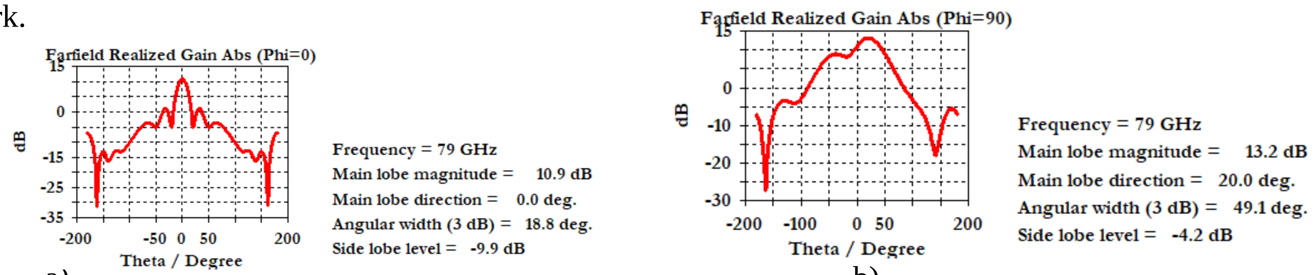


Figure 11: 3D radiation from antenna arrays

Figure 12 shows the radiation pattern in Cartesian form in the E plane and the H plane of the antenna network.



a) b)

Figure 12: Antenna network: a) Plan E, b) Plan H.

With the antenna array we went from 4 to 13.2 dB, which is almost triple what we had with an antenna. The antenna thus designed is linearly polarized or for better coverage, it would be very interesting if the antenna could radiate all around the vehicle. We therefore realized a circularly polarized antenna by using a 3dB loss hybrid coupler at 90^0, the idea of such an initiative is taken from [8.]. An antenna with circular polarization is an antenna which will radiate on 360^0, so it is clear that with the junction of 4 phase couplers 90^0 each one will obtain a radiation on $4x90^0$ or 360^0.

II.2.3 Analysis of a 3dB, 90^0 Hybrid Coupler

The coupler has 4 ports can be perfectly adapted to the working frequency if the impedances of the lines which constitute them are (figure 13) correctly chosen. The input power P1 is divided into 2 output signals P2 (direct channel) and P3 (coupled channel). Port 2 is isolated from the input. The phase difference between the output ports is 90 ° this phase shift is independent of the coupling. To see 3 dB coupling, the horizontal and vertical line segments must have wavelengths and characteristic impedance of 35.4Ω and 50Ω [9] respectively.

Referring to Figure 13, a signal applied to port1 also splits between ports 2 and 3 with one of the outputs exhibiting a 90 ° phase shift. If ports 2 and 3 are properly terminated with matching impedances, almost all of the signal applied to port1 is passed to loads connected to ports 2 and 3. In this case, port 4 receives negligible power and is called isolated [10].

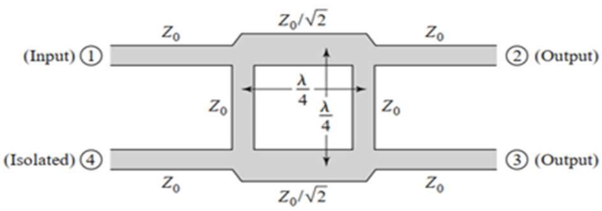


Figure 13: Geometry of the Coupler [7].

II.2.3.1 Pre-dimensioning of the 90-degree Hybrid Coupler

Before starting the parametric study of the coupler, it is advisable to calculate the parameters of the coupler according to the specifications. This parametric study involves the calculation of the following dimensions: The length of a branch: the length of the branch must be equal to a quarter of the wavelength at the desired frequency. The width of a branch, the desired coupling factor here is 3 dB the calculation of the width w is given by the following relation:

- The length of a branch: the length of the branch (L) must be equal to a quarter of the wavelength (λ) at the desired frequency (f), speed of light (c), speed of propagation (sp) and the relative permittivity (ε_r)

$$\boldsymbol{L} = \frac{\lambda}{4} \tag{10}$$

With, $$\lambda = \frac{\boldsymbol{v_p}}{\boldsymbol{f}} = \frac{\boldsymbol{c}}{\boldsymbol{f}\sqrt{\varepsilon_r}}$$

- The width: the desired coupling factor here is 3 dB the calculation of the width w is given by the following relation with the distance (d) and the impedance (Z_0).

$$\frac{\boldsymbol{w}}{\boldsymbol{d}} = \begin{cases} \dfrac{8e^{A}}{e^{A}-2} \\ \dfrac{2}{\pi}\left[\boldsymbol{B}-1-\ln(2\boldsymbol{B}-1)+\dfrac{1}{2}\left\{\ln(\boldsymbol{B}-1)+0.39-\dfrac{0.61}{\varepsilon_r}\right\}\right] ; \dfrac{\boldsymbol{w}}{\boldsymbol{d}} > 2 \end{cases} \tag{11}$$

With $\boldsymbol{A} = \frac{\boldsymbol{Z}_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}$ and $\boldsymbol{B} = \frac{377\pi}{2\boldsymbol{Z}_0\sqrt{\varepsilon_r}}$

II.2.3.2 Presentation of the Coupler

The coupler is sized and simulated with Agilent Design System (ADS) software at the 79 GHz frequency band and the line dimensions are calculated by the Line-calc calculation tool available in ADS. The coupler will be made with the Rogers Duriod 5880 substrate of the same thickness because the antenna is made with the same type of substrate the dimensions of the coupler are specified in table 2.

