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Design of Reconfigurable Power Amplifier Based on Smith Chart Matching

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Abstract: In the architecture of the communication network, the signal passes through various devices and finally reaches the destination terminal. This involves relaying and amplifying the signal, and the power amplifier is the core device in this process and the foundation of the communication system. With the continuous development of communication technology, spectrum resources are becoming increasingly tight, and the principle of fixed frequency band allocation has resulted in underutilized spectrum resources. To make full use of spectrum resources, the realization of the reconfigurable capability of power amplifiers will be studied in the future Focus. Then introduced a power amplifier designed by using Smith chart matching of GaN devices. The reconfigurable aspects of the designed power amplifier are studied. The use of PIN diodes enables the design of reconfigurable switches. Simulate the reconfigurable matching network, through the analysis of the simulation results, realize the switch function, and meet the design requirements. Finally, the input and output matching network and the reconfigurable matching network are tuned and optimized. The simulation results show that the power amplifier can switch between 1680MHz, 1935MHz, and 2040MHz frequency bands, the output power can reach 40-43dBm, and the efficiency is 70%-80%.

1. Introduction

The continuous transformation and upgrading of the communications industry, has driven the reform and innovation of the Internet and Internet of Things industries, accelerated the advancement of the information society and pushed people’s demand for mobile data traffic to show a blow-up growth trend [1]. To meet the increasing demand for data traffic, today, people are still using 4G networks, and the popularity of 5G technology has been raised again. Due to the emergence of new RF front-ends, To fully tap the potential of 4G networks and protect existing large-scale communication assets, during this period of a gradual transition to 5G communication, the new standard LTE Advanced Pro was announced, also known as 4.5G technology [2]. 4.5G technology can improve the network of communication operators’ Network competitiveness, provide users with better data business services, and promote the development of an information society. The main development direction of 4.5G networks is LTE voice technology bearer, multi-antenna, and multi-carrier aggregation [3]. Countries such as the United States, Japan, and South Korea are investing heavily in technology research in the 28GHz band used for 5G testing, and the cost of devices is high. Previously, they were mainly used in satellite communications, radar, and military fields.

In the daily communication mode, various communication standards and different communication methods are developing rapidly. Compared with the past, it is more convenient and fast for people to contact others in their daily life. However, due to its rapid development, the number of users is increasing rapidly and the demand for broadband communication is increasing, which makes the available communication frequency band more and more crowded. To meet the growing demand, it is required to develop a new frequency band, and at the same time, it is necessary to reduce the space and cost as much as possible. The power amplifier is an important device in the bandwidth communication network. The research on power amplifiers has important research value and practical significance. In the field of military industry, especially in electronic countermeasure equipment, the broadband power amplifier is widely used. Broadband technology is the research hotspot of scientific research institutes and military enterprises at home and abroad, and the key technology of broadband technology application is the design of broadband power amplifiers. Based on the consideration of national defense, civil communication, and economic benefits, it is an urgent problem to research and design broadband power amplifiers.

At present, most of the power amplifier designs are based on LDMOS technology. However, 3.5GHz is the limit frequency of LDMOS technology. With the advent of the 5G era and the development of semiconductor technology, third-generation semiconductor materials with high electron mobility will be widely used. GaN HEMT transistor has attracted more and more attention in the microelectronics industry due to their superior performance. It has also become the first choice for research and design of high-efficiency, high-frequency, and high-power RF power amplifiers.

