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A High Efficiency Doherty Power Amplifier for TV Band Applications

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Abstract

This paper presents a high efficiency Doherty power amplifier suitable for TV band applications. A class AB power amplifier is firstly implemented using a commercial GaN HEMT from Cree Incorporation, achieving a high power-added-efficiency of 77.78% and a 40.593 dBm output power with an associated gain of 21.65 dB. The Doherty amplifier has then been designed following the previous class AB scheme for the main amplifier and a class C scheme for the peak one. This amplifier attained a high power-added-efficiency of 81.94%, a 42.77 dBm output power, an associated gain of 21.32 dB, and an operating frequency bandwidth between 550 and 1000 MHz (58.06% fractional bandwidth) which made it suitable for TV band applications.

Keywords

Power Amplifier, Class AB, Doherty Power Amplifier, Efficiency, TV Band

1. Introduction

Recently, the design of RF front-ends in wireless communication for cognitive radio applications has become a hot research area. Highly efficient and linear power amplifier is a key component in these systems. However, the main problems of the design of power amplifier exist in their linearity region and their gain especially in multi-carrier systems (such as orthogonal frequency division multiplexing-OFDM) which are widely used in current wireless communication. Indeed, these systems present high peak-to-average power ratio (PAPR) caused by the large number of independent subcarriers with random phase and amplitude added together at the input of the amplifier which makes the latter impractical to work next to its saturation point [1]. Therefore, a power amplifier with high linearity and efficiency is great of importance. The simplest method is to back-off signals from the saturation region to the linear region at the cost of power efficiency. Another way may use predistortion methods or elimination and restoration techniques. However, these techniques which need additional components

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result in an increase in cost, size, and power dissipation. In order to solve these problems, a Doherty Power Amplifier (DPA) is the most promising candidate with high efficiency in power and bandwidth [2]-[8].

The Doherty amplifier operation can be achieved using two cells with a class-AB biased carrier amplifier cell and a class-C biased peak amplifier cell with respective input matching network and output matching network. The Doherty power Amplifier (DPA) operating principle is based on modulating the load of the active (carrier) device by using a second active peak device. The two power amplifiers are connected at the output through a quarter-wave transmission line to exploit the active load modulation concept performed by the peak amplifier on the main carrier one. This Doherty amplifier has high linearity and efficiency across the wideband signal.

In practice, Doherty amplifiers are the best candidates that can provide higher efficiency among all type of amplifiers. They are widely used for many applications where RF power amplifier efficiency is important. The efficiency of the Doherty amplifier can be improved if the efficiencies of the two amplifiers can be properly increased [4].

The Doherty technique is usually adopted to design power amplifiers for wireless systems and, in particular, in base stations, working in L-S-C Band for applications such as WiMAX, WLAN, cellular network, and others. Drain efficiencies up to 70% have been demonstrated for output powers between 5 W and 10 W [9]-[11], whereas drain efficiency up to 50% has been demonstrated for 250 W output power [12].

However, a well-known disadvantage of the DPA is its typical narrow bandwidth performance. Although significant improvements in bandwidth have been reported recently [13]-[17], the DPA is still fundamentally bandwidth limited by the quarter wave impedance inverter needed to obtain proper load modulation. This results in substantial frequency dependence at the back-off power region where the Power Amplifier (PA) is operating most of the time, and thereby narrow band performance for realistic signals.

In this paper, a class AB power amplifier and a high efficiency Doherty one with operating frequency at 800 MHz were developed and verified for the suitability for TV band applications. In comparison with previously designed power amplifiers, the proposed Doherty power amplifier attains higher efficiency and wider bandwidth. The proposed Doherty power amplifier reaches a power added efficiency of 81.94% with a 58.06% fractional bandwidth, so that it can be used as a high efficiency power amplifier for the TV band from 550 to 1000 MHz. The geometry, the design guidelines, and the results of the proposed amplifiers are presented. In addition, the characteristics of the designed amplifiers are investigated via Agilent Advanced Design System (ADS) software and verified using NI AWR Design Environment software.

2. Design, Simulation, and Results

2.1. Class AB Power Amplifier

The schematic of this proposed class AB amplifier is shown in **Figure 1**. The amplifier is simulated in both software, ADS and AWR. The active device employed in the AB amplifier is the CGH40010 from Cree Inc., a GaN HEMT with a typical output power of 10 W at the suggested drain bias voltage of 28 V. This transistor offers high efficiency, high gain, and wideband capabilities. The amplifier circuit was simulated with a constant drain supply voltage Vsup = 28 V and the gate bias voltage Vg = −2.1 V which represents a bias condition of a conventional class AB amplifier. The substrate parameters were set according to Rogers RO3203 substrate with dielectric constant $\varepsilon_r = 3.02$ and thickness h = 1.6 mm, on which the amplifier is designed.