TABLE 2: COUPLER DIMENSIONS

Paramètres	Valeurs
L_1	0.677742 mm
W_1	0.618022 mm
L_2	0.691995
W_2	0.365889
f_r	79 GHz
Z_0	50 Ω
$Z_0/\sqrt{2}$	35.35 Ω

L is the length of the branch and W is the width of the branch.

The representation of the coupler is given in figure 14 below:

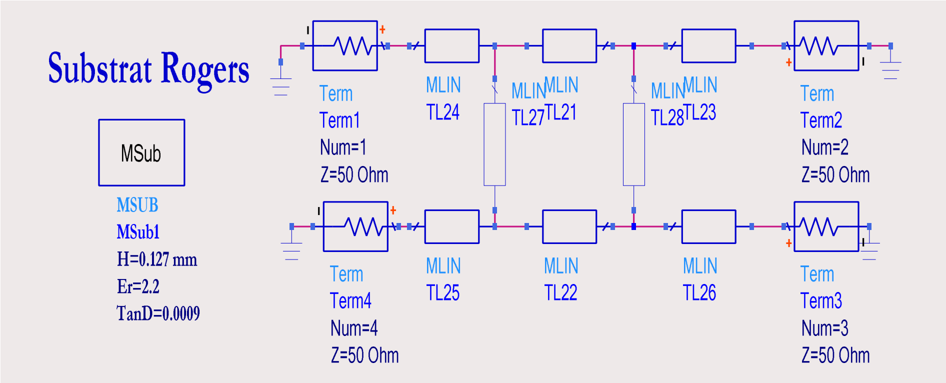


Figure 14: Representation of the Coupler.

Simulation gives us the following results:

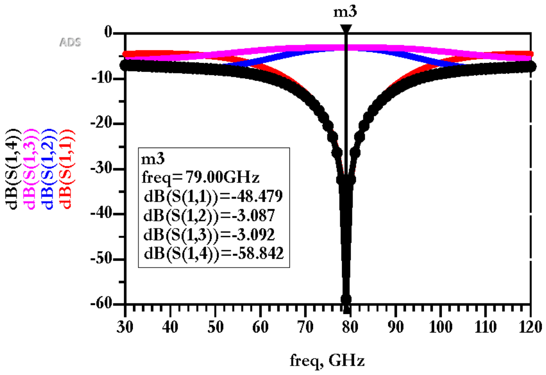


Figure 15: Reflection coefficients Sij as a function of the frequency of the coupler (3dB, 90^0).

Figure 16 shows the phase shift between the output ports.

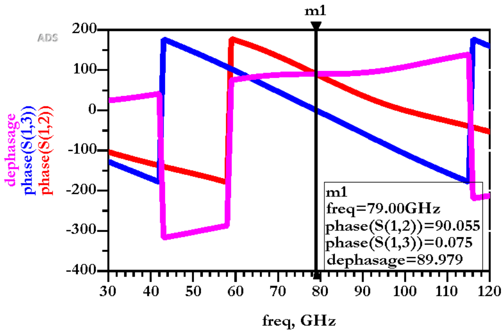


Figure 16: phase shift as a function of the frequency of the Coupler (3dB, 90°).

The phase shift obtained between the output ports which are ports 2 and 3 is 89.979 °, ie practically 90 °. The coefficient S14 being very low, confirms our previous remarks stating that port 4 is the isolation port. After having modeled the coupler with a branch, it is a question of joining these couplers to form a 3-branch coupler. Indeed it is a question of joining 3 couplers of the same nature as the one previously we will therefore have 8 ports in total Port 1 is the input port and ports 4,5 and 8 are the isolation ports where we have a negligible power as at the other ports these can be joined to a load and present between them a phase shift of 90 ° it is about the ports 2, 3 and 6, 7 Figure 17 below therefore shows this coupler has three branches.

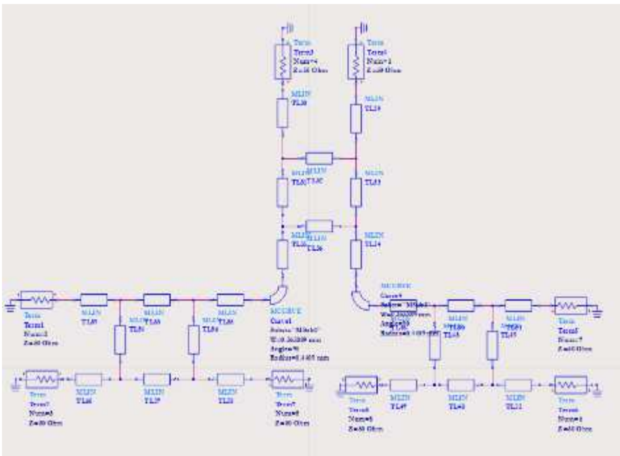


Figure 17: 3 leg Couplers

The simulation of this coupler gives us the following result:

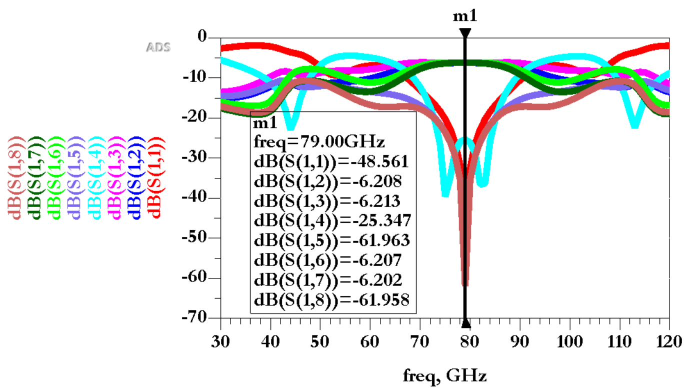
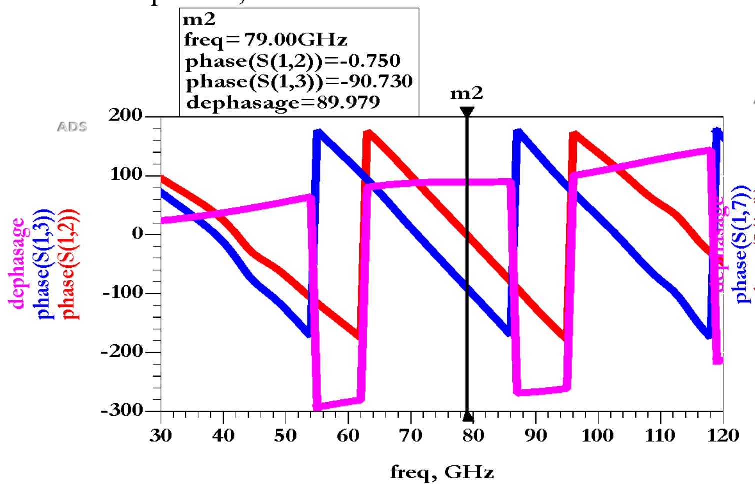
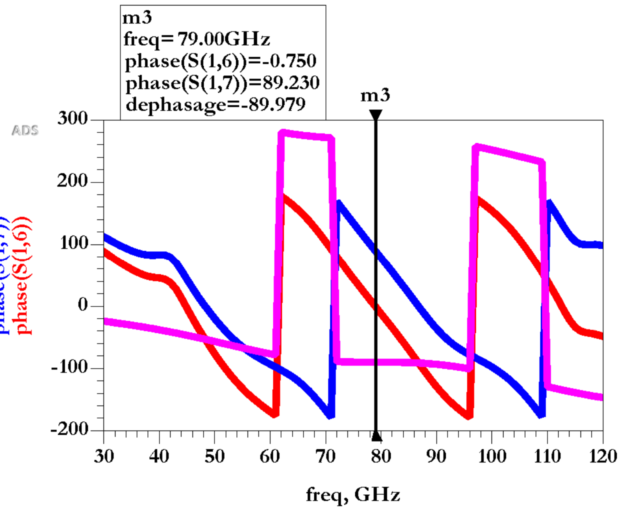


Figure 18 :S_{ij} parameters of the 3-branch coupler

The following figures give us the phase shift between the output ports which are the ports 2,3 and the ports 6,7 we will have to observe a phase shift of 90 degrees between the ports 2,3 and the ports 6,7.



a)



b)

Figure 19: Phase shift between the output ports: a) between ports 2, 3; b) between ports 6,7.

II.3.2.3 Integrations of the load (Antenna) at the outputs of the 3-branch coupler

The integration of the antenna into the couplers is illustrated in Figure 20 below.

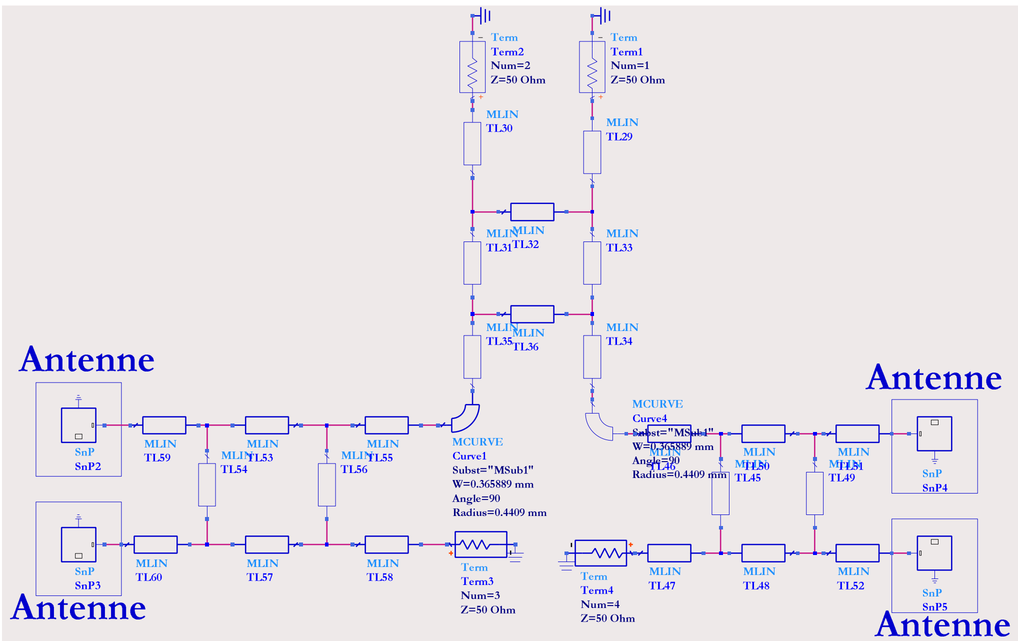


Figure 20: Integration of the antenna into the Couplers.

Because the antenna is placed at ports 2,3 and ports 6,7 then our isolation ports become ports 2, 3, 4 and port 1 is the input port as before. The simulation of this gives us the following results.