The demand for frequency resources is increasing, which is why there are many new requirements for power amplifier applications. The effective use of frequency is a method to solve the problem of the shortage of spectrum resources, and the research of amplifiers that can work in multiple frequency bands will receive more and more attention. Among them, the main methods used are ultra-wideband power amplifiers [4], concurrent multi-band power amplifiers [5], and reconfigurable multi-band power amplifiers. The ultra-wideband power amplifier uses broadband matching technology to extend the working frequency band of the power amplifier, but the bandwidth of the frequency band has a certain limit. The power amplifier works on the frequency band specified by the design, and the frequency band is fixed and not adjustable. The reconfigurable multi-band power amplifier is based on the design of the multi-band power amplifier, and a reconfigurable device is introduced, that is, a reconfigurable device, so that the circuit structure of the power amplifier can be expanded and the number of operating frequency bands is increased. The configurable design of the reconfigurable power amplifier is flexible enough to realize the free switching of the operating frequency band. The reconfigurable power amplifier has the function of switching the frequency band by itself with the help of the peripheral detection circuit: the power amplifier circuit can automatically configure by switching different modes according to the change of the input signal and the power of the working environment to realize the reconfigurable function.

With the further research of reconfigurable technology and the research and development of new semiconductor materials by scientific researchers, the further evolution of the currently popular 4G technology and the development of 5G technology will make the frequency bands and modes supported by the RF front-end more and more many. The reconfigurable solution not only has good compatibility with new frequency bands below 6GHz but also the development of microelectronics technology and the development of core technologies can well support the needs of millimeter wave bands in 5G applications, which will continue to meet future products. It is of great significance to update the demand and continue to provide RF front-end products with better performance and lower costs. The reconfigurable multi-band power amplifier realizes the switching between different frequency bands based on concurrent multiple frequency bands and realizes the work of the power amplifier in different modes and different frequency bands. The reconfigurable power amplifier provides dynamic conditions to the RF power amplifier by introducing reconfigurable components into the input and output matching circuits of the power amplifier, which can significantly reduce the size and circuit complexity of the RF power amplifier. Reconfigurable configuration elements that can be used include microelectromechanical switches [6], PIN diodes, MOS switches [7], varactor diodes [8]-[9], and so on. Many foreign experts in this area have made in-depth research on this area and achieved certain results. W.C. Edmund Neo [10] and others from Delft University of Technology in Turkey use reverse series high-Q varactor diodes to achieve source and load impedance tuning of multi-carrier multi-mode RF power amplifiers. In the 900, 1800, 1900, and 2100MHz frequency bands, they achieved an output power of up to 27-28 dBm, and at frequencies greater than 1 GHz, the additional efficiency (PAE) can reach 30%-55%. In the United States, Dongjiang Qiao of the University of California at San Diego proposed an intelligently controlled RF power amplifier. Mainly by the MEMS switch and the varactor diode to achieve intelligent RF power amplifier control, you can achieve ultra-wideband tuning from 8 to 12GHz. Also in the United States, Georgia Institute of Technology's Joonhoi Hur and others [11] designed a multi-band multi-mode class D CMOS power amplifier using 0.18umCMOS technology through PMOS switching devices and tunable array resonators. Mehmet Kaynak of Sabanci University, Turkey, etc [12]. proposed a multi-band multi-mode power amplifier. The power amplifier is based on two MOS switches and can work in the 2.4GHz, 3.6GHz, and 5.4GHz frequency bands, respectively. The power amplifier achieves an output power of approximately 25 dBm at each frequency point and an efficiency of around 12%. In Europe, Roman Gloeckler[13] of the University of Erlangen-Nuremberg in Germany has proposed a new method of using a barium strontium titanate (BST) varactor diode to implement a multiband tunable power amplifier, which can achieve continuous operation in the range of 1700MHz to 2300MHz Adjustable.

At present, the low-power power amplifiers studied at home and abroad are not efficient. If the reconfigurable device has a large output power in the design of the power amplifier, in the design of the matching circuit of the power amplifier, add the reconfigurable switch to the matching circuit, and after adding the reconfigurable switch, the original matching circuit may be added. Have adverse effects and minimize them. Therefore, in the process of designing high-power amplifiers, the relevant indicators of reconfigurable devices will have higher requirements, and the design of matching circuits will be more difficult. Research work on reconfigurable multi-band RF power amplifiers still has a long way to go.

