EE-67031-01 Final Report: Dual-band Power Amplifier

Guoyue Xu

***Abstract*—This report simulated a dual-band power amplifier working at 2.4 GHz and 3.5 GHz using Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT), which operates from DC-6 GHz. In this amplifier, a dual-band transmission line impedance matching networks are used to match two different complex impedances to 50Ω.**

***Index Terms*—Dual-band, Power amplifier, GaN, Matching Network**

I. Introduction

Nowadays, the demand for dual-band RF systems increased with the multiband applications in wireless communication systems. Hence wireless systems are required to handle diverse signals at different frequencies while meeting the requirements for the signal quality and power efficiency. A dual-band amplifier can operate over two different frequency bands, which can be useful in applications where multiple bands are required. This can reduce the number of amplifiers needed and simplify the design of the system. By using a dual-band amplifier, it is possible to increase the capacity of the system by using multiple frequency bands. This can be particularly useful in applications such as wireless communication systems, where additional capacity may be needed to handle a large number of users or data streams.

At present, a lot of wireless systems work at 2.4 GHz, such as Wi-Fi, and Bluetooth... The 3.5 GHz is halfway between the existing WiFi bands (2.4 GHz and 5 GHz) and was used by naval radar systems and for satellite ground communications previously. In the 5G era, this 100MHz bandwidth was reallocated for commercial use. At the same time, the dual-band power amplifier gradually attracted attention. The dual-band design can reduce the number of different components that use to need in the systems. Therefore, using a dual-band design is a promising way to reduce the size and cost of the whole wireless system. The performance of the power amplifier determines the overall performance of the communication link, so designing a dual-band with good performance is required.

Several approaches have been proposed to design multi-frequency PAs. One way to create a dual-band amplifier is to use multiple amplifier stages, each designed to amplify a specific frequency band. This approach allows for good control over the frequency response of the amplifier, but can be more complex and require more components, such as Doherty structure [8]. In the Doherty structure, two transistors are being used, one works when the input is small, and another one works in a high-efficiency state. If the input increases, both transistors work simultaneously. The working state of one transistor will determine the working efficiency of the other. Furthermore, using electronical tunable devices such as micro-electro-mechanical systems (MEMS) to achieve a changeable matching network. In [3], a triple-band PA is designed. However, there are certain switch requirements to reach. These kinds of tunable devices suffer from the low switching speed and limited power handling of the tunable devices. Similar to the previous method, another approach is also working on the matching network, using a filter to separate the two frequency bands and then amplify each band separately. This can be done using a passive filter, such as a resonator or a transformer, or an active filter, which uses amplifiers to shape the response of the filter. Passive transformers can be using multiple matching networks to provide necessary impedance transformations at multiple frequencies to realize dual-band PA. In [7], the author did a detailed analysis for dual-band T and π quarter wavelength transformers. Furthermore, in [5], they proposed a dual-band PA optimized the fundamental impedance and correct impedance terminations up to the third harmonic frequency.

The transformer is chosen in this report for its simplicity. In [1], they developed a dual-band two-section $\frac{1}{3}$-wavelength transformer that operates at the fundamental frequency and it is first harmonic. A two-section transformer to deal with any two uncorrelated frequencies was purposed in [6]. It is worth being noticed that dual-band PA design, requires different complex loads for the two bands of operations.

In this report, we illustrate a dual-band GaN-based power amplifier working at 2.4 GHz and 3.5GHz, using transformers to match the unequal and complex impedance at two frequencies. We use the two-section shun-stub impedance proposed in [2], for it can match a load of unequal complex impedances at two uncorrelated frequencies. Dual-band matching networks are using to match two different impedance to 50Ω at two uncorrelated frequencies. The amplifier design process is introduced in section II.

II. Amplifier Design

In this report, we use GaN HEMT transistor CGH40010F, which has an operation frequency from $DC - 6GHz$. The design focus on the 2.4 GHz and 3.5 GHz with 50Ω. The diagram of the circuit is shown in Figure 1.

