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Design and Simulation of Doherty Power Amplifier for 2.4 GHz Frequency Applications

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Abstract: **The Doherty Power Amplifiers (DPA) are specialized Radio Frequency (RF) amplifiers designed to improve efficiency, particularly at high output power levels. They are used in base stations of cellular communication systems, and other wireless infrastructure applications. This work endeavors the design and simulation of a Doherty Power Amplifier (DPA) utilizing the Cadence Virtuoso environment using 45nm technology, precisely tuned to operate at 2.4 GHz frequency. The DPAs are pivotal components in modern RF communication systems, renowned for their efficiency and linearity. The work begins with a detailed examination of DPA architecture, focusing on key components such as power splitter, main amplifier, auxiliary amplifier, transmission line, and matched network. Each component is meticulously designed and optimized to ensure precise operation. Advanced simulation techniques are employed to analyze the performance of the DPA, including power gain, and Power Added Efficiency (PAE). Leveraging 45 nm VLSI process semiconductor technology, the undertaking aims at achieving high efficiency and signal integrity while minimizing power consumption and distortion. The tuning process entails iterative adjustments to component parameters guided by simulation results to achieve optimal performance characteristics, with a focus on impedance matching, power combining, and phase alignment. The final outcomes are evaluated based on comprehensive simulation results, offering valuable insights into the design and optimization of DPAs using advanced semiconductor technology.**

Index Terms: **Doherty Power Amplifier, Wi-Fi Standard, RF Design, Wireless Communications, VLSI Design, Power Added Efficiency.**

I. Introduction

The world is full of data and this data needs to be exchanged and communicated among several people. Data can be any confidential information about a country or a simple telephonic voice conversation between two friends. When communicating, this data needs to be transferred properly with no information loss along with privacy. This is a challenging task. As there are changes in communication mode from wired to wireless, this task has become even more challenging. So, a system is needed that can communicate wirelessly with no information loss and complete security. Any basic wireless communication system has three main components as shown in Figure 1 i.e., Transmitter, Channel, and Receiver. When transmitting, the signal must be strong enough to reach the base station and these base stations further need to remove noise and increase the signal strength. This also needed to be done at the receiver portion to read the information to the fullest. Therefore, the task is to amplify the signal to overcome noise, signal attenuation and improve signal to noise ratio.

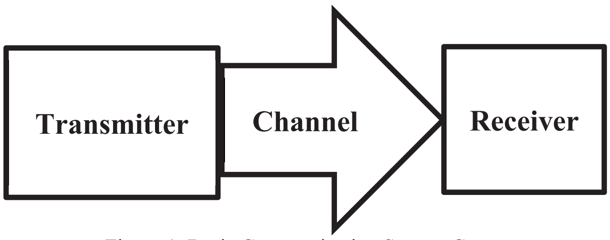

Figure 1. Basic Communication System Components

The bigger issue is that most of the power amplifiers are lumped devices that are not present on the chip. Bringing complex and bulky power amplifier circuits onto a chip is a very challenging task.

The strategy employed aimed at reducing the size of the amplifier and matching the network to the best, complexity of the power divider while preserving the objectives [1]. There is a need to choose a power splitter network, transmission line and matched network for the design so that maximum power transfer takes place from input to output. Then appropriate R, L, and C values must be calculated for the frequency. This is designed on a Cadence virtuoso design tool using 45 nm CMOS technology. The simulation and the parameter extraction of the design are done using Periodic Steady State (PSS) analysis.

An overview of the types of Power Amplifiers is given in section II. Section III explores the design approach of Doherty Power Amplifier (DPA). Section IV shows the design of a Doherty Power Amplifier (DPA) using Cadence Electronic Design Automation (EDA) tools. The input, output simulation results and performance analysis of the DPA are discussed in section V. The conclusions drawn are given in section VI.

II. Overview of Power Amplifiers

The Power Amplifiers (PAs) are vital components in communication systems, amplifying signals for transmission. PAs are the major basic blocks in communication systems, playing a crucial role in ensuring that signals are transmitted

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effectively over long distances and through various obstacles. These amplifiers are used in wireless communications, broadcasting, radar, and medical equipment etc. The challenges include optimizing efficiency, managing the amount of heat dissipation, and maintaining impedance matching. In wireless communication systems, such as cellular networks and Wi-Fi, power amplifiers are integral to amplifying signals from base stations or access points to reach mobile devices or other receivers situated over considerable distances [2]. Power amplifiers enable wireless communication systems to achieve widespread coverage and support high data rates, facilitating seamless connectivity for users. Despite their importance, power amplifiers face challenges such as balancing efficiency and linearity, managing heat dissipation, and ensuring impedance matching for optimal performance [3, 4].