2. Design of input and output matching

2.1. Matching structure theory

Most power amplifiers have a similar structure, mainly composed of four parts, including a transistor, an input-matching network, an output-matching network, and two bias circuits. Fig.1 is a schematic diagram of a power amplifier composed of four parts. The realization of the power amplifier's gain, output power, and other indicators in a power amplifier is based on the characteristics of the transistor. In the design process, we will find that when the input and output impedances of the transistor have a certain deviation from the 50-ohm point, it is necessary to use the Smith chart to perform Any text or figures outside the aforementioned margins will not be printed.

In the design of power amplifiers, the design of the bias network is also a very important step. The bias is connected to the input and output matching circuit. As can be seen in the main structure of the power amplifier in Fig.1, there will be two bias circuits in the general power amplifier circuit. The gate bias circuit is connected to the gate. It supplies power to the gate, determines the static operating point of the tube, and can directly affect the working state of the power amplifier; the drain bias circuit is connected to the drain, which determines the drain voltage. Generally, its voltage is large, so it needs to carry a large current during operation. The bias circuit also needs to isolate signal interference to prevent some undesirable consequences. If the bias circuit is not well designed, the linearity of the power amplifier will change to a certain extent.

At the same time, stability is the premise to ensure that the RF power amplifier can work normally in the given frequency range, and is the necessary condition to ensure the safe and reliable operation of the communication system. If the power amplifier does not meet the stability conditions, it may lead to oscillation. Some external clutter signals also enter the power amplifier module. In serious cases, the RF power amplifier will self-excite, causing equipment damage and economic loss. Therefore, before designing the power amplifier, it is very necessary and meaningful to analyze the stability of the power amplifier. The S parameter can be simulated, and whether the power amplifier works stably in the working frequency range can be determined by the value on the chart.

In the stability analysis, if the stab fact is less than 1, it means that the power amplifier is unstable in the whole frequency band. At this time, some additional devices need to be added to enhance the stability. In the design process, we usually add a lossy component to the input end of the amplifier. The common method is to connect a resistor with a smaller resistance after the isolated capacitor at the input end, or connect a capacitor in parallel with the pin near the power tube, and then connect a small resistance to the ground in series. These methods can make the stability better, but they also have disadvantages, that as reducing the gain, that is, to improve the stability through the loss of gain, so these methods are not suitable to improve the stability when the input power is large.

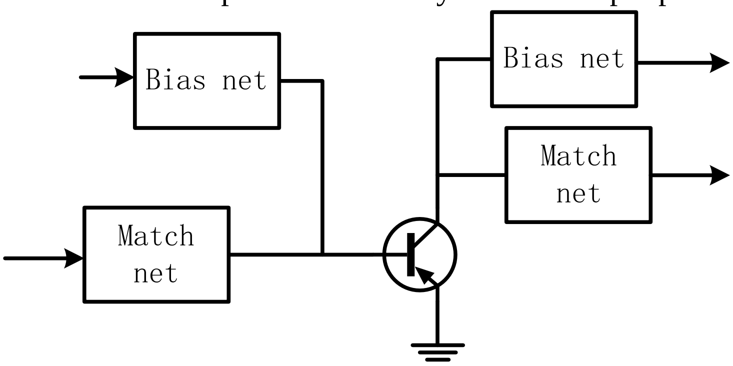


Figure 1: The main structure of the power amplifier.