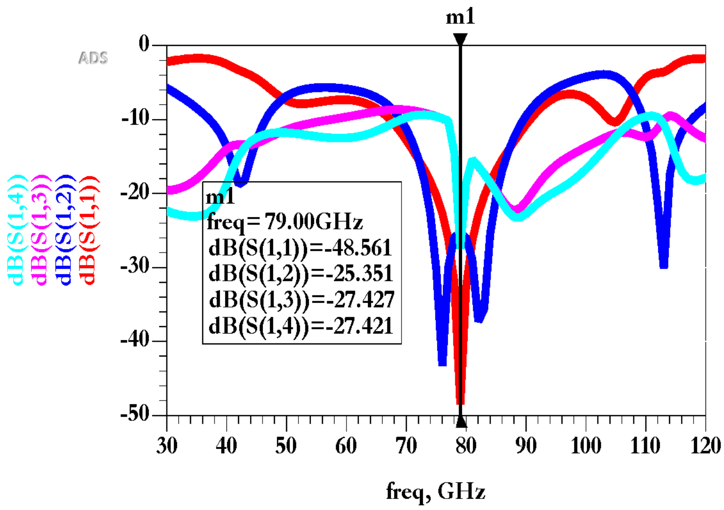


Figure 21: Parameter S_{ij} obtained after integration

We find that our antennas are well suited to couplers and that although polarization is not seen for the sake of displaying antenna radiation, the circular polarization approach with coupler is functional.

III. AMPLIFIER

An amplifier is an electronic device so the role is to enlarge the power of a signal at its input to be sent into free space so that the target can detect this despite all the disturbances it will undergo in return for being able to detect an identifiable echo that can be processed by the system. The design of a transistor microwave amplifier begins with the quality of the transistor. In our work we were interested in a FET transistor with the same substrate as the one designed with the antenna. Figure 22 shows us the transistor.

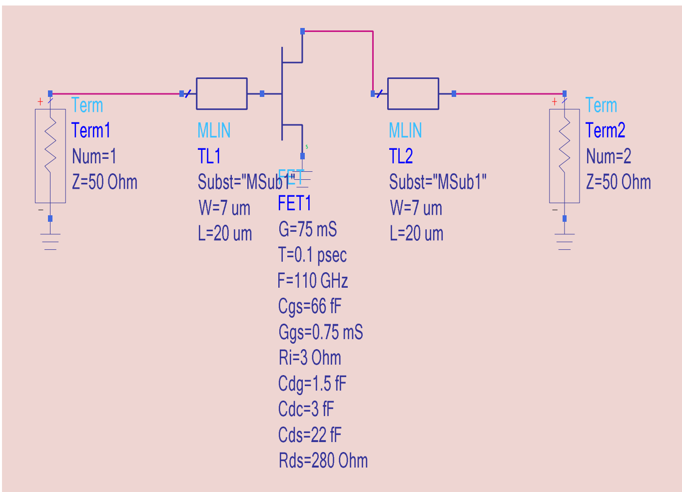


Figure 22 :FET transistor with Rogers substrate

To obtain the dimensions of our transistor, we were inspired by works [11]. The simulation of the S parameters of our transistor correspond to the bias voltages Vds = 4V and VGS = -0.1V for a consumed power of 27 mw.

Figure 23 below illustrates the S parameters obtained. That although polarization is not seen for the sake of displaying antenna radiation, the circular polarization approach with coupler is functional.

To obtain the dimensions of our transistor, we were inspired by works [11]. The simulation of the S parameters of our transistor correspond to the bias voltages Vds = 4V and VGS = -0.1V for a consumed power of 27 mw.

Figure 23 below illustrates the S parameters obtained.

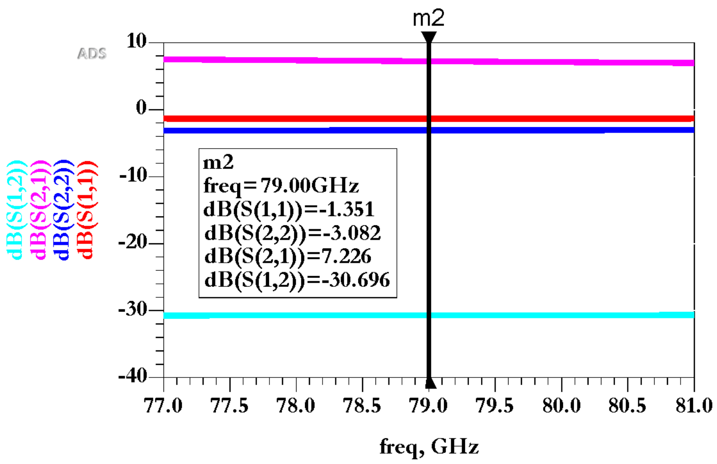


Figure 23: Parameter Sij of the Transistor

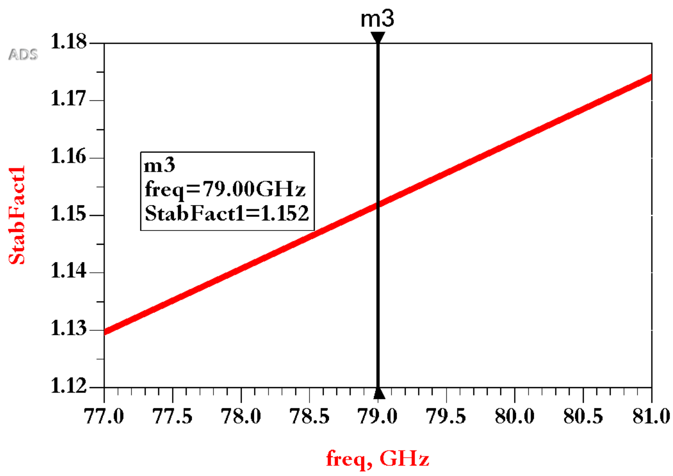


Figure 24 : Rollet's Stability Constant

We can summarize the results obtained in table 3 below

TABLE 3: TRANSISTOR PARAMETERS

Paramètres	**Valeur**
S_{11}	-1.351 dB
S_{12}	-30.696 dB
S_{21} ou Gain en Puissance	7.226 dB
S_{22}	-3.082 dB
Constante de Stabilite de Rollet	1.152

The stability constant K> 1 therefore the transistor is unconditionally stable. Now it is a question for us of adding elements while checking the adaptation at 50 ohms to be able to constitute our microwave amplifier for this we start by modeling a stub resonating at 79 GHz Figure 25 shows this Stub.