A. Bias and Bias Tee

Determining bias is an important step as it will decide the transistor's class of operation. Once the bias voltage is decided we can know the cutoff region of the transistor and facilitates is to get the gain and efficiency of the amplifier. In this design,

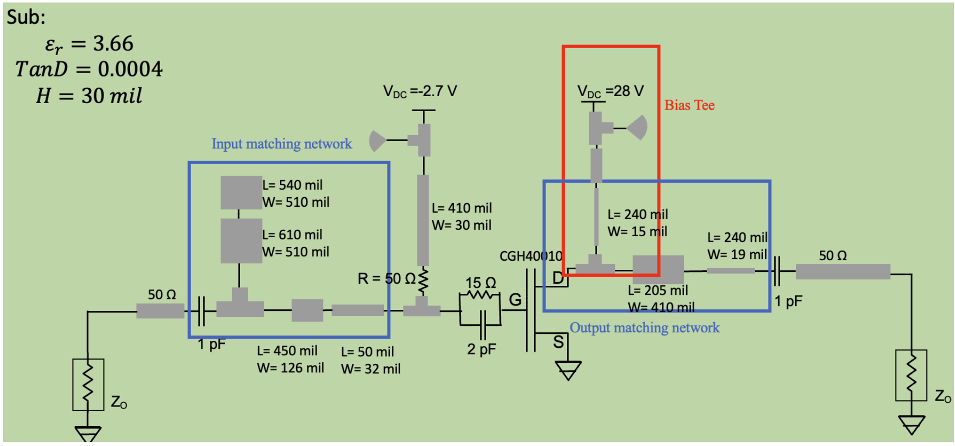

Fig. 1. Dual-band PA circuit schematic

we will keep the lab 3 setting, using the Gate-Source voltage V_{GS} at $-2.7V$, Drain-Source voltage V_{DS} at $28V$ and the drain current at 200mA. The Load Line provides us maximum possible signal swing at the drain of the transistor. We want the transistor works at class AB, then we need to choose the points from the middle of the load line (class A) to the bottom of the load line (class B). Bias tees are used to supply DC currents

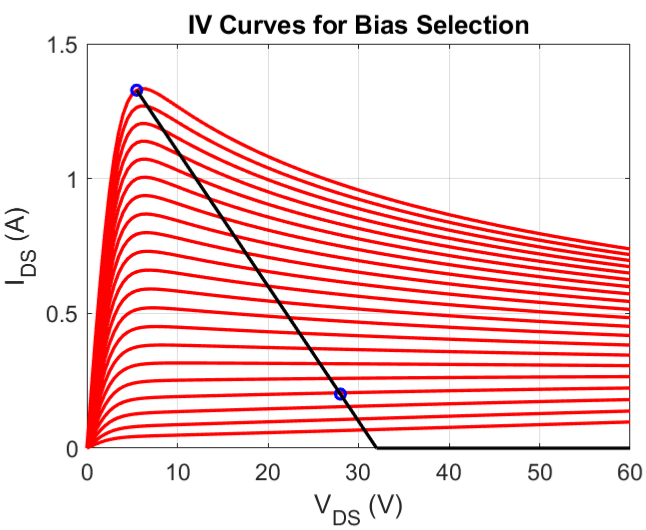

Fig. 2. IV Curves with Load Line

or voltages to bias RF circuits. It provides a low impedance for DC and a high impedance for RF signals. The schematic is shown in Figure 3, the inductor works as an RF block to prevent the RF signal going to the DC path. The capacitor works as a DC block to prevent the DC signal interfere with the RF. This kind of structure can isolate RF signals and provide power for the transistor. However, lumped bias tee is complicated to fabricated even though it has wider bandwidth. In this design, we use transmission line to realize it, the structure is shown in Figure 4. The radial stub is used due to its simplicity, more compact than linear stubs, and wider band than linear stubs. In order to provide good isolation for RF

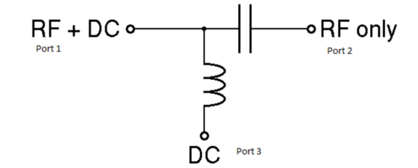

Fig. 3. Bias Tee Structure

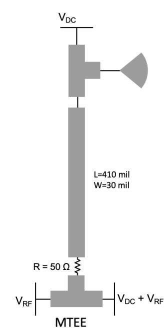

Fig. 4. Distributed Bias Tee with Radial Stub

signals at 2.4 GHz and 3.5 GHz, I choose the center frequency in the middle of these two to get relatively good isolation for the RF signal at both frequencies. The impedance of the radio stub is close to 0, after the quarter transmission line, the impedance changed from short to open. The S-parameter of the Bias Tee circuit and harmonic are shown in Figure 5. We can see that the S_{RF-DC} is close to 0 and $S_{RF-(RF+DC)}$ are relatively low at both frequencies, close to $-40dB$, which is acceptable.