The PAs are crucial components in communication systems amplifying signals for transmission.

Types of Power Amplifiers

1. *Application based PAs*
    - Audio Amplifiers: Amplify audio signals, typically used in audio systems, speakers, and musical instruments.
    - Radio Frequency (RF) Amplifiers: Amplify signals in the radio frequency range, crucial in communication systems and RF applications.
    - Intermediate Frequency (IF) Amplifiers: Amplify signals in the intermediate frequency range, often used in radio, Radar and television receivers.
    - Instrumentation Amplifiers: Designed for precision measurement applications, offering high common-mode rejection, sensitivity, and accuracy.
2. *Operating Frequency based PAs*
    - Low-Frequency Amplifiers: Operate at frequencies up to a few kHz, common in audio applications.
    - Medium-Frequency Amplifiers: These amplifiers operate in the frequency range of hundreds of kHz to a few MHz
    - High-Frequency Amplifiers: Operate at frequencies above a few MHz, common in RF and microwave applications.
3. *Configuration and Connection based PAs*
    - Voltage Amplifiers: Increase the voltage level of a signal.
    - Current Amplifiers: Increase the current level of a signal.
    - Power Amplifiers: Increase both voltage and current to deliver higher power levels to a load.
    - Common Emitter/Common Source Amplifiers: Commonly used in transistor amplifiers
    - Common Collector/Common Drain Amplifiers: Another configuration used in transistor amplifiers.
    - Common Base/Common Gate Amplifiers: Yet another configuration used in transistor amplifiers.
    - Class A, B, AB, and C Amplifiers: Classifications are done using the amplification characteristics and efficiency in power amplifiers [5].
4. *Input and Output Signals based PAs*
    - Unipolar (Single-Ended) Amplifiers: Amplify signals that only have positive voltage levels.
    - Bipolar (Double-Ended) Amplifiers: Amplify signals that have both positive and negative voltage levels.
5. *Electronic Components based PAs*
    - Transistor Amplifiers: Use transistors as the amplifying elements, including BJT and MOSFET amplifiers.
    - Operational Amplifiers (Op-Amps): Specialized amplifiers with high gain, often used in feedback configurations for various applications.
6. *Feedback and Gain based PAs*
    - Feedback Amplifiers: Include configurations with positive or negative feedback, influencing gain, stability, and linearity.
    - Low-Gain Amplifiers: Provide minimal gain.
    - Medium-Gain Amplifiers: Offer moderate gain.
    - High-Gain Amplifiers: Provide significant amplification.

These classifications provide a framework for understanding and categorizing amplifiers based on their characteristics and applications. The choice of amplifier type depends on the frequency range, power levels, and desired performance parameters.

7. *Special amplifiers*

There is another type of classification of amplifiers called special amplifiers are listed below from A to I. These amplifiers are designed from pre-existing amplifiers having certain traits. Although many of these operations of amplifiers look different, each has its unique characteristics, advantages, and limitations [6-8].

A. Doherty Power Amplifier

It is a special amplifier which is a combination of two amplifiers where one amplifier amplifies small signals, and the other amplifier amplifies large signals. This amplifier was largely used in lumped components [9-11].

B. Envelope Tracking (ET) Power Amplifiers

Envelope tracking Pas adjusts the amplifier's power supply voltage to the input signal of envelope [12]. This helps to maintain high efficiency, especially during periods of low power, like the Doherty approach [13].

C. Outphasing Power Amplifiers

The Outphasing power amplifiers use multiple amplifiers that are combined to achieve high efficiency [14]. Each amplifier is modulated with a phase and amplitude adjustment, and then the outputs are merged to reconstruct the required output signal. This method is used to increase efficiency across varying power levels.

D. Chireix Outphasing Amplifiers

A variation of outphasing, Chireix outphasing amplifiers utilize a specific combining network to achieve higher efficiency. The concept is to use a constant envelope modulation scheme, like Doherty, but with a different combining network.

