Research on Key Technology of Tile T/R Module Design

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Abstract. Tile T/R module has the characteristics of miniaturization, lightweight, high integration and high performance, which are very difficult to develop. This paper studies the key technologies involved in the development of T/R module, and focuses on the key technologies such as high integrated multifunction chip technology, high performance Radio Frequency (RF) 3D interconnection technology, high integrated multichannel RF design technology and thermal design technology. Through research and analysis, a design scheme of tile T/R module with miniaturization, high performance and high reliability is proposed.

1. Introduction

T/R module is the core part of millimetre wave system. It is widely used in electronic communication systems such as active phased array radar, satellite navigation communication and electronic countermeasures. The performance of T/R module will directly affect the technical indicator of the whole system. Improving the performance of T/R modules and reducing volume, weight and manufacturing cost are the continuous goals of T/R module technology research [1-2].

In the development of millimetre wave circuits and systems, T/R module shows the development trend of miniaturization, high integration, high performance and multichannel. The tile T/R module developed on the basis of 3D high density integration technology [3-4], has incomparable advantages in reducing module cost, volume and weight compared with the current block T/R module, and is easier to array integration.

The development of tile T/R module involves many key technologies, which is very difficult. Fortunately, in recent years, some tile T/R modules realized by 3D packaging technology have appeared in China. In 2019, Liu Weiqiang of the 20th Research Institute of China Electronics Technology Group Corporation presented a multichannel, low cost and high density broadband tile T/R module integration scheme [5]. In 2020, Yu Lei of Science and Technology on Electronic Information Control Laboratory introduced the design of a 3D broadband tile T/R module that can be applied to phased array system [6]. In 2021, Wang Qingyuan of the 13th Research Institute of China Electronics Technology Group Corporation designed a four channel tile type 3D integrated T/R module for radar by using MEMS bulk silicon 3D heterogeneous integration technology [7].

The design of tile T/R module needs to meet the requirements of miniaturization, high performance, good heat dissipation and good electromagnetic compatibility, etc. Therefore, the key technologies of module design lie in the aspects of high integrated multifunction chip technology, high performance Radio Frequency (RF) 3D interconnection technology, high integrated multichannel RF design technology and thermal design technology, etc. as shown in Figure 1.
2. High integrated multifunctional chip technology

2.1. Design of four channel multifunctional chip
The difficulty in the design of four channel multifunctional chip lies in the design of high precision amplitude and phase indicator under high integration. Relying on the multifunctional RF chip design, process, detection and reliability platform for T/R, high precision amplitude and phase control circuit, low gain temperature variation technology, power amplification and other technologies are studied. At the same time, separate external power modulation circuits and serial-parallel conversion circuits which are usually required in T/R channels are integrated to complete the product development. It greatly reduced the production and manufacturing costs of traditional analog T/R modules, and greatly saved the volume of modules, as shown in Figure 2.

2.2. Integrated design of multifunctional chip
The integrated design of multifunctional chip includes low noise amplifier and switch matching technology and switch and power amplifier large signal matching technology.
The application of high integrated multifunction chip effectively saves space, which is a necessary means for the development of tile T/R module.

3. High performance RF 3D interconnection technology

The core of tile T/R is the high density assembly and interconnection of chips and components. The electromagnetic field structure presents 3D characteristics and the size is reduced. At present, the assembly density of 2D Multi Chip Module (MCM) has reached the theoretical limit, and the packaging density of 3D-MCM based on 2D-MCM has been greatly improved. The advantages of 3D-MCM mainly include: ① The interconnection between components is shorter, which can obtain lower digital delay and smaller parasitic parameters; ② MCMs are stacked and interconnected along the vertical direction, which can obtain greater assembly density and realize the miniaturization of the system; ③ It can reduce the system noise, reduce the overall power consumption and improve the transmission rate.

For 3D integrated microwave circuits, the key to forming 3D structure is how to realize the vertical interconnection between planar microwave circuits. The main microwave vertical interconnection methods used in this design include RF connector interconnection and new vertical interconnection between boards, which has the advantages of small space, low insertion loss and easy installation.

(1) RF connector

Compared with fuzz buttons and other currently developed vertical interconnection methods, RF connectors occupy less space, have better performance in high frequency and broadband modules, have low cost and easy assembly, and provide convenience for repair. The traditional vertical interconnection structure is that the RF connector is sintered on the box body, and the pin of the connector is connected with the strip line by soldering tin, bonding gold wire or gold belt. The amount of solder is difficult to control during welding, and the amount of solder directly affects the output stationary wave of the cascade. Therefore, the mode of bonding gold belt is used in this paper.