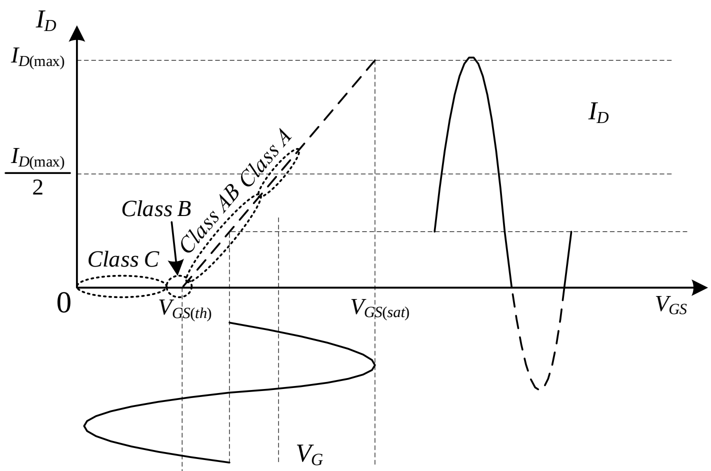


Figure 2: Relationship between input/output and bias of power amplifier.

According to the results of the ratio of input to output of the power amplifier, it can be divided into linear and nonlinear power amplifiers. The output voltage of the linear power amplifier will change with the change in input voltage, and there is a certain linear relationship. The relationship between the bias circuit, the selection of static operating point, and the input and output of the power amplifier tube are shown in Fig. 2. The bias states of the four types of linear power amplifiers are indicated in the figure.

Among them, class A, class B, and class AB belong to the linear amplifier, while class C, class D, class E, and class F belong to nonlinear amplifiers. The following is a brief introduction to various types of amplifiers.

(1) The static working point of class a power amplifier is selected at the middle point of the load line, and always works in the linear area. That is to say, during the whole period of input signal fluctuation, there is a current at the drain end of the transistor, and the transistor is always in the state. It should be noted that to keep the transistor from being driven in the on-off mode, there must be a certain limit on the amplitude of the input signal. Class a power amplifier is a kind of power amplifier with the best linearity and the worst efficiency of all RF power amplifiers. Theoretically, the highest efficiency is 50%. Therefore, class A power amplifiers are mostly suitable for communication systems with low output power and low-efficiency requirements.

(2) The bias static operating point of the class B power amplifier is lower than that of the class A power amplifier. The conduction period is equal to half of the input signal period. In half of the cut-off period, the power amplifier itself does not consume energy. Therefore, the efficiency of the class B power amplifier is significantly improved compared with 50% of class A power amplifiers, and the ideal state can reach 78.5%. However, its linearity is not as good as that of class a power amplifier.

(3) Class AB power amplifier is a type of power amplifier whose working state and characteristics are between class A and class B. It can be said that the performance of the class AB power amplifier is compromised. The theoretical efficiency is between 50% and 78.5%, and its linearity is higher than that of class B and lower than that of class A.

(4) The static working point of the class C power amplifier is selected in the cut-off area, and the conduction angle is less than 180 °. Compared with the above power amplifiers, the linear distortion is more serious, but the efficiency is better than that of class A and class B. Class C power amplifier in the actual working situation will only have more than 80% efficiency, and from the theoretical point of view, the reduction of the conduction angle will further improve its efficiency and ultimately can reach 100%, but there will be no power output. This kind of high-efficiency power amplifier is not of great practical value.

(5) Class D and class E power amplifiers are voltage-switching mode power amplifiers with a single transistor structure. Transistors are driven to work alternately in the saturation region and cut-off region, which is equivalent to an ideal switch. Through the special design of the load network structure, the working conditions of the zero voltage switch and zero voltage slope switch are realized. The voltage and current waveforms are not overlapped with each other in the drain of the power amplifier tube, and its loss is reduced, to achieve 100% ideal working efficiency.

(6) Class F power amplifier is an extension of class C power amplifier. Their bias circuits are very similar. They can realize the working state of different voltage and current waveforms seen from the current source reference plane of power devices through harmonic control, which does not make the power devices only work in the cut-off or on-off modes. Therefore, in a strict sense, they do not belong to the switch-type power amplifier, but their characteristics are the same as those of the switch-type power amplifier in theory, the efficiency can reach 100%, so it is classified as a switching power amplifier.