E. Switch-Mode Amplifiers

Switch-mode power amplifiers operate in a switched mode, providing high efficiency by minimizing power dissipation during the "off" state. These amplifiers are commonly used in applications where power efficiency is critical, such as in base stations. Switch-mode amplifiers are commonly used in audio amplification, especially in portable audio devices like smartphones, tablets, and Bluetooth speakers.

F. Load Modulated Amplifiers

Load modulated amplifiers dynamically adjust the load impedance seen by the amplifier to optimize efficiency. This technique is used to improve efficiency over a range of input power levels, like the Doherty approach [15].

G. Digital Pre-Distortion (DPD)

Digital pre-distortion is a signal processing technique that compensates for the nonlinearities in the amplifier, improving linearity and efficiency. It is often used in conjunction with various power amplifier architectures to enhance overall performance.

H. Hybrid Amplifiers

Hybrid amplifiers combine multiple amplifier technologies to achieve improved efficiency and linearity. For example, combining a Class A amplifier with a switching amplifier can offer benefits in terms of both linearity and efficiency.

I. Dynamic Load Modulation Amplifiers

These amplifiers dynamically adjust the load impedance to optimize efficiency and linearity, especially during varying power levels.

Among these above-mentioned special amplifiers, the Doherty power amplifier is selected because of the following reasons:

1. Increased linearity range

Doherty power amplifier amplifies both small signals as well as large signals increasing the linearity of the system. Achieving an increased linearity range in Doherty power amplifiers presents a notable challenge due to the inherently asymmetric property of the Doherty architecture.

2. High Peak Added Efficiency (PAE)

This is a very important parameter in identifying the capability and performance of the amplifier. Doherty amplifiers offer large PAE compared to other special amplifiers [16,17].

3. Large output power gain

When compared to other amplifiers, this design has more output power gain due to the usage of two power amplifiers.

4. High Peak-to-Average Power Ratio

Another advantage other power amplifiers don't give but Doherty does is that it has a high peak-to-average power ratio. This is possible because of two amplifier circuits embedded into a single circuit.

5. Design to bring it onto the chip

This is the biggest advantage of the DPA. Even though other power amplifiers can be brought onto a chip, this design doesn't need any additional circuit or supporting circuit. Other circuits are quite like the Doherty power amplifier or just act as a supporting block.

With these advantages, the Doherty power amplifier shows a promising solution for on-chip design compared to other amplifier circuits [18].

The Power amplifiers are crucial electronic devices used to boost signal power while minimizing waveform distortion.

They find applications in telecommunications, audio amplification, and RF transmission. Understanding their operation is vital for appreciating their significance in signal amplification.

1. Input Stage

Initial reception of the weak input signal occurs here. A small signal amplifier increases the voltage level, preparing it for further processing.

2. Amplification Stage

This core stage amplifies the signal significantly, utilizing active components like transistors or vacuum tubes. Distortion is minimized during amplification.

3. Output Stage

Amplified signal passes through this stage, further boosting its power to drive the load (e.g., speaker or antenna) effectively without fidelity loss.

4. Biasing and Control Circuitry

These circuits optimize performance and stability. Biasing sets component operating points, while control circuits manage protection, stability feedback loops, or dynamic parameter control.

5. Power Supply

A stable, appropriately sized power supply converts AC mains voltage to DC, powering the amplifier circuitry within specified limits.

Overall, power amplifiers accurately amplify weak input signals to higher power levels while maintaining integrity. Achieving this requires meticulous design to ensure desired performance characteristics such as linearity, efficiency, and reliability.

III. Design Approach of Doherty Power Amplifier

The DPA is a type of Radio Frequency (RF) Power Amplifier architecture used in wireless communication systems to efficiently amplify signals, particularly in applications such as cellular base stations and broadcast transmitters [19, 20].

The key feature of a Doherty power amplifier is its ability to achieve high efficiency [21] at both low and high output power levels. This is accomplished through a combination of two amplifier stages: a main (carrier) amplifier and a peak (peaking) amplifier. The main amplifier handles most of the signal's power, while the peak amplifier provides additional power when needed, particularly during signal peaks [22]. The block diagram of DPA is shown in Figure 2 [23].

