Design of a Ku-band Tile T/R Module

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Abstract. This paper introduces a 16 channel Ku-band tile T/R module design in 3D highly integrated packaging. The technical indicator design of T/R module is completed by using four channel amplitude phase multifunctional chip and various design methods. Through reasonable indicator distribution and structure layout, the miniaturization design of T/R module is realized by using high-density substrate and 3D interconnection structure. Through process optimization, structural design and simulation verification, the reliability and producibility of T/R module is studied, and the consistency of products is improved. The test results show that the design has good microwave performance and can meet the requirements of high performance, low cost and batch production of Ku-band T/R module.

1. Introduction
T/R module is an important part of phased array radar, and its performance indicator directly affects the performance of the whole phased array radar [1]. Modern military and civil electronic equipment, especially active phased array radar and communication system, is developing towards miniaturization, high working frequency, high integration and low cost, which puts forward higher and higher requirements for T/R modules.

With the rapid development of integrated circuit, the integration of T/R module used in active phased array radar becomes higher and higher [2]. Conformal antenna requires T/R module to have small size and ultra-thin structure. At present, there have been tile T/R modules integrating antennas on T/R modules [3]. The lightweight of tile T/R modules can better meet the needs of radar and is the inevitable result of the development of radar system. This T/R module adopts 3D assembly technology to integrate the antenna unit and module circuit into one circuit module, which avoids the connector interconnection between the T/R module circuit and antenna unit, greatly reduces the cost of T/R module, improves the integration, reduces the volume and weight, improves the stability of radar in complex environment [4], and meets the development requirements of phased array radar miniaturization and lightweight [5]. It is an important direction of T/R module development at present.

According to the requirements of phased array radar for micro tile T/R module, a new highly reliable Ku-band tile T/R module with 16 channels and 4*4 structure is designed in this paper.

2. Overall indicator design
Due to the complexity of T/R module system, many problems are involved, including the internal details of the module, the relationship between the module and the outside, signal quality, delay, distribution, noise, etc. The overall indicator design should be considered in many ways. One of the key problems is the layout and wiring of components and the signal interconnection between layers. It is necessary to comprehensively consider the crosstalk, noise, electrical path radiation and other problems between the signals of each chip and component on the substrate under the small cavity body.
The second key problem is the design of passive device in the carrier, which needs to comprehensively consider the limitations (accuracy) of the passive device process, quality factor (Q), resonance frequency, etc. With the increase of module complexity and the decrease of module size, the difficulty of system design will increase. In addition to using the design software, the numerical simulation of system performance should also participate in the design process, such as high frequency electromagnetic field simulation, heat transfer simulation, and reliability.

The design ideas of T/R module in this paper are as follows: complete the technical indicator design of T/R module through various design means, solve the problem of rationality of indicator distribution, and solve the problem of realization of technical indicator and optimum process route; through the redundancy analysis of process error, solved the influence of process deviation on technical indicators and device compatibility; through the time domain analysis of power supply and wave control devices, realize the accurate control of power management and wave control timing; through the performance analysis of the whole module, solve the problem of matching with the technical indicators of the whole machine; through testing and debugging, solve the problem of technical indicator compliance, and solve the problems of signal crosstalk, noise, circuit radiation, etc.

The microwave link block diagram of T/R module is shown in Figure 1.

![Microwave link block diagram of T/R module](image)

Figure 1. Microwave link block diagram of T/R module

After receiving from the antenna, the receiving branch signal is amplified by the switch and low noise amplifier, then phase shifted and attenuated by four channel amplitude phase multifunctional chip, and output through the quasi coaxial transmission via or connector. NC (Numerical Control) attenuator digits, NC attenuation amount, NC attenuation step, NC attenuation accuracy, NC phase shifter digits, NC phase shift range, NC phase shift step, phase shift accuracy RMS (Root Mean Square) error and other indicators can be guaranteed by the device. The main indicators are designed as follows:

1. **Noise figure, R-branch gain**
   The theoretical calculated value of noise coefficient of the whole R-branch is about 4dB, and the theoretical value of module receiving gain is about 12dB.

2. **Gain flatness design of R-branch**
   In order to improve the gain flatness of R-branch, two measures are taken in the design. First, the flatness of the devices used is optimized. Secondly, on the RF (Radio Frequency) transmission path, especially in 3D interconnection, ensure that the in-band insertion loss curve is relatively smooth. Through the above measures, the gain flatness of R-branch can be controlled within ±1dB at room temperature.

3. **Design of phase shifting accuracy and attenuation accuracy of NC phase shifter**
   The NC phase shifter chip in the amplitude phase multifunction chip is 6 bits, and the minimum step is 5.625°. Within the module working frequency band, the 64 state RMS phase shift error of the
NC phase shifter is \( \leq 2^\circ \). The phase shifter is installed inside the module. Due to the influence of the cavity and the port stationary wave, the indicator will deteriorate by about 1\(^\circ\), and the RMS phase shift error can be controlled at about 3\(^\circ\).