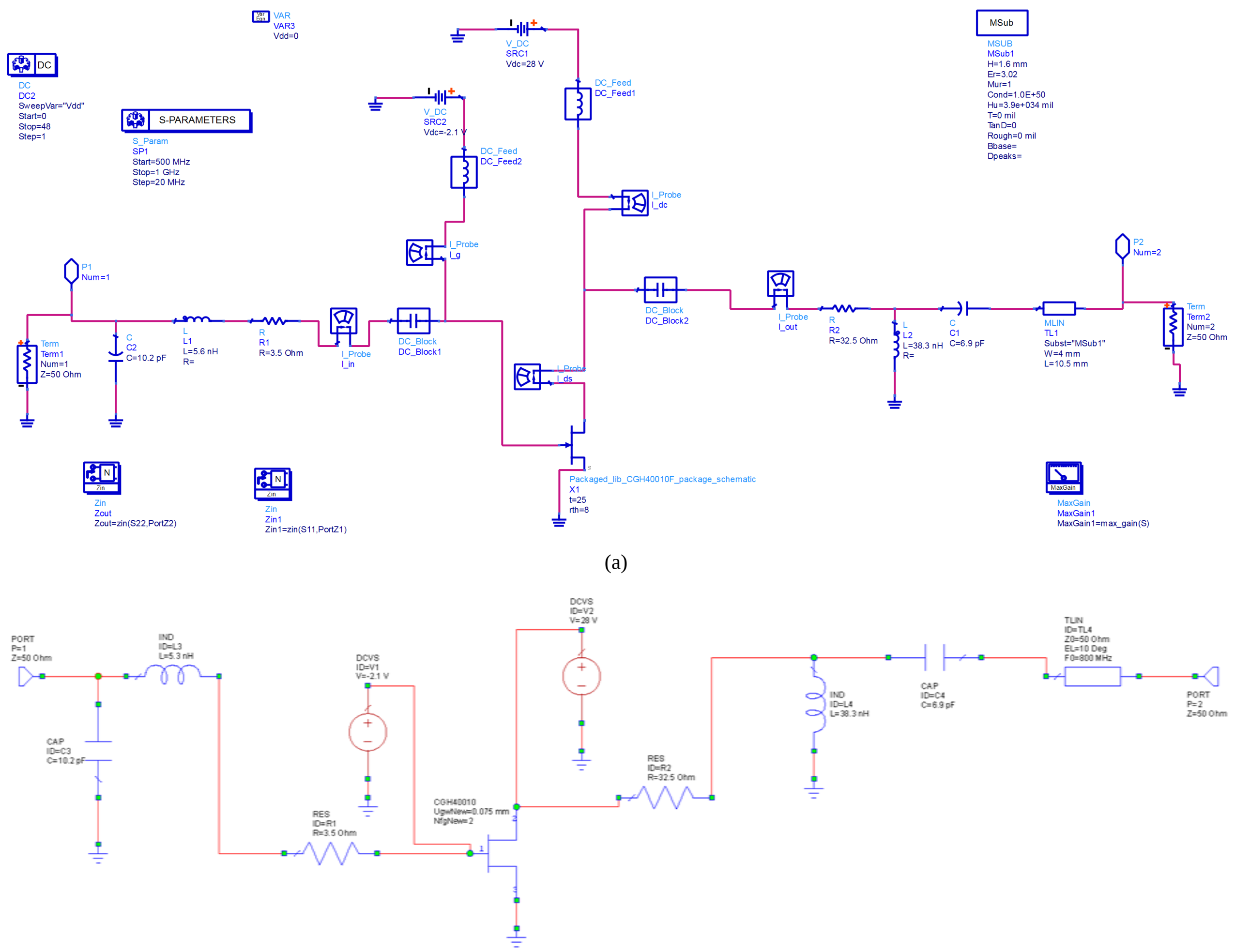
To verify the accurate representation of the Cree CGH40010 model, the signal scattering parameters generated from ADS for the frequency 800 MHz were compared to the ones given in the datasheet. Close agreement, as presented in **Table 1**, is obtained.

After carrying out the stability test of this amplifier, it is found that the device is potentially unstable in the frequency range of interest. Indeed, the stability parameters, Δ, and the rollet factor *k* are calculated and found to be:

$$\Delta = 0.092 \angle -8.6^\circ$$

$$k = 0.163$$

This means that the device is potentially unstable. Stabilization methods were performed and series resistances were added to the input and the output of the transistor as shown in **Figure 1**. The input resistance is 3.5 Ohms and the output resistance is 32.5 Ohms. After adding these resistances, the stability parameters were recalculated and found to be:



(a)

(b)

Figure 1. Schematic of the AB power amplifier with input and output stability resistors and matching circuits. (a) In ADS; (b) In AWR.

Table 1. S-parameters of the GaN transistor at 800 MHz.

	S11	S12	S21	S22
Simulation	$0.911 \angle -154^\circ$	$0.023 \angle 3.54^\circ$	$11.933 \angle 89.38^\circ$	$0.298 \angle -132.5^\circ$
Datasheet	$0.894 \angle -146.96^\circ$	$0.029 \angle 6.84^\circ$	$11.58 \angle 91.78^\circ$	$0.317 \angle -109.84^\circ$

$$\Delta = 0.162 \angle -146.4^\circ$$
$$k = 1.57$$

After adding the stability resistances, the signal scattering parameters at 800 MHz had changed. The scattering parameters were simulated and found to be (at 800 MHz):

$$S11 = 0.772 \angle -157.51^\circ$$
$$S12 = 0.016 \angle -0.034^\circ$$
$$S21 = 8.057 \angle 85.81^\circ$$
$$S22 = 0.17 \angle -39.773^\circ$$

In order to maintain maximum power transfer, we need to match the impedance of the load to that of the source, so matching circuits are designed at the input and the output of the transistor. These circuits are accomplished by using passive networks and microstrip transmission lines as shown in **Figure 2**.