The major components of a DPA include the following components [24]:

1. Power Splitter
2. Main Amplifier
3. Auxiliary Amplifier
4. Transmission line and Matched Network

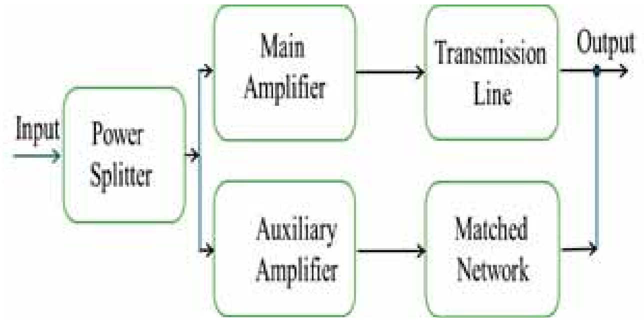

Figure 2. Block diagram of Doherty Power Amplifier (DPA)

1. Power Splitter

In a DPA, the power splitter plays a crucial role in distributing the input signal to the main amplifier and the peak amplifier. Its primary function is to divide the input signal into two branches with controlled power levels, allowing each amplifier stage to operate optimally within its power range [25].

The power splitter typically divides the input signal into the main path and peaking path. The main path, which feeds the main amplifier, and the peaking path, which feeds the peak amplifier. The power splitter needs to ensure that the main amplifier receives most of the input power, while the peak amplifier receives a fraction of that power. Any power divider circuit has three important traits: matching, reciprocal and lossless. For any design, one can get only two out of three. That is, a design can be either matched and reciprocal and lossless or matched and lossless. Hence, the power splitter used in this design is the Wilkinson Power Amplifier [26].

2. Main Amplifier

In a DPA, the main amplifier plays a central role in handling most of the input signal power. Its primary function is to provide efficient amplification of the input signal during normal operating conditions when the input power is relatively low [27, 28]. The main amplifier is typically designed to operate in its linear region, ensuring that the amplified signal faithfully reproduces the input signal without introducing significant distortion.

3.Auxiliary Amplifier

In a DPA, the auxiliary amplifier, also referred to as the peak or peaking amplifier, is a critical component that works in conjunction with the main amplifier to achieve high efficiency and linearity [29]. The DPA architecture is designed to optimize power efficiency by combining the strengths of both the main and auxiliary amplifiers [30, 31]. The auxiliary amplifier is responsible for handling the peak power levels of the input signal. During periods when the input signal exhibits high amplitude, the auxiliary amplifier contributes additional power to the output. Using this amplifier increases the linearity of the power amplifier [32]. Class C power amplifier is used as auxiliary amplifier [33].

The structure of DPA is shown in Figure 3 [35].

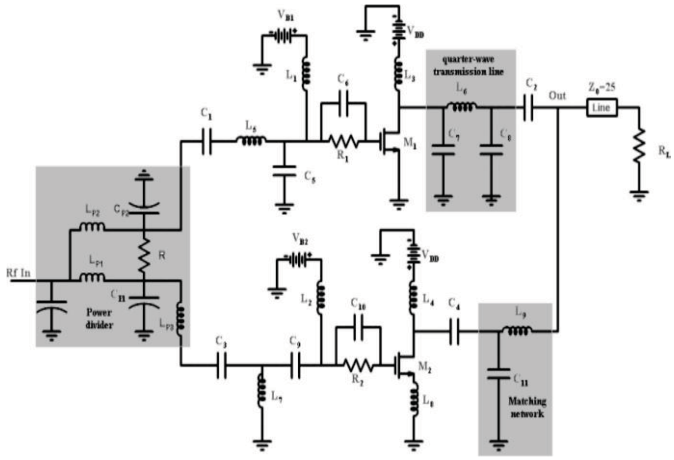

Figure 3. Structure of Doherty Power Amplifier

4.Transmission Line and Matched Network

In a DPA, transmission lines play a crucial role in facilitating the combining of signals from the main and auxiliary amplifiers to produce the final amplified output [34]. These transmission lines are part of the combining network, which ensures that the amplified signals from both amplifiers are combined constructively at the output port. The transmission lines are typically designed to have specific lengths and characteristic impedances to achieve optimal signal combining and phase alignment.

IV. Design of Doherty Power Amplifier

The design of Doherty Power Amplifier uses a design flow starting from user requirements and non-functional VLSI constraints [36]. The major requirement of this amplifier is center frequency of operation on which the selection of component values of amplifier structure is selected. The design flow using Cadence EDA tool is shown in Figure 4, in the next page.