The digits of NC attenuator are 6, the step is 0.5dB, and the total attenuation is 31.5dB. The attenuation accuracy of the NC attenuator is determined by the attenuation accuracy of the selected NC attenuator itself. The attenuation accuracy of 64 attenuation states of the NC attenuator selected in this paper have is \( \leq 0.5dB \).

(4) P-1 design of R-branch input
The input P-1 at the receiving end of the four channel amplitude phase multifunction chip is -5dB, the gain of the low noise amplifier is 26dB, and the loss of connector and switching is about 1dB, then the module receiving input P-1 is: 1-26-5=-30dBm.

(5) Design of port stationary wave
The receiving input port is the antenna port, the microwave connector is the standard SSMP connector, and the stationary wave coefficient is 1.25. Cascaded with the connector is a GaN multifunctional device with a port stationary wave of 1.6. After reasonable matching design, it can ensure that the stationary wave of the receiving input port is within 1.8. The output port of R-branch is SSMP connector and power divider chip, and the chip stationary wave is 1.3, which meets the requirements of receiving and output stationary wave \( \leq 1.8 \).

(6) Design of saturated output power and output power flatness of T-branch
The transmitted signal enters from the assembly port of the module, passes through the one point four power divider, and then reaches the port of the four channel amplitude phase multifunction chip. The signal is phase shifted by the amplitude phase multifunction chip, and then saturated outputs by power amplify. After the signal passes through the port insulator or connector, one point four power divider and four channel amplitude phase multifunction chip, the loss is about 0.5dB, and the power gain of the power amplifier is \( \geq 20dB \). Therefore, when the input power is greater than 14dBm, the power amplifier can approach the saturated output, and the saturated output power is about 34dBm. Minus the loss of the output port connector, the output power of the transmission channel is about 33dBm.

The saturated output power of GaN power amplifier chip is within the working bandwidth and the flatness is within \( \pm 0.5dB \).

(7) Top-down design of launching pulse
The indicator requires that the top-down of transmitted pulse is \( \leq 0.5dB \) (pulse width 200us, 30% duty cycle). If the power modulator is close to the amplifier, and the transmission length of the circuit board and wire is reduced, the top-down of the transmitted pulse can be controlled at about 0.4dB.

3. Miniaturization design
The function of T/R module is complex, the number of channels is large, and there are many microwave chips and control chips. It is very difficult to develop it to achieve certain power and sensitivity in order to realize the transmission and reception of RF signals in a very small volume. This design reduces the chip space through reasonable indicator allocation and improving the multifunction chip; through reasonable structural layout, a 3D interconnection structure of RF and control lines is formed to reduce the size and weight of modules; the miniaturization and high performance of T/R module are realized by using high-density substrate. The mixed signal design of microwave transmission line, logic control line and power line is integrated into the same 3D microwave transmission structure, which minimizes the volume and weight of the T/R module.

PCB substrate is used in this design. PCB substrate has low dielectric constant, low RF loss, low coefficient of thermal expansion and high glass transition temperature \( T_g \). It can realize the interconnection of any layer, and has extremely dense wiring and low processing cost, which is the preferred plate to realize high-density assembly products. PCB substrate can achieve thinner thickness, which is more suitable for tile modules with strict size requirements.
There are 4 layers of copper foil on the substrate, and the overall plate thickness is designed to be 0.3mm. In the design, the substrate stack is designed as follows: the top layer is RF microwave layer, mid1 layer is microwave ground layer, mid2 layer is power supply and controlling wire and the bottom layer is GND layer. Most of the lines that can be fully utilized are in mid2 layer, and mid1 layer is only used in areas other than microwave flooring. The wiring density of circuit board is very high and the requirements are higher. In the design, the continuity of microwave ground shall be fully considered to ensure the RF performance of the module; isolation between low frequency and RF signals shall also be carried out to avoid crosstalk.

A variety of vertical interconnection modes such as substrate vertical interconnection, insulator or transition block interconnection, BGA ball planting, fuzz button are compared. In this design, microwave multilayer substrate is used to solve microwave interconnection. Microwave vertical interconnection transmission between substrates is the simplest and easy way of 3D transmission of microwave signals. It is mostly realized by multi-layer microwave boards, which takes up a small space. Mature process assembly methods can be used for module assembly, which will not increase the difficulty of assembly. After the signal is vertically transmitted, the connection part of the microstrip or stripline should be well matched and designed, which can be applied to higher frequencies. Because there are microwave circuits, power supply and control circuits on the whole circuit board, attention should be paid to avoid crosstalk between signals during design.