B. Stability Analysis

To prevent the amplifier from self-oscillation, we need to do the stability analysis to stable the amplifier. We choose the transistor as an AB class amplifier, it will amplify the wave at an angle between $180°$ to $360°$. Once the angle of amplification adds the angle of (output-ground- input) equal

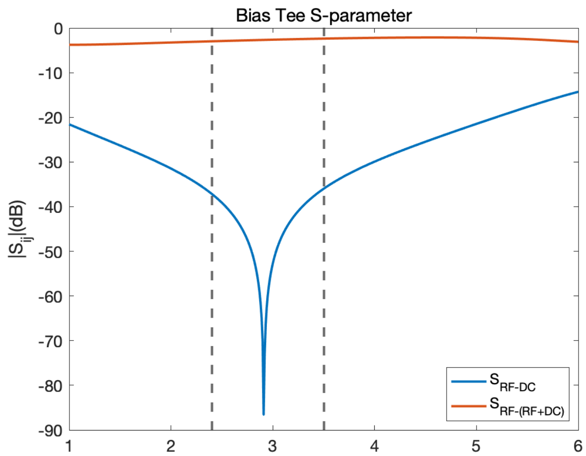

Fig. 5. Bias Tee Frequency Response

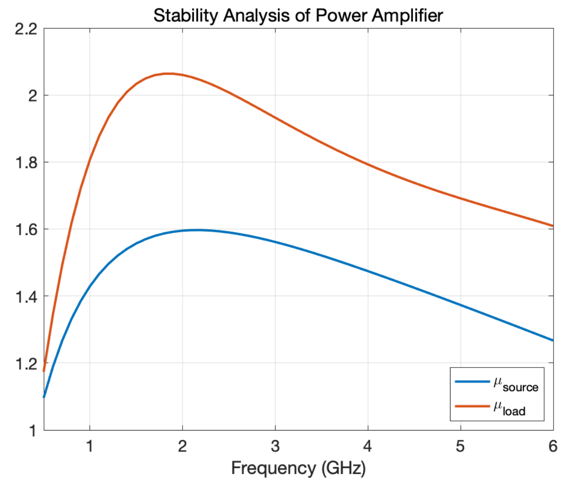

Fig. 6. Simulated Stability

to 360° in phase shift, and the gain is greater than 1, it will trigger the oscillation.

1) Conditionally Stable: It means the network that is stable when its input and output reach the intended characteristic impedance Z_0, but if there is a mismatch in the network, an oscillation will appear either in the source or load impedance.
2) Unconditional stability: The amplifier will be stable for any load and source connected, and it does not have a reflection coefficient greater than one in magnitude $|\Gamma_L|<1, |\Gamma_S|<1$.

To indicate the stability, we have stability factors to look at:

$$K = \frac{\left(1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2\right)}{2\,|S_{21}S_{12}|} \tag{1}$$

where $\Delta = S_{11}S_{22} - S_{12}S_{21}$. Another stability factor is μ actor.

$$\mu = \frac{1 - |S_{22}^2|}{|S_{22} - \Delta S_{11}^*| + |S_{12}S_{21}|} \tag{2}$$

The μ factor means the distance from the center of the smith chart to the nearest output stability circle, if μ>1, K>1 then the circuit is unconditionally stable, which means the circuit will remain stable for all passive loads.

To increase stability and prevent the oscillation from happening like in Lab 3, a 15Ω resistor is added at the gate of the transistor, so it will dampen the potential oscillating input. To decrease the resistor's effect on the RF signal, we parallel connect a capacitor so the RF signal can short the resistor. As we can see in Figure 6, when $V_{GS} = -2.7V$, $V_{DS} = 28V$, the network is unconditionally stable from 500 Mhz to 6 GHz, which means the circuit will remain stable for all passive loads in this frequency region. The negative effect of this is once we added the resistor, the gain dropped.

C. Matching Network

Before we move to the matching analysis, we need to know the input impedance and output impedance of the stabled transistor. To find an accurate value, we use the load pull instrument in the ADS to get the input and output simulation impedance. Since we are doing dual-band matching, we need to pull the input and output resistance in two frequencies. At 2.4 GHz, the input impedance is $13.51 + j * 0.4$ and the output resistance is $20.91 + j * 15.7$. At 3.5 GHz, the input impedance is $11.921 + j * 7.237$ and the output resistance is $15.193 + j * 8.51$. To maximize the power transfer, we will use conjugate matching in the input matching network.