(2) Vertical interconnection between boards

For 3D integrated microwave circuits, the key to forming 3D structure is how to realize the vertical interconnection between planar microwave circuits. Vertical interconnection refers to the interconnection required for the design of power supply, grounding and inter-layer signals in 3D modules. Interconnection should not only ensure the integrity of microwave signal, but also have the characteristics of simple structure. The 3D vertical interconnection technology adopted by this module is substrate vertical interconnection. The simulation and results of microwave substrate 3D vertical interconnection are shown in Figure 3 and Figure 4.

Figure 3. Simulation of 3D vertical interconnection of microwave substrate
Figure 4. Simulation results of 3D vertical interconnection of microwave substrate

The upper and lower cavity microwave interconnection adopts the way of serial holes on the back of the microwave board and interconnection between plates. Although coplanar waveguide is used, there are still some risks in microwave broadband performance. The local circuit is modelled and simulated for microwave discontinuity. The simulation results are shown in Figure 5 and Figure 6, which can meet the performance requirements of modules.

Figure 5. Microwave discontinuity simulation
4. High integrated multichannel RF design technology

The solution of miniaturized multichannel RF Design of high density integration is to adopt multilayer interconnection substrate technology. The key technologies involved include MCM multilayer wiring technology, high density assembly technology and multichannel isolation technology.

4.1. MCM multilayer wiring technology

Multilayer board and multilayer wiring is the basic way to realize miniaturization. We must start with design and simulation to optimize circuit design and reduce parasitic effect and crosstalk between circuits. For the process manufacturing, the process parameters should be strictly controlled to improve the consistency of the performance of multilayer microstrip circuits, so as to facilitate the correction and modification of the design.

4.2. High density assembly technology

At present, it has a variety of micro assembly processes: thin film, thick film, rack bonding, bonding, mounting, welding, spot welding, welding, etc. The assembly process is directly related to the reliability of the module, so the process route suitable for the module should be formulated on the basis of the existing mature process technology.

4.3. Multichannel isolation technology

The isolation of module circuit design is realized through reasonable layout. In the layout of the overall circuit, the digital circuit, analog circuit and RF circuit can be partitioned to reduce the coupling of electric field and magnetic field and achieve the effect of circuit isolation. Adding ground wall isolation between RF modules to isolate the electric field coupling path between modules can significantly reduce the coupling between circuits. When the common power supply of multiple circuit modules is grounded, the static current in the circuit will produce a voltage drop on the power line. For RF circuits, the dynamic current on the power supply will also form a dynamic voltage drop, resulting in crosstalk between modules. In this design, each amplifier is equipped with a separate power modulation circuit, and the in-chip filter capacitor is used to achieve the purpose of power isolation between amplifiers.

In the module structure design, the partition wall is designed in the key circuit with high gain in the cavity, which can effectively avoid signal crosstalk. There shall be no gap between the height of partition wall and box cover to prevent the formation of resonant cavity.

Figure 6. Microwave discontinuity simulation results
5. Thermal design technology
The thermal design of tile T/R module is an important part of tile module design. When designing heat dissipation, it is necessary to consider how to further improve the transmission efficiency of T/R modules and optimize the heat dissipation performance of the module while meeting the requirements of output power. The chips and devices in the T/R module have the highest withstand temperature. When the temperature of some chips increases by 10°C, the failure probability will increase by an order of magnitude. When the temperature of the chip is higher than the maximum temperature required for the chip to work normally, the chip may be permanently damaged and the whole T/R module may fail.

The heat dissipation mode of T/R module is usually comprehensively selected by measuring the power per unit area of each chip in the module. By comparing the power consumption and working state of components, the device can meet the heat dissipation requirements while working and make the structure compact. The thermal design is mainly carried out in the following ways:

1. Optimize the power chip, reduce the thermal resistance of the chip, and improve the output power and efficiency;
2. Select the metal aluminium alloy shell material with high thermal conductivity, and weld the power single chip to the molybdenum copper carrier as the heat sink to effectively transfer heat;
3. Evenly arranged the heating devices through reasonable circuit layout and process design;
4. By studying the heat dissipation measures and heat dissipation paths, ensure the metal under the heating device is continuous and complete, so that the heat can be transmitted in time;
5. Verified by thermal analysis software. Build the thermal analysis model by finite element analysis software and perform thermal simulation. By reducing the junction temperature of the semiconductor chip through the thermal design, the reliability of the circuit can be better improved.

6. Conclusion
In order to meet the development requirements of miniaturization and high integration of active phased array radar, tile T/R module needs to have the characteristics of miniaturization, high performance and high reliability, etc. The development process involves a variety of key technologies. Through high integrated multifunction chip technology, high performance RF 3D interconnection technology and high integrated multichannel RF design technology, the integration of T/R module is improved, the volume and weight of T/R module are reduced, and the performance of T/R module is improved. Through high performance RF 3D interconnection technology, high integrated multichannel RF design technology and thermal design technology, the structure, layout and packaging process of T/R modules are optimized and the reliability of modules is improved.

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