After completing the stability and the matching of the amplifier, the final signal scattering parameters at 800 MHz were simulated and found to be:

$$S11 = 0.056 \angle -119.8^\circ$$

$$S12 = 0.024 \angle -72.2^\circ$$

$$S21 = 12.073 \angle 13.6^\circ$$

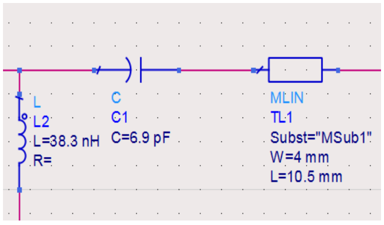
$$S22 = 0.438 \angle -89.4^\circ$$

By feeding the amplifier with an optimum 800 MHz, 18.943 dBm input power, the output power of the amplifier circuit was found to be 40.593 dBm and the gain is 21.65 dB. The DC power is simulated and found to be:

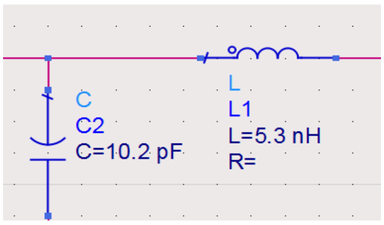
$$Pdc = 28 \times 0.522 = 14.62 \text{ W}$$

Thus, the power added efficiency (PAE) is computed to be around 77.78%. All the results are summarized in **Table 2**.

The amplifier efficiency depends on the DC supply voltage and respectively on the input power. **Figure 3** shows the output power sweep curve as well as the corresponding PAE. As the DC voltage increases, the output power increases fairly linearly indicating that the amplifier has a constant gain. The efficiency also increases approximately linearly until it reaches the maximum at the optimum 28 volt DC supply voltage.



(a)



(b)

Figure 2. (a) Input matching network; (b) Output matching network.

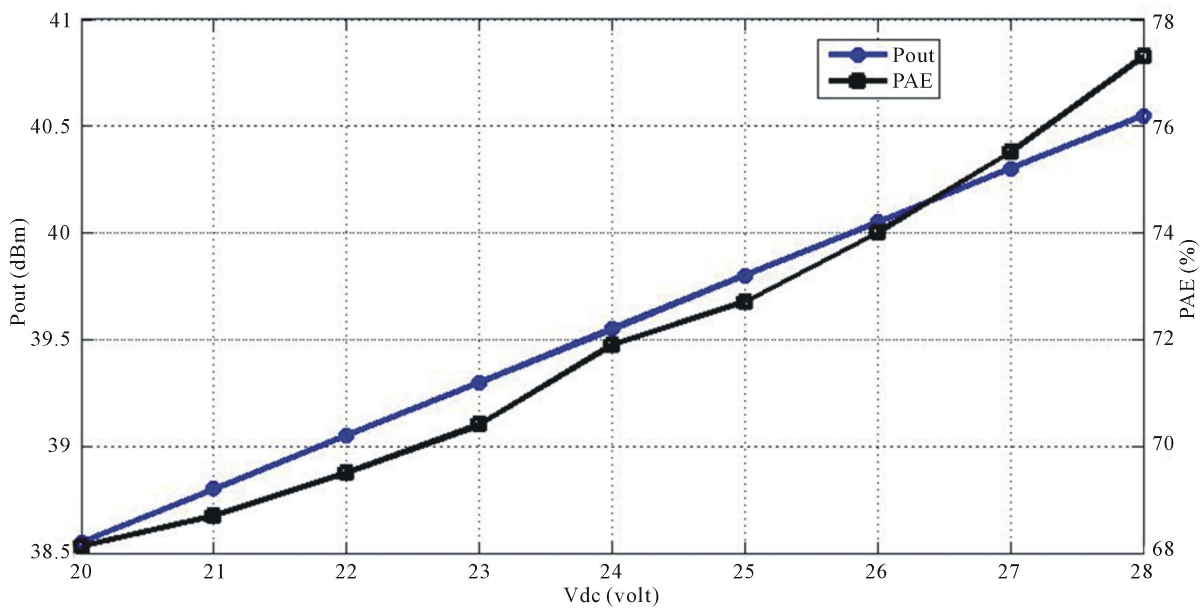


Figure 3. Output power and PAE versus DC voltage in the class AB amplifier.

Table 2. Final results of the class AB amplifier.

Input power (dBm)	DC power (W)	Output power (dBm)	Gain (dB)	PAE (%)	Drain efficiency (%)
18.943	14.62	40.593	21.65	77.78	78.43

The simulated reflection coefficient plots of the class AB amplifier are given in **Figure 4**. The amplifier is simulated via ADS and AWR software. It is clearly shown that this amplifier can operate from 650 MHz to 910 MHz, thus it is suitable for applications in the TV band. It is observed that the simulation results of the two software tools follow the same pattern with little difference.

The percentage bandwidth or the fractional bandwidth which is a measure of how wideband the amplifier is, is given by this equation:

$$\%BW = (f2 - f1)/((f1 + f2)/2)$$

The percentage bandwidth of this amplifier is 33.33%.

The power gain plot of the class AB amplifier is given in **Figure 5**. It is clearly shown that this amplifier has a good power gain above 19 dB for the operation frequency bandwidth.

2.2. Doherty Power Amplifier

As mentioned earlier, the Doherty amplifier procedure can be attained using two amplifiers with a class-AB biased carrier amplifier cell and a class-C biased peak amplifier cell with respective input matching network and output matching network. The two power amplifiers are connected at the output through a quarter-wave transmission line.