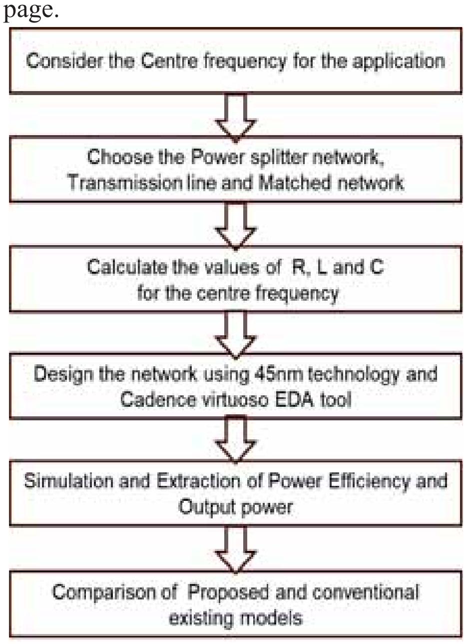

Figure 4. Design flow of Doherty Power Amplifier

The detailed description of each step of design flow is given below.

1.Center Frequency: Center frequency or operating frequency is an important parameter in any design and need to be rightly chosen according to the application. Since this power amplifier is meant for digital communication as well as for Wi-Fi protocol, the operating frequency of 2.4GHz is chosen.

2.Power Splitters and Matched Networks: Power splitters and matched networks are, in general, very bulky in size and complex in nature. Therefore, the π-LC network as a matched network is chosen because of its simplicity and the Wilkinson power divider as a power splitter.

3.Calculation of R, L and C values: This is the toughest part of the design. Calculation of R, L and C values is done for Wilkinson power divider and matched network whereas R, L and C values in amplifier part can be extracted using PSS analysis. Using circuit analysis models and maintain proper matching within the circuit as well as compatibility for the chosen operating frequency.

4.Designing using Cadence EDA tool: The R, L and C values, power splitters and a matched network are calculated. With these values and circuits, design is placed on the Cadence Virtuoso tool [37, 38] The issue here is, that calculated values of circuit elements might not work on the tool because it considers parameter values along with real time constrains and check if these values are feasible for fabrication. Therefore, further adjustment of these values using the special analysis (PSS and PAC) given by the tools is another necessary step [39, 40].

V. Simulation Results and Discussion

The schematic diagram, test bench and simulation results of DPA are shown in simulation results. Figure 5 shows the basic block diagram of DPA along with its internal components.

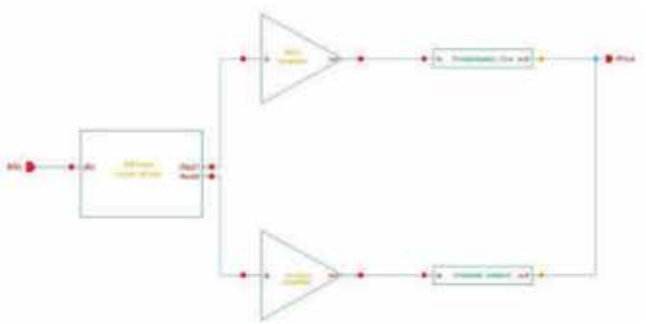

Figure 5. Block Diagram of DPA

The internal component design of Wilkinson Power Splitter is shown in Figure 6.

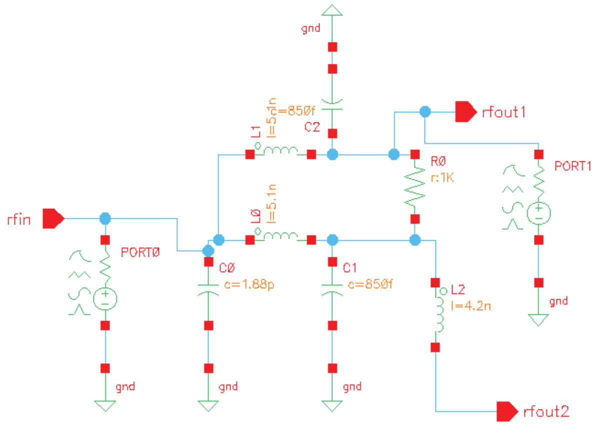

Figure 6. Wilkinson Power Splitter

The main amplifier component design schematic is shown in Figure 7. The Auxiliary amplifier component design is shown in Figure 8. The Transmission line component design is shown in Figure 9. The matched network component design is shown in Figure 10. The detailed structural components connection of DPA is shown in Figure 11.