According to the classification method of RF power amplifier by f.h.rabb, the RF power amplifier is divided as shown in Fig. 3.

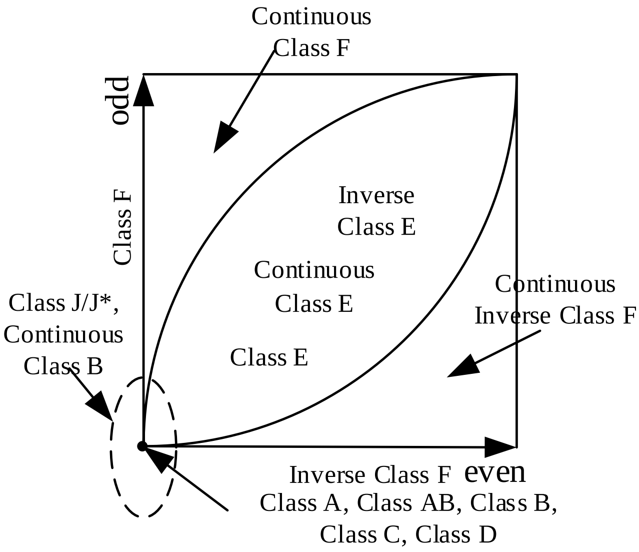


Figure 3: Division of various RF power amplifiers.

2.2. Simulation of matching circuit

When we design the matching network, the first thing we need to do is power matching. According to some knowledge in the RF circuit, when the transmitted power reaches the maximum value, the input impedance and the load impedance are exactly conjugate matched. In the radio frequency circuit, the matching network has a very important role, it can allow the signal of the input transistor to enter the transistor to the maximum, to better achieve the purpose of amplifying the signal.

Generally, when designing and simulating an RF power amplifier, a Smith chart is usually used to design and simulate a matching network. Enter the impedance value that needs to be matched on the Smith chart window that is called up, and connect a series of devices in parallel or series between the two ports, and this is to match the 50-ohm point with the impedance value through the circle on the Smith chart. Together, and more intuitive and faster. Fig.4 is a process diagram of the matching network design. By adding some devices, the impedance value of the Smith circle is matched with the center of the circle, that is, the 50-ohm point.

The extreme test conditions of an open circuit or short circuit will damage the device under test. To avoid this situation, we think that the module under test with source and load impedance Z_0 is connected to a lossless transmission line with impedance Z_0 as a dual port network, and the network characteristics of the two ports are reflected in the transmission line power wave according to the relationship between the incident power wave and the input power wave. Here, the scattering parameter (s parameter) is introduced.

The scattering parameter (S-parameter) is widely used in RF systems in related data manuals and technical materials. The S parameter is used to describe the complex characteristics and bias points of RF devices at different frequencies. The gain, return loss, stability, reverse isolation, matching network, and other important parameters can be calculated by some simple formulas. The S parameter can be used in both active and passive devices. S parameter is widely used in the calculation of matching circuit components and Simulation of complete high-frequency circuit design. Hardware engineers need to understand the circuit performance accurately so that the parameters of the designed circuit can better achieve the technical indicators when designing the circuit. The S parameter can help hardware engineers achieve this goal better. Using the S parameter, the characteristics of almost all RF devices can be determined by two-port network analysis under the condition of avoiding unrealistic open circuits and short circuits, as well as avoiding damaging the equipment under test. In essence, the S parameter is a parameter describing the relationship between incident voltage wave and reflected voltage wave.

On the Smith chart, the impedance value drawn is used to generate an ideal transmission line model. After the circuit diagram is generated, we need to convert the output to match the ideal transmission line into a microstrip line. In this design, the Rogers R04350 plate is used. The parameters are as follows: the dielectric constant is 3.66, the dielectric thickness is 0.762 mm, and the tangent loss angle is 0.02. The simulation circuit is shown in Fig.5, and the result is shown in Fig. 6.