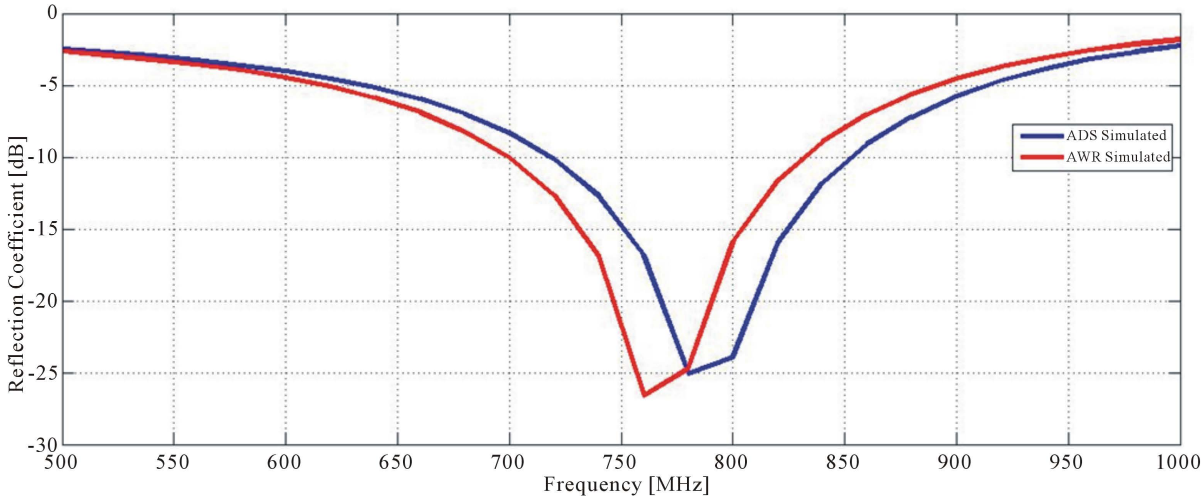


Figure 4. Simulated (ADS and AWR) reflection coefficient plot of the class AB amplifier.

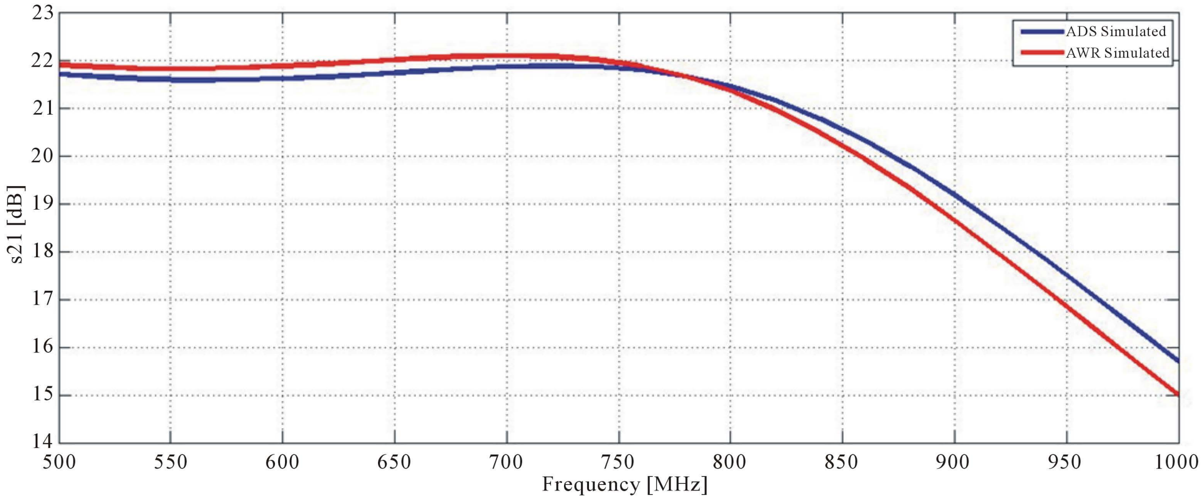


Figure 5. Simulated (ADS and AWR) power gain plot of the class AB amplifier.

Hereby is a detailed procedure used in designing a Doherty power amplifier followed with a flow chart, shown in **Figure 6**, which describes this procedure briefly.

Steps for Design of Doherty Amplifier:

1) The active devices (such as transistors) employed in the DPA are specified. They must operate on a wide range of frequencies and have an adequate output power.

2) These active devices are fully matched to ensure maximum power transfer, so input and output matching networks are implemented in the main and the peak amplifiers.

3) Stability of the main and the peak amplifiers are investigated to make sure the two amplifiers are unconditionally stable.

4) The two amplifiers are connected to each other following the well-known Doherty circuit with two transmission lines serving as impedance transformers in order to achieve the main load modulation.

5) An input power divider is inserted before the two amplifiers in order to split the power between the main and the peak amplifiers.

6) The DPA is then matched to attain maximum power transfer, so input and output matching circuits are designed for this purpose.

7) The stability of the DPA is examined and updated so that the DPA is unconditionally stable.

8) Finally, the circuit is fabricated on a primarily specified substrate.

The DPA configuration used in this paper is the well-known conventional AB-C scheme as shown in **Figure 7**, with a class AB amplifier used as a main stage and a class C amplifier used as a peak stage.