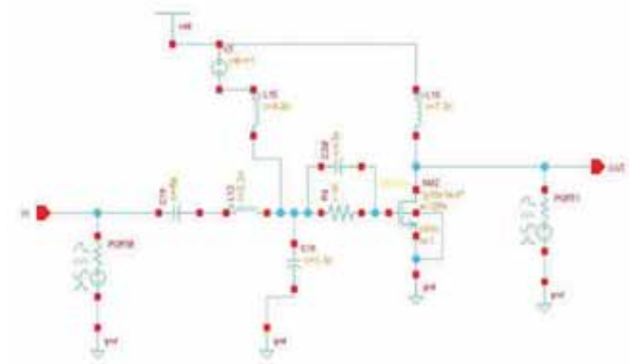

Figure 7. Main Amplifier

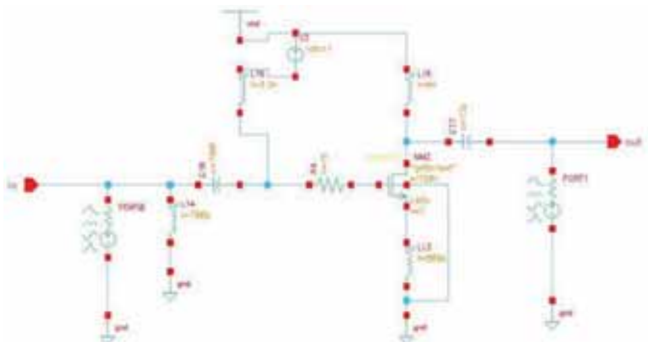

Figure 8. Auxiliary Amplifier

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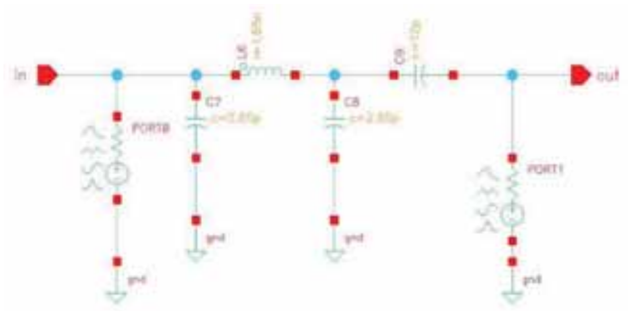

Figure 9. Transmission Line

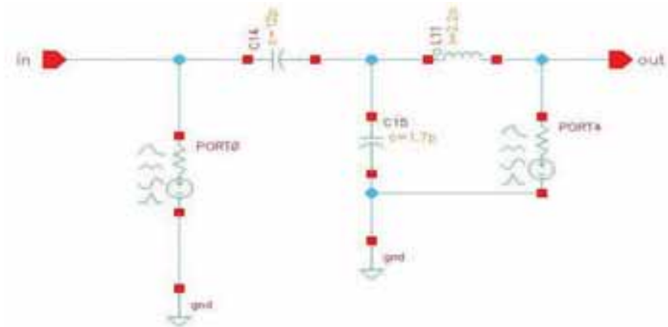

Figure 10. Matched Network

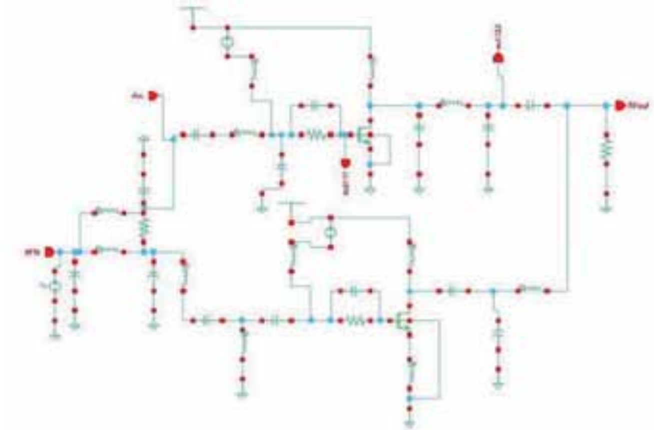

Figure 11. Doherty Power Amplifier

The operating frequency of 2.4 GHz of each component of Doherty Power Amplifier (DPA) is individually tuned and their results are shown below. The power splitter design operating at 2.4 GHz is shown in Figure 12. The main amplifier operating at 2.4 GHz is shown in Figure 13. The auxiliary amplifier operating at 2.4 GHz is shown in Figure 14. The transmission line operating at 2.4 GHz is shown in Figure 15. The Matched network design operating at 2.4 GHz is shown in Figure 16. The complete design of DPA operating at 2.4 GHz is shown in Figure 17.