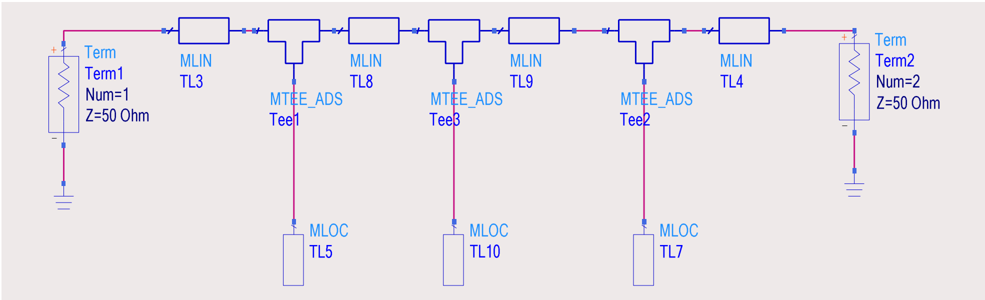


Figure 25 : Stub Circuit

Figure 26 shows us the simulations obtained from the modeled stub

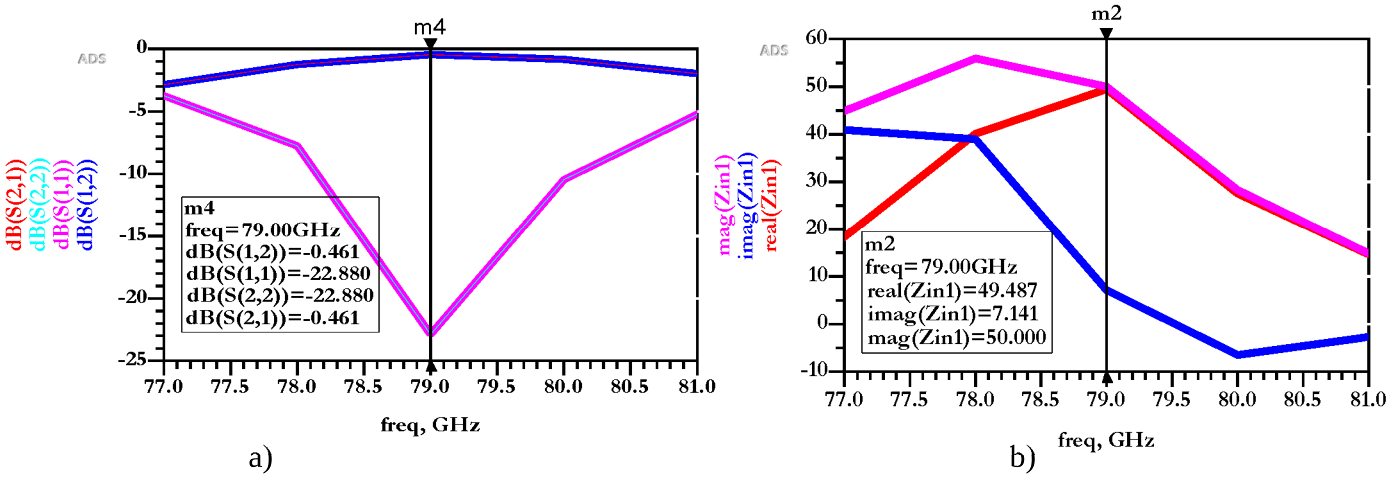


Figure 26: a) Sij parameter of the Stub, b) input impedance of the Stub

The stub has a perfect match, ie an impedance of 50 ohms at the input and at the output. The reflection coefficients S11 = S22, S12 = S21 show that very little power input is reflected or a large part of that power is returned to the output with a very small standing wave ratio. The modeling of our amplifier is shown below.

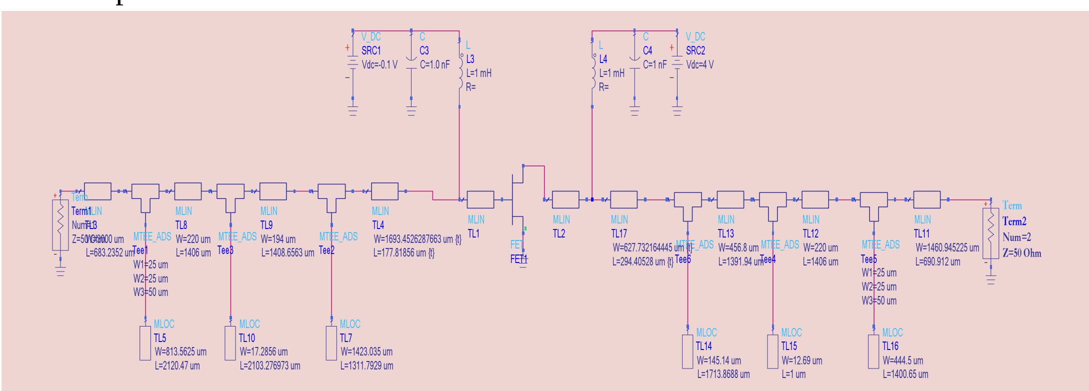


Figure 27 : Microwave amplifier.