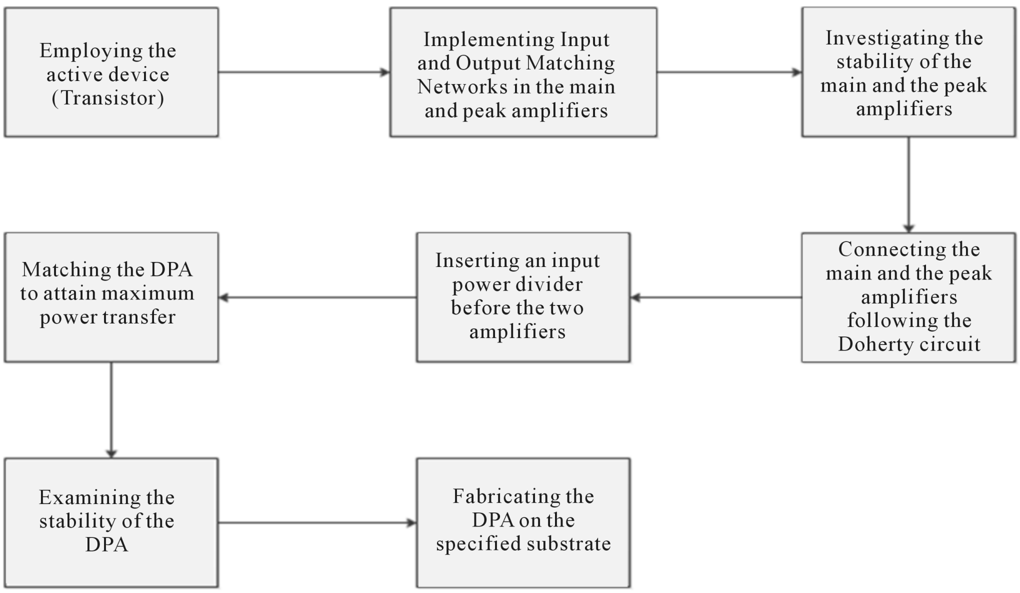


Figure 6. A flow chart of the steps of designing a Doherty power amplifier.

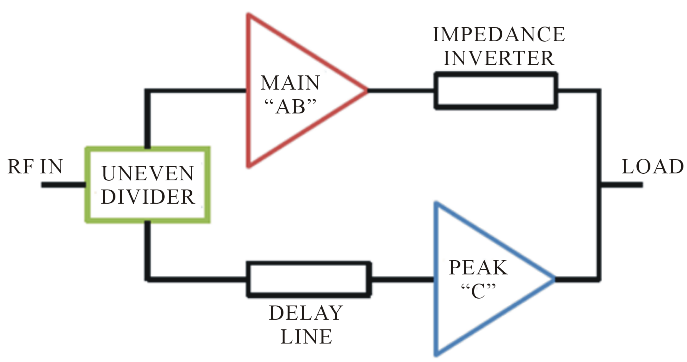


Figure 7. Block scheme of the designed AB-C DPA.

In our design, the previously designed class AB amplifier was used as the main amplifier. Hence, to complete the Doherty design, a class C amplifier is necessary as a peak amplifier. The schematic of this proposed class C amplifier is shown in **Figure 8**. The active device employed in the C amplifier is the ADL5602, an InGaP HBT with a single supply voltage of 5 V. This transistor offers high dynamic range and low noise figure in addition to that it is stable over frequency, temperature, and power supply. The amplifier circuit was simulated at 800 MHz using ADS with a supply voltage Vsup = 5 V and with input and output matching networks realized by passive elements as well as bias networks. The substrate parameters were set according to Rogers RO3203 substrate with dielectric constant $\varepsilon_r = 3.02$ and thickness h = 1.6 mm, in which the amplifier is designed on.

Figure 9 shows the simulated circuit schematic of the proposed AB-C DPA, where the main and the peak amplifiers are as mentioned before. The amplifier is simulated in both software, ADS and AWR. A broadband 90˚ hybrid coupler was used at the input in order to split the signals between the carrier and the peak amplifying paths. The electrical lengths of the delay and the impedance inverter microstrip lines were optimized to ensure maximum power transfer, maximum efficiency, and adequate output power.

After carrying out the stability test of the Doherty amplifier, it is found that the device is unconditionally stable in the frequency range of interest. The stability parameters, Δ, and the rollet factor *k* are calculated and found to be:

$$\Delta = 0.43 \angle -61.48^\circ$$

$$k = 1.4$$

In order to maintain maximum power transfer, matching circuits are designed at the input and the output of the transistor. These circuits are accomplished by using passive networks and microstrip transmission lines as shown in **Figure 10**.