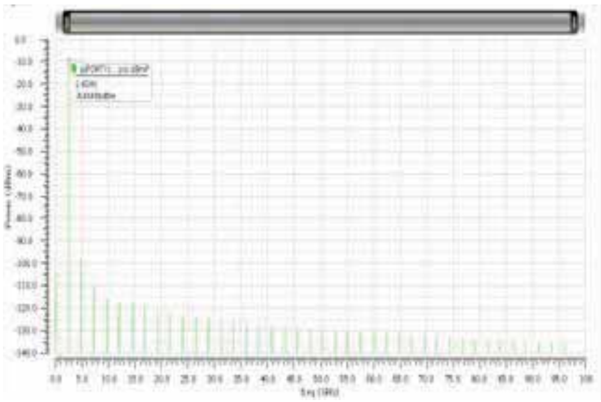

Figure 12. Power splitter operating at 2.4 GHz

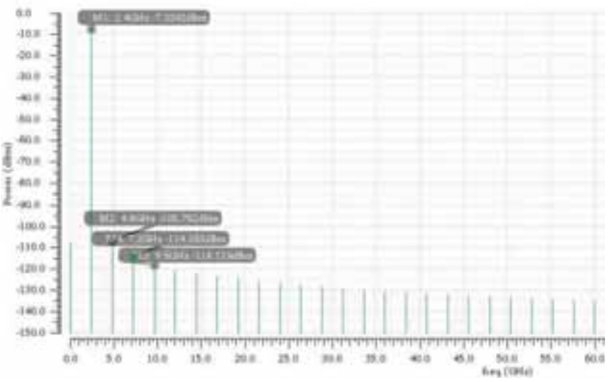

Figure 13. Main amplifier operating at 2.4 GHz

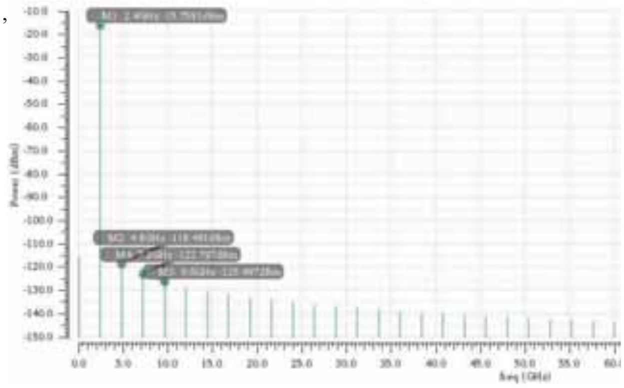

Figure 14. Auxiliary amplifier operating at 2.4 GHz

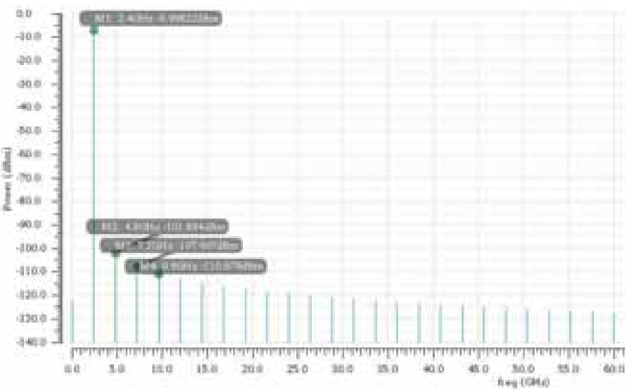

Figure 15. Transmission Line operating at 2.4 GHz

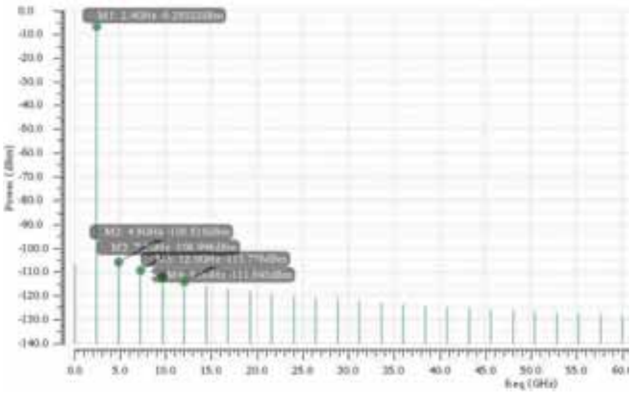

Figure 16. Matched Network operating at 2.4 GHz

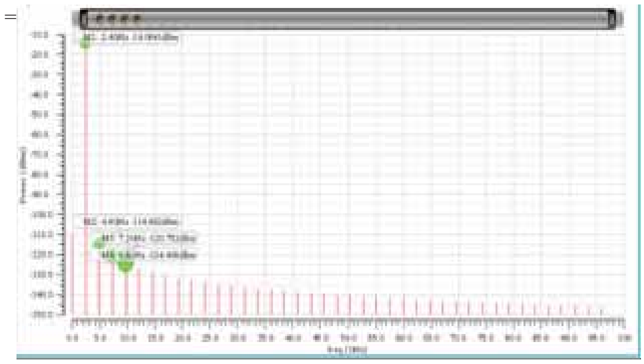

Figure 17. Doherty Power Amplifier operating at 2.4 GHz

The power gain of DPA is shown in Figure 18 with a value of 87.08 dB. The Power Added Efficiency (PAE) of Doherty Power Amplifier is shown in Figure 19.

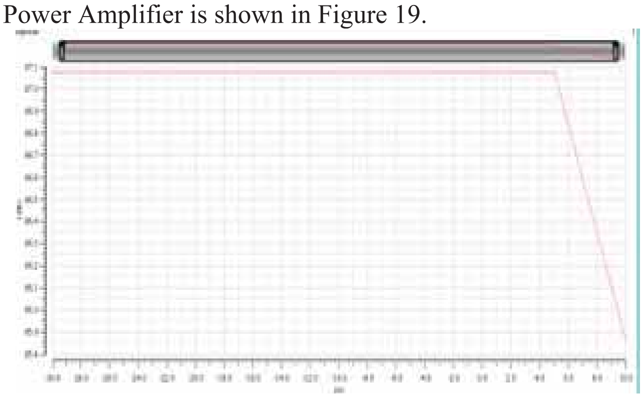

Figure 18. Power Gain of Doherty Power Amplifier

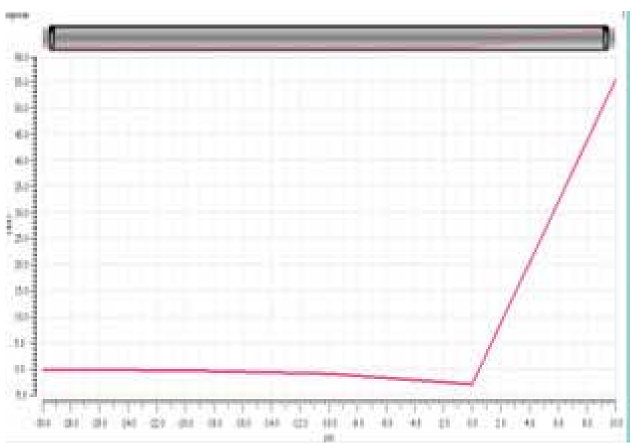

Figure 19. Power Added Efficiency (PAE) of Doherty Power Amplifier

VI. Conclusions

The design and analysis of DPA using Cadence Virtuoso have yielded promising results. The careful tuning of essential components, including the power splitter, main amplifier, auxiliary amplifier, transmission line, and matched network, to operate at the 2.4GHz frequency has ensured optimal performance within the desired frequency band. With a remarkable power gain of 87.08 dB, the amplifier demonstrates its effectiveness in significantly boosting signal strength. Furthermore, the observed increase in Power Added Efficiency (PAE) from 0% to 55% over the input power should also be given in range underscores the amplifier's ability to efficiently convert input power into useful output power. These findings highlight the success of the DPA design in achieving high performance, efficiency, and signal amplification, making it an asset for various RF applications, particularly those operating at 2.4 GHz frequencies. Overall, this work contributes valuable insights into the design and optimization of RF amplifiers, paving the way for advancements in wireless communication and RF systems.

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