To match the two uncorrelated frequencies, the method in [2] is used for its versatility, and easy to design and it can match a load of unequal complex impedances at two uncorrelated frequencies. Using two transmission lines in series and two shunt stubs, this paper also shows the matching network in a variety of stub configurations. The equations were also presented in the paper to calculate the electrical lengths of the four sections.

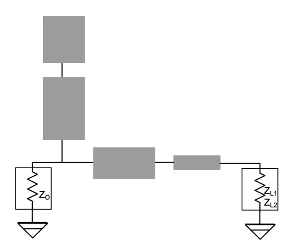

Fig. 7. Topology for the dual-band impedance matching network

In the input matching network, one port terminated in 50Ω and another in the conjugate of the optimal impedance for each of the two frequencies. The S-parameter is shown in Figure 8, as we can see, the S_{11} parameter got below -20 dB at desired frequencies, and S_{21} parameter got nearly 0 at these two frequencies, which means we have a good input matching network.

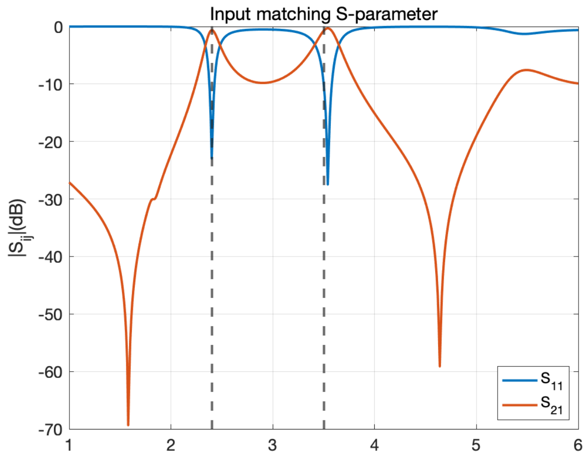

Fig. 8. Input Matching Network Frequency Response

In the output matching network, part of the bias tee transmission line becomes the shunt component. The output matching network S-parameter is shown in Figure 9. As we can see, the output matching network got a relatively wide bandwidth and nearly 0 insertion loss. This structure can be further improved as a narrow band design to decrease the possibility of oscillation and the effect of harmonics or added harmonic control stub to dissipate the harmonics.

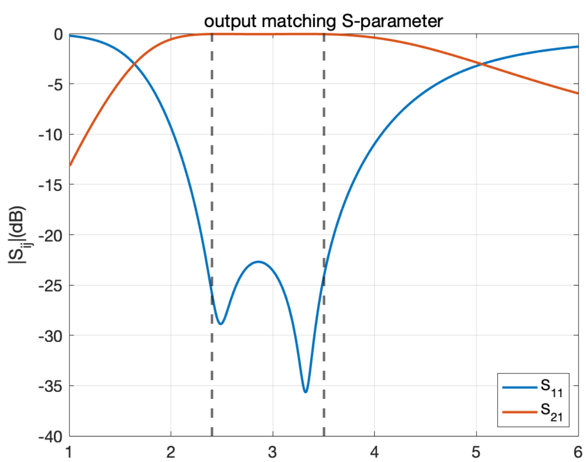

Fig. 9. Output Matching Network Frequency Response

D. Overall Performance

Once we simulated the impedance transformers, we can connect these structure together. The schematic is shown in Figure 1.

In the Figure 10, we can see the small signal gains are 10.9 dB at 2.4GHz and 9.1 dB at 3.5GHz.