### 4. Reliability design

Due to the 3D integration mode, tile T/R modules face greater challenges than "brick" in the design of signal transmission, module coupling, heat dissipation performance and power integrity. This paper mainly optimizes the reliability from the aspects of electromagnetic compatibility design, heat dissipation design and sealing design.

Because T/R module encapsulates all RF chips and components in one cavity, it is easy to produce coupling effect, resulting in mutual interference between different modules [6]. This design mainly analyses and solves this problem from the following aspects: ① In the design, appropriate filtering and shielding are added between the connection of microwave circuit, wave control circuit and power supply, and reasonable layout is adopted, avoiding long distance parallel lines of signals; ② The multi-channel local direct cavity division design is adopted in the structural design, which has good channel isolation, small crosstalk and high circuit stability; ③ A whole sheet of absorbing material is pasted on the box cover to absorb the space radiation of the transmission line; ④ In the 3D microwave transmission structure, the quasi coaxial and coplanar waveguide mode is adopted, which has good stability, and realizes the maximum possible spatial isolation and shielding measures with the wave control and power supply circuit to avoid crosstalk.

When the T/R module works, the shell structure will affect the heat dissipation performance of the module. When the output power of the module is high, it will obviously heat up. When the module temperature exceeds the normal working temperature of the chip, the chip and device may fail. This paper considers heat dissipation from two aspects: ① For internal device heat dissipation, power amplifier devices (including GaN power amplifier and circulator, et al.) are sintered on molybdenum copper carrier with gold-stannum solder, and molybdenum copper carrier is sintered on the box body to ensure sufficient heat dissipation; ② For external heat dissipation of module, when the system is integrated, the modules are first fixed to the cold plate, and the heat is quickly exported through the cold plate. The contact surface between the modules and the cold plate is fully considered in the structural design.

The function of T/R module is complex, there are many chips, and there are aluminium pressure point chips that need aluminium wire bonding, which has strict requirements on the sealing of the environment. This paper solves the sealing problem of T/R module from the aspects of packaging material, packaging structure and packaging technology: ① SSMP connector and micro torque low frequency connector are gas sealing structure; ② Microwave connector and low frequency connector
are welded on the box body at one time by welding process; ③ The box body is sealed by laser sealing welding, so as to meet the sealing requirements of modules.

5. Producibility design
In order to meet the requirements of batch production of tile T/R modules, it is necessary to design the modules with low cost and producibility: through reasonable process design, select mature process routes as far as possible to solve the problem of high density assembly of tile modules; solve the problem of testing and installation of modules by using the opposite plug connector and setting the installation hole at the appropriate position; control the cost of equipment and outsourcing, and optimize the design to make the modules free of debugging or micro debugging, so as to reduce the processing cost of modules. Producibility design mainly includes: process optimization design, free (micro) debugging design and automatic production.

5.1. Process optimization design
The traditional T/R module all adopts serial operation, which restricting the production cycle of T/R module. By optimizing the structure layout and adopting parallel modular design, the production cycle can be reduced and the production efficiency can be improved. At the same time, due to the modular design of the cavity, the performance of the modules has been improved to a certain extent, and it is convenient for module maintenance to ensure that T/R modules can realize mass and efficient production.

5.2. Free (micro) debugging design
There are many test indicators of T/R modules, which bring huge workload to debugging and production. Therefore, in order to implement producibility, it is necessary to be free (micro) debugging. 3D electromagnetic field software simulation can effectively simulate the transmission characteristics of microwave signals. By using 3D electromagnetic field software to simulate interconnection matching, cavity effect and system cascade, it can effectively guide the design layout and reduce the debugging workload in the early stage of design. At the same time, the first piece design is carried out according to the simulation result, and then the software simulation is fed back according to the first piece debugging result, and the joint design is carried out again, so that the batch product is free of (micro) debugging as much as possible.

5.3. Automatic production
Due to the complex structure of T/R components, the variety and quantity of chips, and the limited space and volume, to a certain extent, the utilization rate of automatic assembly and automatic bonding of T/R modules is reduced to a certain extent. Therefore, it is hoped to formulate design specifications for T/R automatic assembly, optimize cavity structure design process, and design corresponding tooling for T/R automatic assembly through this project, so as to improve the automation rate of assembly bonding and improve product consistency.

6. Conclusion
Process implementation was carried out after the design was completed. The test results show that the technical indicators of this design meet the requirements, and the microwave performance is good, which simplifies the production process, reduces the production cost, and can meet the requirements of high performance, low cost and batch production of T/R modules. After the implementation of the project, it can realize technological leapfrog development, promote the engineering application of a new generation of miniaturized T/R modules, provide conditions for the development of a new generation of phased array radar, promote a significant leap in the performance of T/R modules for Ku-band radar, and meet the requirements of conformal phased array radar for Ku-band high power and small size.
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