The results obtained after simulating our Amplifier on ADS give the following result:

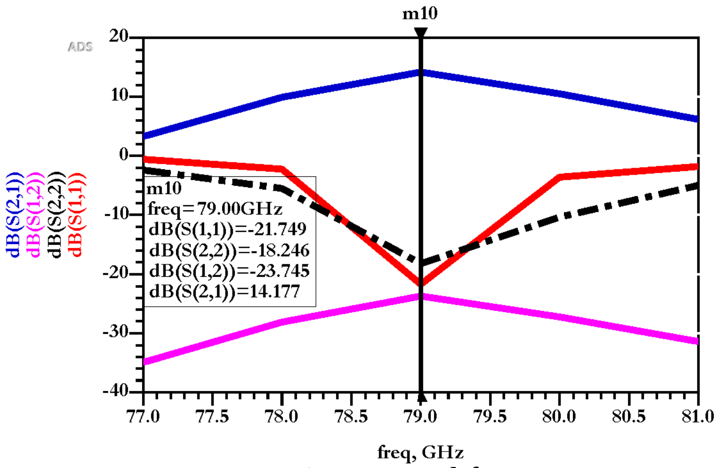


Figure 28 : Sij Amplifier Parameters

The amplifier is properly matched with a power gain of 14.177 dB and isolation of -23.745 dB. The validation of our results conforms by an input impedance match of 50 ohms shown in Figure 29.

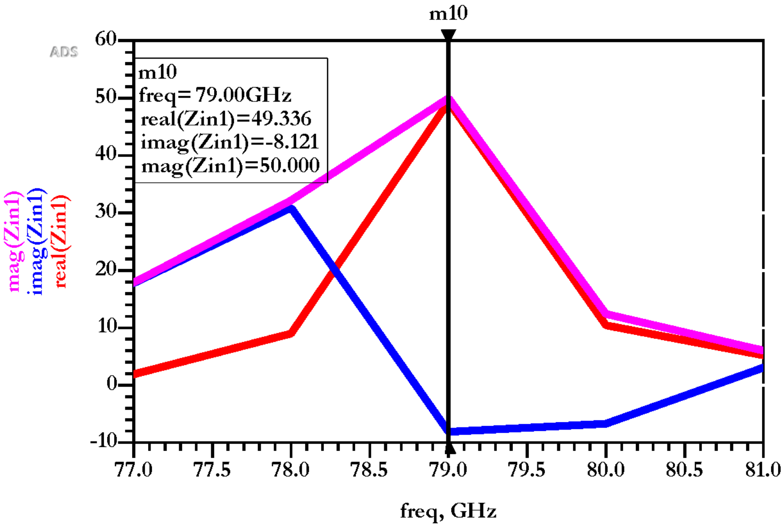


Figure 29 : Amplifier input impedance

TABLE 4 BELOW SUMMARIZES THE RESULTS OBTAINED

Parameters	Values
S_{11}	-21.749 dB
S_{12}	-23.745 dB
S_{21} or power of Gain	14.177 dB
S_{22}	-18.246 dB
impédances	50Ω

For the needs of improving the parameters of the signal to be transmitted, we have made a two-stage amplifier. This was made possible by cascading two previous amplifiers in figure30.

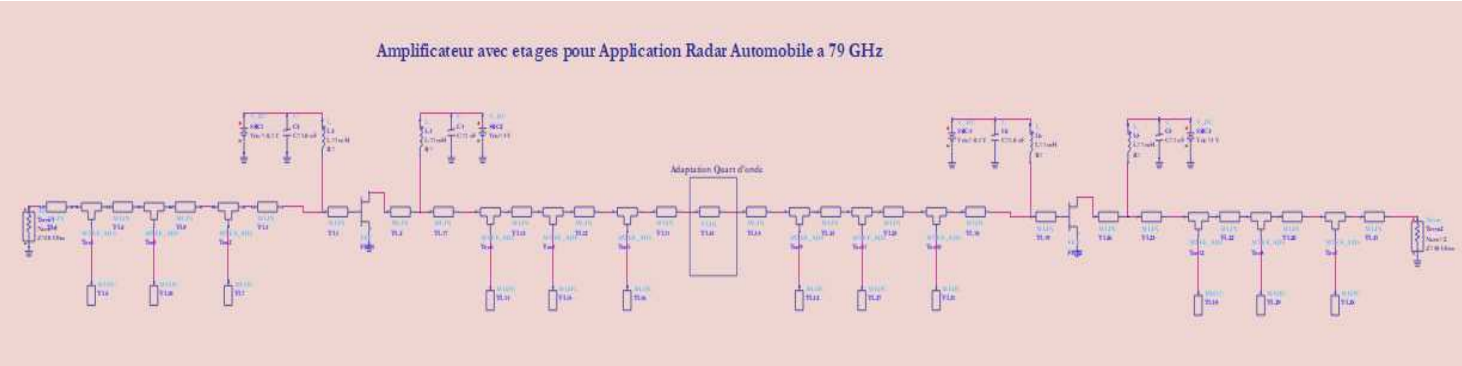


Figure 30 : Cascaded amplifier.

The simulation of our amplifier in Figure 31 allows us to observe that the input impedance is rated at 50 ohms.