Once the amplifier matching is complete, the final signal scattering parameters at 800 MHz were simulated and found to be:

$$S11 = 0.198 \angle -99.259^\circ$$

$$S12 = 0.035 \angle -55.086^\circ$$

$$S21 = 11.407 \angle 94.509^\circ$$

$$S22 = 0.175 \angle -90.038^\circ$$

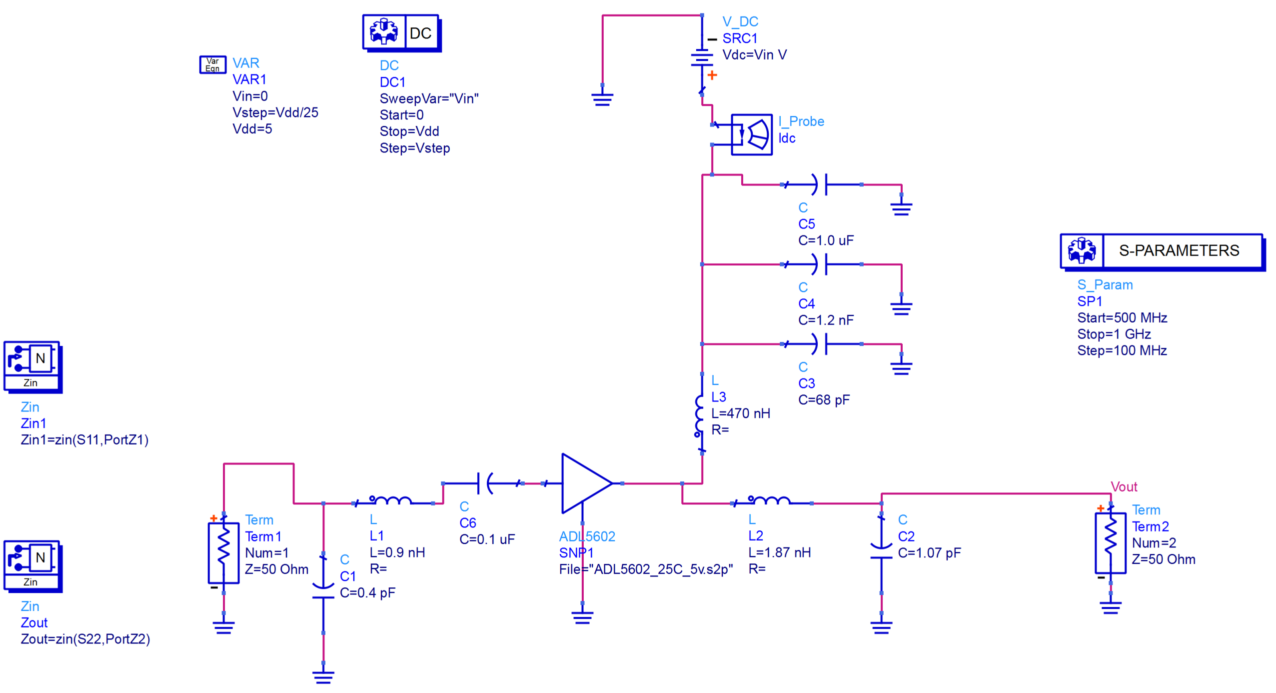


Figure 8. Schematic of the C power amplifier with bias and matching circuits.