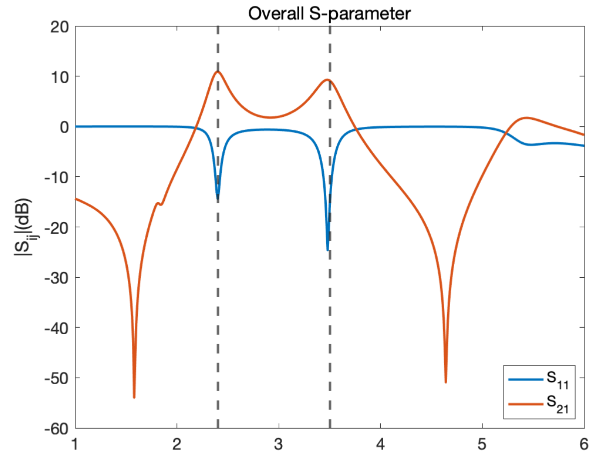

Fig. 10. Overall Performance S-parameter

III. Nonlinear Analysis

In the nonlinear measurement, according to our simulation, the IP1dB at 2.4 GHz is 34 dBm, and OP1dB is 40.3 dBm shown in Fig 11. At 3.5 GHz the IP1dB is at 36 dBm and OP1dB is at 40.08 dBm. The input-output power curves for two frequencies were simulated individually and processed on one figure. To do the two-tone tests, we use the Harmonic

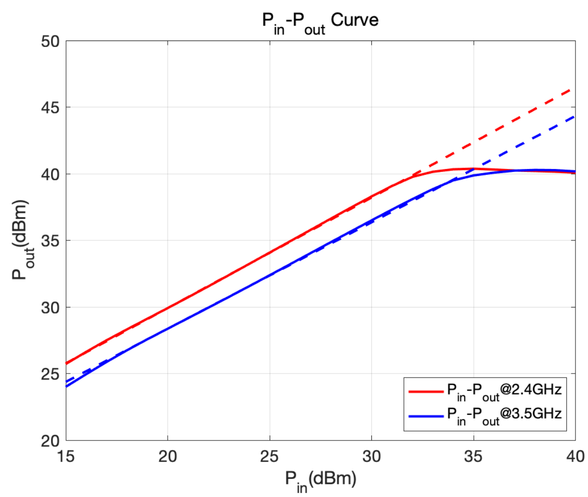

Fig. 11. P1dB and Pin Pout Curve

Balance (HB) Analysis to simulate the nonlinearity of the network. The RF input power is at 29 dB and frequency spaced 20 MHz. The reason we choose 20 MHz is that the Wi-Fi channel bandwidth at 2.4 GHz is 20 MHz, we may see how much energy spread into adjacent channels. The two-tone test at 2.4 GHz is shown in Figure 12. After the analysis, we can get the transducer power gain of 8.325 dB, Third Order Intercepts at Input (IIP3) equal to 40.2 dBm, and OIP3 equal to 48.5 dBm. The two-tone test at 3.5 GHz is shown in Figure 13. After the analysis, we can get the transducer power gain of 6.63 dB, IIP3 equal to 41.07 dBm, and OIP3 equal to 47.7

dBm. The fundamental and third-order harmonic power curve is in Figure 14.