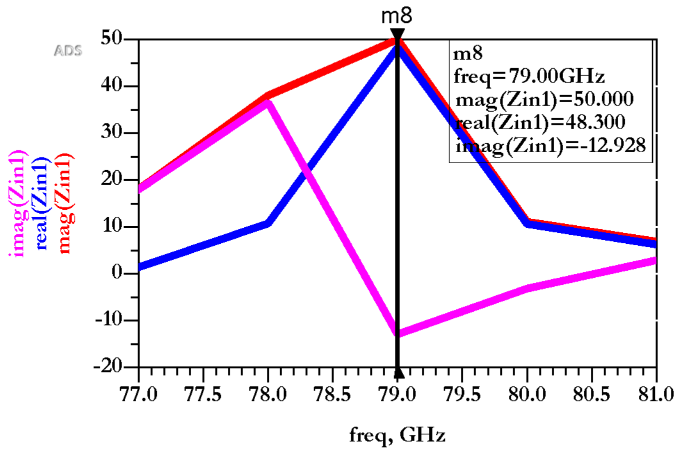
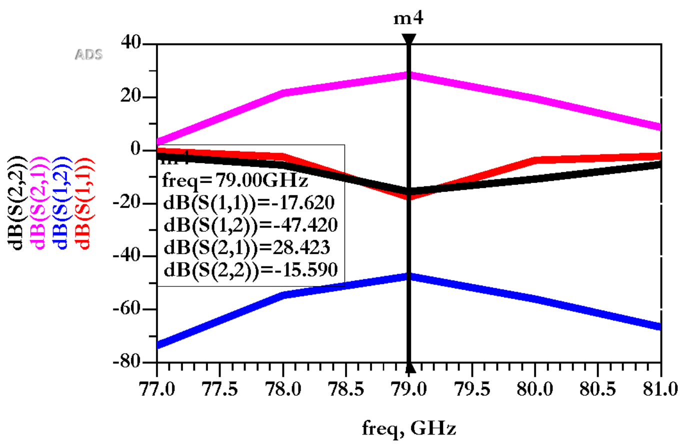


Figure 31: Input impedance of the cascade amplifier

The Sij parameters obtained are presented in figure 32 below.



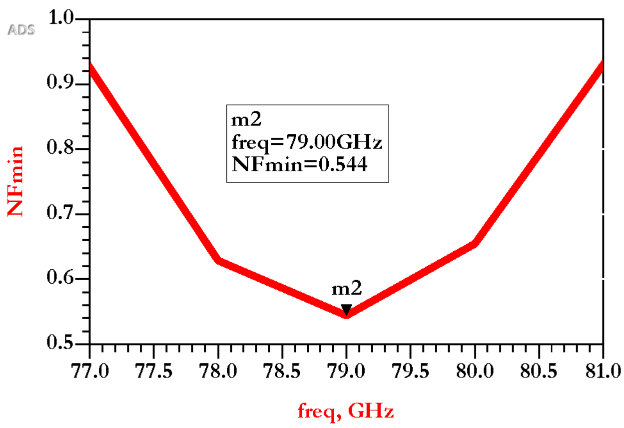


Figure 32: Sij parameters of the cascade microwave amplifier. Figure 33: Figure 33: Noise figure of the cascade amplifier.

La figure 33 shows the noise figure generated by the amplifier

T ABLE 5: PARAMETERS OF THE CASCADE AMPLIFIER**.**

Paramètres	**Valeur**
S_{11}	-17.620 dB
S_{12}	-47.420 dB
S_{21} ou Gain en Puissance	28.423 dB
S_{22}	-15.59 dB
Figure de Bruit	0.544
impédance	50Ω

According to Table 5, the gain obtained with this amplifier is almost double that obtained with an amplifier stage and also has excellent isolation, ie S12 <-40 dB.

IV RESULTS AND DISCUSSIONS

After having modeled on both sides the different transmitters, namely the antenna and the amplifier, it was time for us to propose an Antenna-Amplifier Unit (P A-Antenna), but before doing, let's recap in the table below.

TABLE 6: SUMMARY OF THE RESULTS OBTAINED WITH THE ANTENNA

Parameters	**Antenna**	**Antenna network**
Gain (dB)	5.593	13.2
Directivity (dBi)	6.906	13.69
ROS	1.007	1.1519
S_{11} (dB)	-48.553	-23.02
Efficiency of radiation (%)	73.91	89.85
Bandwidth (GHz)	3.0251	1.4506
Opening on E plane (degree)	80.9	18.8
Opening on H plane (degree)	87.5	20

From Table 6, we find that our antenna has acceptable return losses and ideal characteristics for our application.

TABLE 7: SUMMARY OF THE RESULTS OBTAINED WITH THE AMPLIFIER

Parameters	Amplifier	Amplifier
S_{11} (dB)	-21.749	-17.620
S_{12} (dB)	-23.745	-47.420
S_{22} (dB)	-18.246	-15.59
S_{21} (dB)	14.177	28.423
Input impedance	50Ω	50Ω
Noise Figure	0.461	0.544

Like the antenna, our amplifier also has ideal characteristics for our application. In what follows we do the Co-design of the Amplifier-Antenna block. Figure 34 below shows its principle.

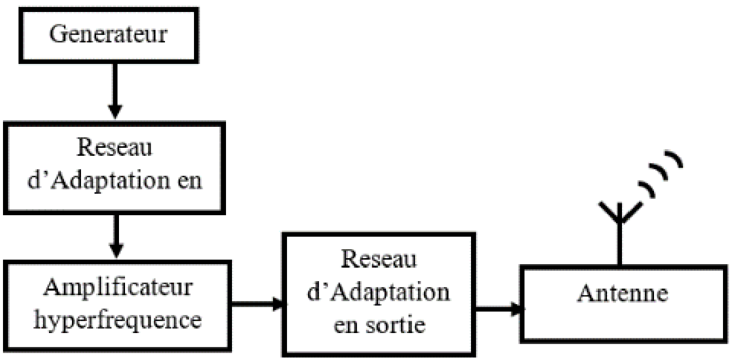


Figure 34: PA-Antenne Co-Design Principle**.**

The modeling of the PA-Antenna block is given to the figure35 below.