It can be seen from Fig. 5 that in the range of 2.2-3.0GHz, S11 is less than -10dB, which is the lowest at the center frequency of 2.58GHz, proving that the matching circuit isolation is good; S21 between 2.5-2.7GHz is very small, almost zero, It shows that the matching circuit has no loss on the fundamental wave signal, and meets the design requirements.

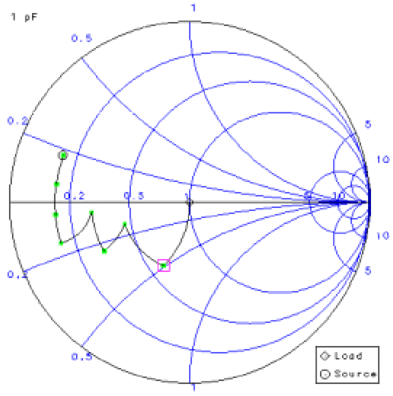


Figure 4: Design principle of the matching network.

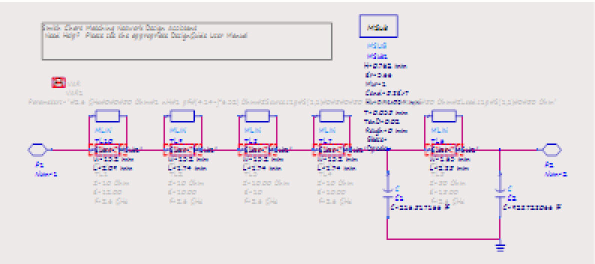


Figure 5: Simulation circuit diagram.

3. Design of reconfigurable switch

3.1. Research on reconfigurable devices

With the development of communication technology, all industries need communication technology to develop in a higher direction. Therefore, higher performance, maximum cost reduction, and less space occupation have become the main goals of researchers. Commercially available commercial wireless communications and military systems have special frequency band requirements, and their frequency bands must be broad and continuous, which has promoted the development of reconfigurable technologies. The same matching network, the same signal path, but operating in different frequency bands and modes. Power amplifiers are part of these systems with different operating modes and are crucial to the development of reconfigurable technologies.

The reconfigurable technology is implemented in a multimode multi-band wireless communication network, and the same matching network can operate in different frequency bands and different modes. There are two types of structures commonly used in applications to implement reconfigurable power amplifier designs. One is a broadband power amplifier, which is designed with a band-selective output matching network, as shown in Figure 7; and the other is used as shown in Figure 8 to switch between stage matching and band output matching through on-chip inductors.

In practice, it is difficult to achieve power amplifier operation in multiple frequency bands. A common and easy-to-implement method is to use multiple single-band power amplifier units and unidirectional multipath RF switches, as shown in Figure 8. RF switches are located at the input and output ends of these power amplifier units, and then these two switches are used to select different power amplifier units to achieve the purpose of selecting the operating frequency band. The disadvantage of this method is that as the number of frequency bands increases, the number of power amplifier units increases and the structure becomes more complicated, which inevitably greatly increases the size and cost of the system. At the same time, the loss of the output switch will cause the amplification efficiency to decrease [14].

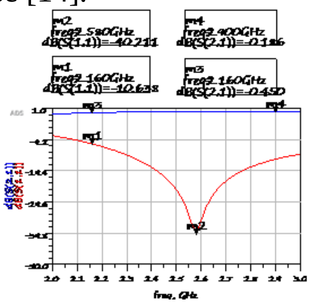


Figure 6: S-parameter simulation results.

The commonly used reconfigurable devices are MEMS switches and adjustable devices. MEMS switch is the result of the application of MEMS technology. The concept of the MEMS switch was first proposed in the late 1980s and early 1990s. With the continuous development of technology, the application prospect of MEMS switchs in microwave circuits has been greatly improved. RF devices made by MEMS technology are also widely used in RF circuit design.