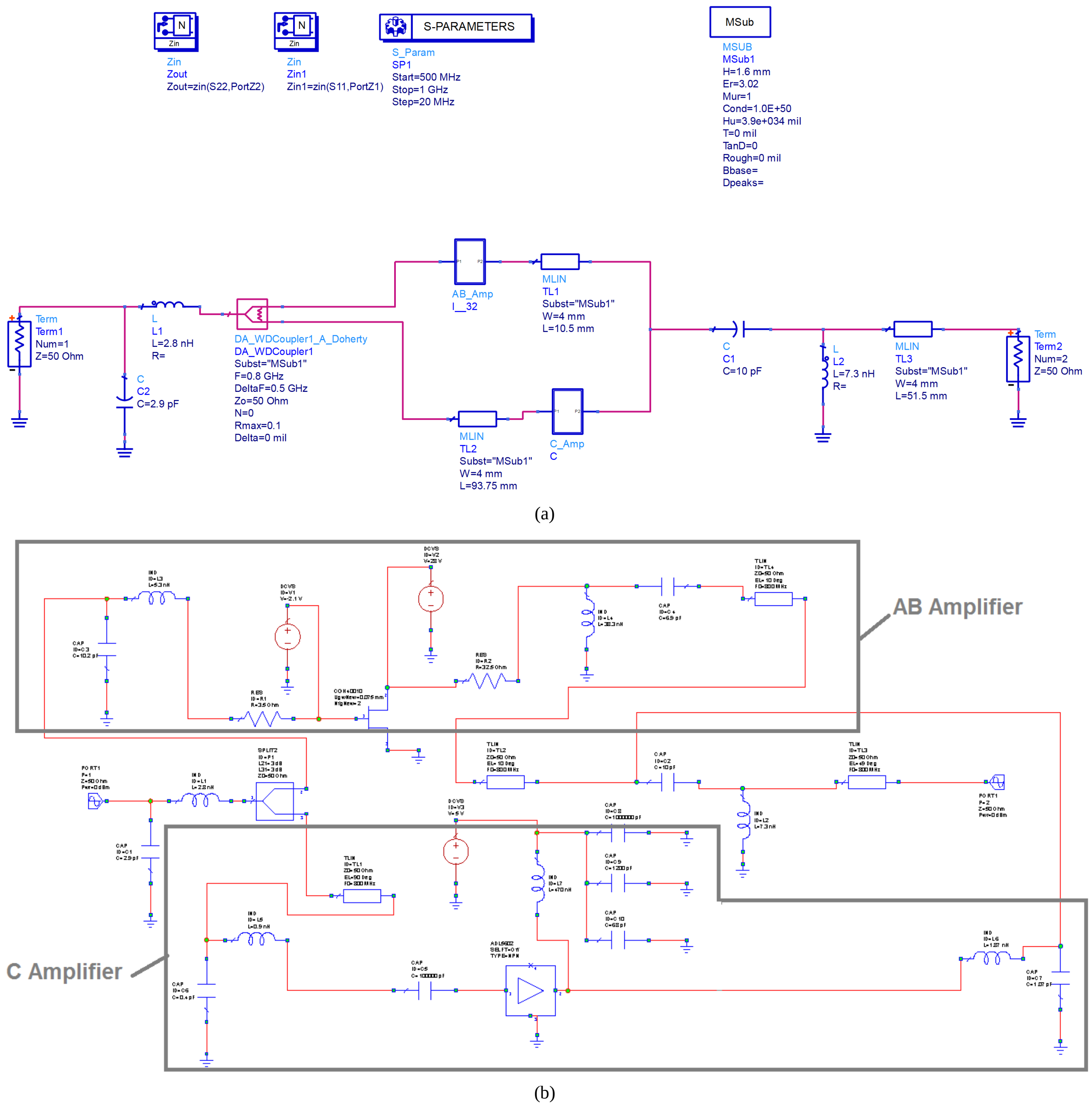


Figure 9. Schematic of the Doherty power amplifier with matching circuits. (a) In ADS; (b) In AWR.

By feeding the Doherty amplifier with an optimum 800 MHz, 21.45 dBm input power, the output power of the Doherty amplifier circuit was found to be 42.77 dBm and the gain is 21.32 dB. The DC power is simulated and found to be: Pdc = 22.92 W. Thus, the power added efficiency (PAE) is around 81.94%. All the results are summarized in **Table 3**. It is clearly shown that the efficiency of the DPA is higher than that of the class AB power amplifier. This is due to the Doherty principle implemented in this design and to the electrical lengths of the delay and impedance inverter transmission line previously mentioned.

Figure 11 shows the output power sweep curve as well as the corresponding PAE. As the DC voltage increases, the output power increases fairly linearly indicating that the amplifier has a constant gain. The efficiency also increases approximately linearly until it reaches the maximum at the optimum 28 volt DC supply voltage.

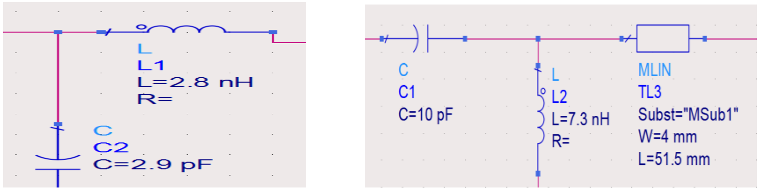


Figure 10. (a) Input matching network; (b) Output matching network.

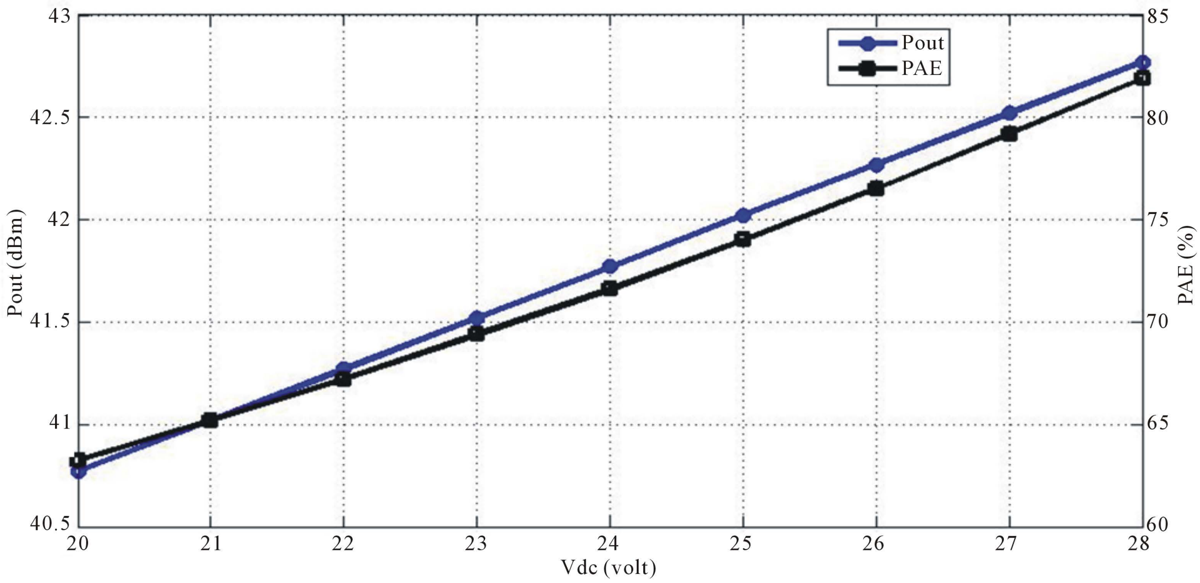


Figure 11. Output power and PAE versus DC voltage in the DPA.