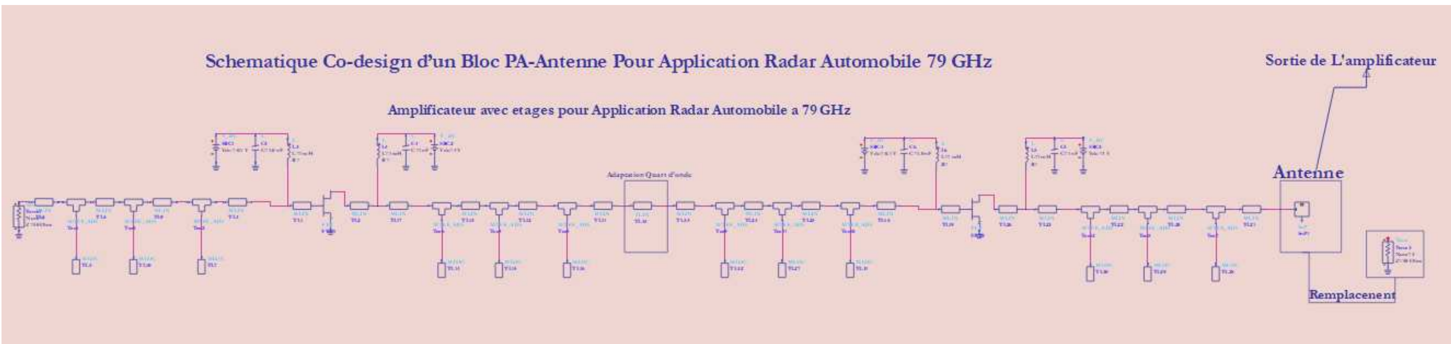


Figure 35 : Co-Design PA-Antenna for automotive radar application with 79 GHz

After simulation of this block we obtain the following results in figures 36 and 37:

- The impedance of the PA-Antenna Co-Design is given by the figure below

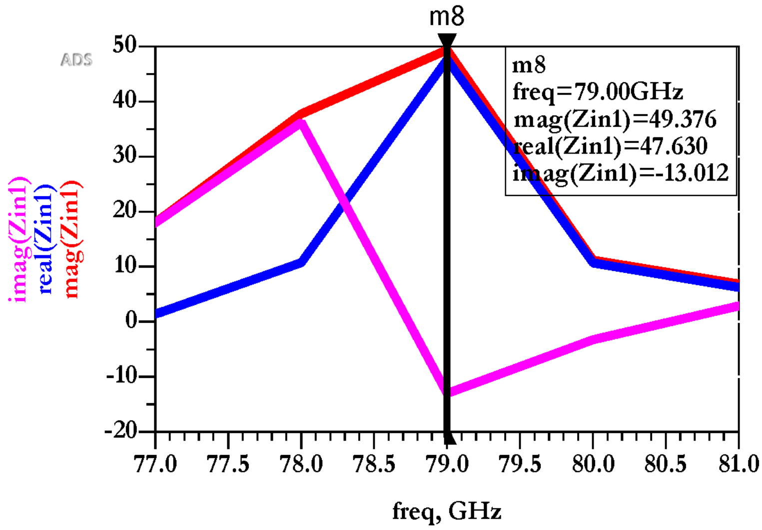


Figure 36: Impedance of the PA-Antenna Co-Design

Co-Design P A-Antenna S11 reflection coefficient

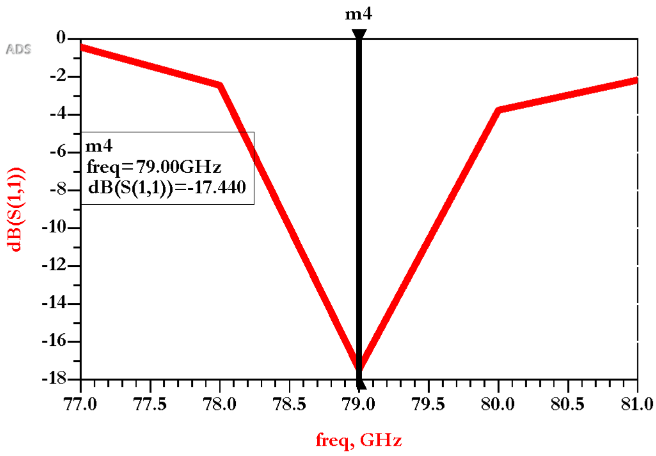


Figure 37 PA-Antenna S11 reflection coefficient

The PA-Antenna Co-Design is functional because the two attached transmitters have acceptable reflection coefficients.

V CONCLUSION

Having reached the end of our work, it is important to note that the proposed Block has characteristics that are ideal and essential in the architecture of the transmission chain for new Automobile Radar systems. Before producing the PA-Antenna unit assembly, we previously designed the antenna unit and the amplifier unit separately. It is interesting to note that the addition of a 3-branch coupler to our antenna was intended to be able to give it a circular polarization. In addition, it is important to point out that work aimed at improving these is in progress, firstly we obviously notice that the level of side lobes proposed by our antenna networks turns out to be quite large so we will therefore propose in the upcoming works an antenna array so the sidelobe level is better than that designed in this work.

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