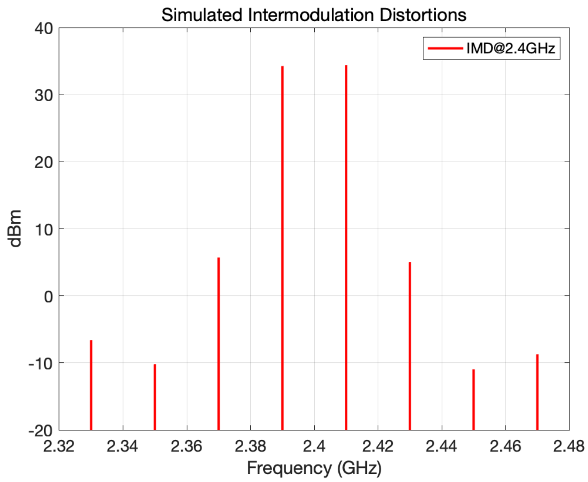

Fig. 12. Simulated inter-modulation distortion at 2.4GHz

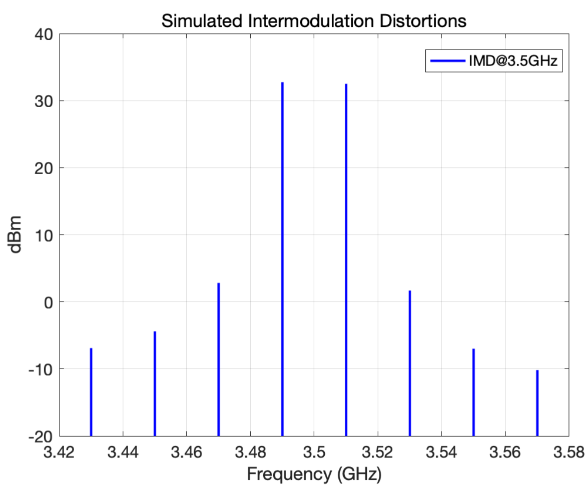

Fig. 13. Simulated inter-modulation distortion at 3.5GHz

Figure 15 shows the simulation results of the dual-band PA amplifier Gain and Power Added Efficiency (PAE). At 2.4 GHz, the amplifier achieved a maximum gain of 10.9 dB and a maximum PAE of 35%. At 3.5 GHz, the maximum gain was 9.1 dB, and the maximum PAE was 26.5%. We can see the gain decreased as the power input increased because the slope of power output versus power input is not 1, it is around 0.8 at this point.

IV. Conclusion

In this report, we simulated a dual-band power amplifier. The dual-band power amplifier uses a dual-band transmission line impedance matching network to realize dual-band operations. In the output matching network, the bias tee structure and output matching network are parts integrated.

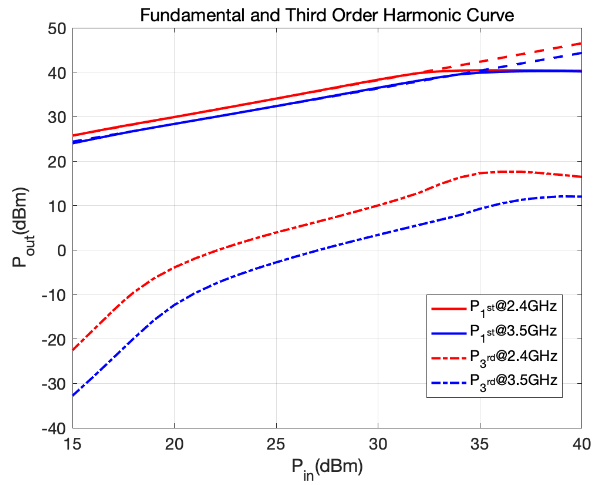

Fig. 14. Fundamental and Third Order Power Curve

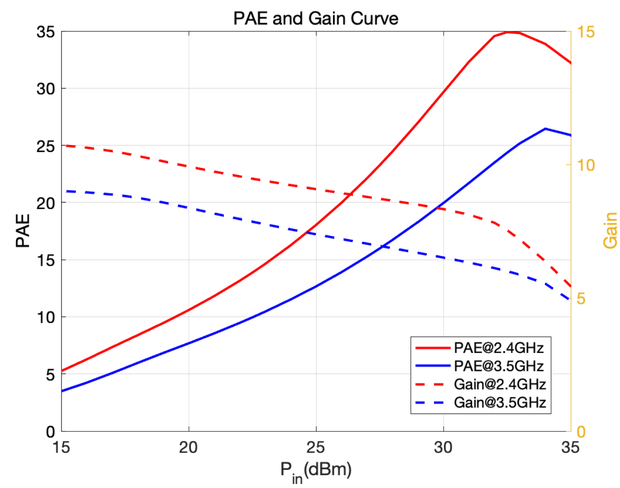

Fig. 15. Simulated inter-modulation distortion at 3.5GHz

To prevent self-oscillation from happening like in lab 3, a 15Ω resistor is added in front of the transistor gate. But adding this resistor dropped the power amplifier's gain and PAE in the end. As we can see from the last section, the gain and PAE are not high.

Improving the PAE of the power amplifier should be an important work to improve the performance of this dual-band power amplifier. There are several directions we can think of and try to improve:

1) Optimize the bias point: The bias point is the operating point of the transistor, and it determines how much current is flowing through the transistor. Setting the bias point correctly can improve the PAE of the amplifier.
2) Use a more efficient amplifier architecture: Different amplifier architectures have different levels of efficiency. For example, Class-D amplifiers are generally more efficient than Class-AB amplifiers. We can also consider adding one more transistor to use the Doherty structure,

similar in [9].

3) Use feedback: The circuit structure containing the feedback network can effectively change the performance of the amplifier. After the feedback circuit and the amplifier circuit of the power amplifier form a closed loop, the output signal is transmitted to the input terminal again to achieve the purpose of forward feedback, thereby improving the gain and efficiency of the amplifier. This method also can improve the stability and linearity of the amplifier [4].

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