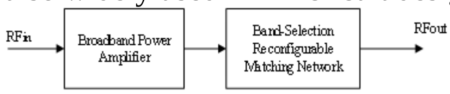


Figure 7: Broadband Power Amplifier with Band Select Output Matching Network.

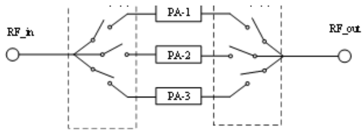


Figure 8: Power amplifier multi-path selection structure.

Adjustable equipment usually adjusts the capacity of the equipment by controlling the external voltage. A varactor diode is the most widely used tunable device. When the frequency is low, it has a single conductivity. With the increase in frequency, the capacitance effect of the PN junction becomes more obvious. At this time, changing the applied voltage can change the width of the PN charge area, thus changing the capacitance. Using the characteristics of a varactor diode, the nonlinear capacitance device can be realized, and the circuit can be reconstructed.

In this article, PIN diode switches are used. The PIN diode is based on a common PIN diode, and a thin intrinsic semiconductor layer is doped between the P and N junctions [15]. Its application range is very wide, mainly used as a radio frequency switch and RF protection circuit. There are two main differences between the turn-on and turn-off of PIN diodes at positive and negative DC voltages. The special impedance characteristics of PIN diodes can be used to achieve switching effects.

3.2. Simulation of reconfigurable switch

Using the characteristics of PIN diodes, switching functions can be designed and implemented. Fig. 8 shows the application circuit of a PIN diode used to implement a single-pole single-throw switch, which is mainly composed of a bias network and a PIN diode. The PIN diode used in this design is smp1307, which constitutes a reconfigurable switch. The designed circuit diagram is shown in Fig. 9.

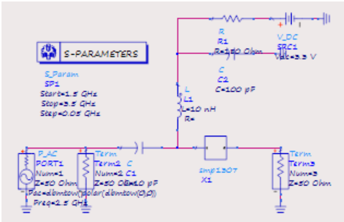
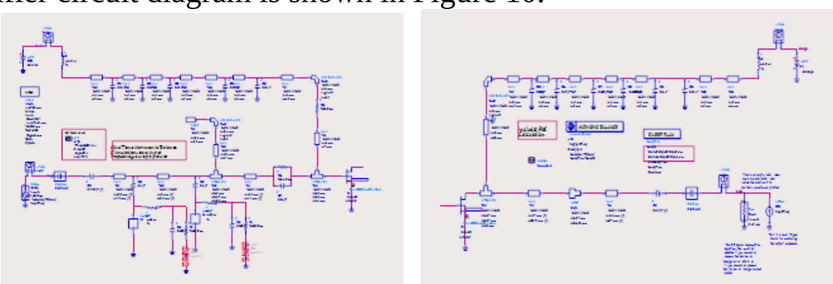


Figure 9: Reconfigurable Switch.

4. Simulation of the overall circuit

The efficiency of an RF power amplifier refers to the module's ability to convert DC input power into AC output power, which is the proportion of output power to DC power. When the power is converted, there must be a loss. The higher the efficiency, the lower the power consumption of the power amplifier module, and the less heat generated, and the efficiency and linearity are often in conflict. In the design and Simulation of the amplifier, we need to adjust the efficiency and linearity according to the specific index required by the amplifier to obtain the most suitable result.

Add some modules required for harmonic simulation based on the overall circuit diagram, add the input and output matching circuits of the power amplifier to the stability analysis circuit, and add microstrip lines to simulate the discontinuities between different microstrip lines, add current probe and voltage label to calculate and analyze the electrical parameters, tune the parameters of the circuit components to meet the design specifications, complete the harmonic simulation circuit diagram, the final power amplifier circuit diagram is shown in Figure 10.