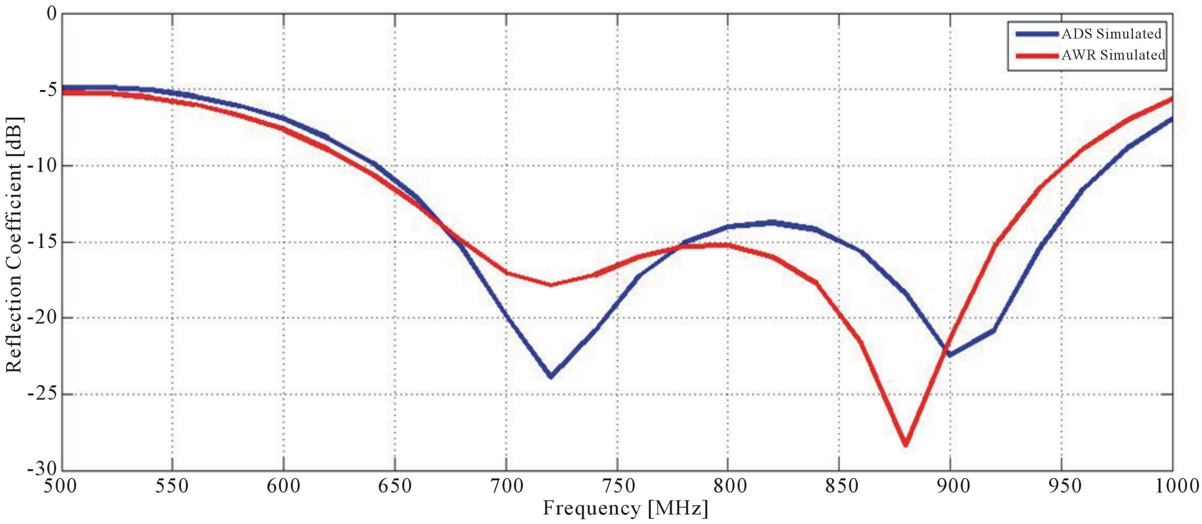


Figure 12. Simulated (ADS and AWR) reflection coefficient plot of the DPA.

Table 3. Final results of the Doherty power amplifier.

Input power (dBm)	DC power (W)	Output power (dBm)	Gain (dB)	PAE (%)	Drain efficiency (%)
21.45	22.92	42.77	21.32	81.94	82.55

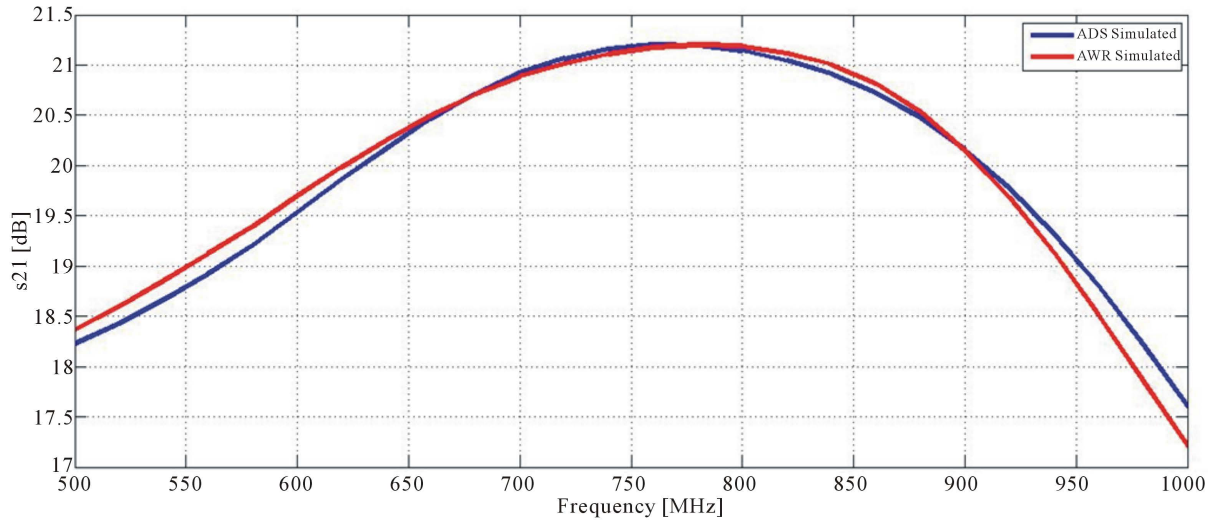


Figure 13. Simulated (ADS and AWR) power gain plot of the DPA.

The reflection coefficient of the DPA is given in **Figure 12**. It is clearly shown that this amplifier can operate from 550 MHz to 1000 MHz, thus it is suitable for all applications in the TV band.

Another advantage of the proposed Doherty amplifier rather than the efficiency increment is that the bandwidth has increased, and the proposed DPA can be suitable for more applications in the TV band. The percentage bandwidth of this DPA is 58.06% which is higher than that of the class AB power amplifier and higher than Doherty power amplifiers previously designed such as in [13], [15], and [17].

The power gain of the Doherty power amplifier is given in **Figure 13**. It is clearly shown that this amplifier has a good power gain above 20 dB for the operation frequency bandwidth.

3. Conclusion

A class AB power amplifier and a high efficiency Doherty one were implemented for the TV band applications. A class AB power amplifier was first designed using a commercial GaN HEMT from Cree Incorporation. The Doherty amplifier has been implemented, using the previous class AB amplifier as the main amplifier and a proposed class C amplifier as the peak one. This proposed DPA attained a high power-added-efficiency of 81.94%, a 42.77 dBm output power, an associated gain of 21.32 dB, and an operating frequency bandwidth between 550 and 1000 MHz which made it a convenient power amplifier that could be used in TV band applications.

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