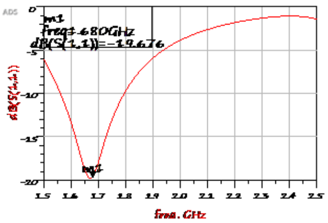


(a) (b)

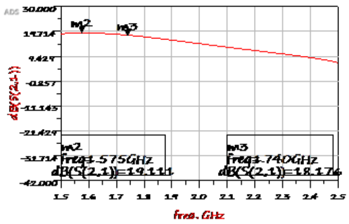
Figure 10: Harmonic simulation circuit diagram.

Through the simulation results of Figure 11, we can see that the power amplifier can achieve the purpose of switching between the three frequency bands of 1680MHz, 1935MHz, and 2040MHz through the switch. In the three frequency bands of MHz, the S11 parameters are all below -10dB. From the S21 parameters, it can be seen that the gain flatness is less than 1dB. It can be seen from Figure 12(g) that the output is 40.6dB, and from Figure 12(h) that the additional power efficiency is 76.3%, and the above data all meet the design specifications.

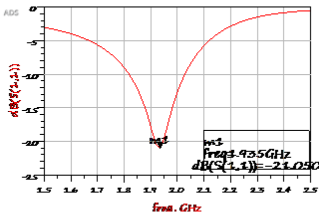
5. Conclusions



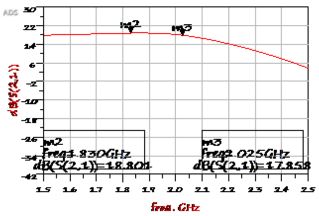
(a) S11 parameters in the 1680MHz band



(b) 1621MHz S21 parameters

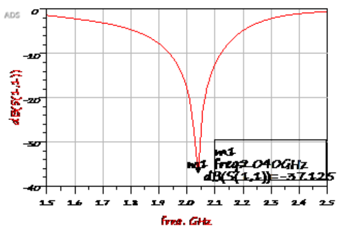


(c) 1935MHz band S11 parameters

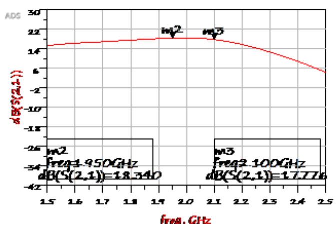


(d) S21 parameters in the 1935MHz band

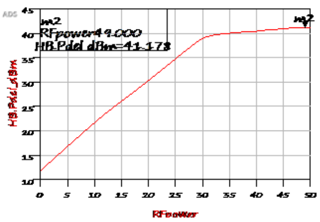
Figure 11: Simulation results (1)



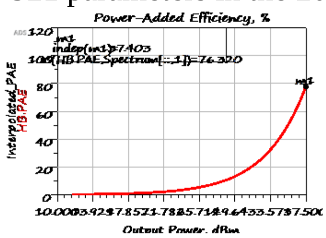
(a) S11 parameters in the 2040MHz band



(b) S21 parameters in the 2040MHz band



(c) Output Power



(d) Power added efficiency

Figure 12: Simulation results (2).

This paper mainly aims at designing future wireless communication reconfigurable power amplifiers. Firstly, the relevant knowledge and theory of power amplifiers are introduced and simulated. According to the simulation results, some amplifier parameters are tuned. The reconfigurable multi-band power amplifier is designed and simulated. The simulation results are analyzed and optimized. The PIN diode is used to design the reconfigurable switch. Simulate the reconfigurable matching network, through the analysis of the simulation results, realize the switch function, and meet the design requirements. Finally, the input and output matching network and the reconfigurable matching network are tuned and optimized. The simulation results show that the power amplifier can switch between 1680MHz, 1935MHz, and 2040MHz frequency bands, the output power can reach 40-43dBm, and the efficiency is 70%-80%. It solves the problems of difficult design, low efficiency, and mutual influence between working modes, making the communication system more ”intelligent” and more suitable for the needs of modern wireless communication multi-mode multi-band and high efficiency.

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