Reliability Design and Simulation of High Density Packaging T/R Module

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Abstract. The requirements, development, packaging characteristics and existing reliability problems of high density packaging T/R modules are introduced, and the importance of reliability design is recognized. Aiming at the reliability problems of Electro Magnetic Compatibility (EMC), heat dissipation and electrostatic discharge, the reliability design and simulation scheme are given, and some cases are provided. Through design analysis and improvement, the reliability of 3D high density packaging T/R modules can be effectively improved.

1. Introduction

In recent years, phased array has been widely used in radar communication and electronic countermeasure, and T/R module is the key module of active phased array system. Limited by specific use environment and conditions, T/R modules have strict requirements on volume, weight, vibration resistance and impact resistance [1]. At present, the widely used microwave Multi-Chip Modules (MCM), whose microwave module assembled by its 2D plane assembly process technology cannot meet the characteristics of miniaturization, lightweight, conformal and stealth, are facing another breakthrough in process integration technology [2]. In recent years, the technology hotspot of 3D integrated packaging process is an effective way to achieve the integration, reduction, lightweight, high density and excellent electrical performance of microwave modules.

3D-MCM refers to a 3D structure module obtained by aligning and stacking a plurality of packaged 2D-MCM through a partition or other physical structure in the vertical direction in addition to expanding the electronic components and layout on the horizontal plane. Compared with conventional MCM, 3D-MCM can make the chip interconnection shorter, the transmission delay less, the working speed of modules faster, greatly reduce the physical size of the system and improve the assembly efficiency, so as to achieve higher chip integration [3].

With the development trend of miniaturization, high integration, high performance and multi-channel of T/R modules, tile T/R modules developed on the basis of 3D high density integration technology [1,4] have incomparable advantages in reducing module cost, volume and weight compared with current brick T/R modules, and are easier to array integration. At the same time, in the 3D tile multi-channel T/R module with higher integration, due to the denser arrangement of various devices, it is easier to produce reliability problems than brick T/R module. Reliability design and simulation technology is an important mean to solve the reliability problems of T/R module.

2. High density packaging features

Generally, brick structure and tile structure are the most common T/R modules. In the brick module,
each transceiver channel is integrated into a unit module, and finally spliced into a complete subarray. The integration mode is relatively simple and the process flow is relatively mature. Because its longitudinal size is too large, it is usually suitable for the research and design of single channel transceiver modules. This form of structure has low integration and occupies a large transverse area, which cannot meet the application requirements such as array conformal. In addition, because the receiving branch and transmitting branch are located in the same plane, it is easy to form a closed-loop structure, resulting in mutual interference between the transmitting and receiving branches, so there is a very serious problem of Electro Magnetic Compatibility (EMC).

The tile T/R module is to layer a complete subarray according to functions. Each layer has some specific function of all channels of the subarray. Finally, all functional layers are connected together through 3D interconnection to form a fully functional phased array front-end. Compared with traditional brick modules, tile T/R modules have the advantages of high integration, small volume, flexible use and strong reconfigurability. In the development tide of miniaturization, reconfiguration, integration of electronic systems and the extension of the use frequency band of phased array systems to W-band or even terahertz band, tile T/R modules will replace brick modules and become the mainstream design direction [5]. Figure 1 shows the structural diagram of a typical 3D integrated tile multi-channel T/R module [6].

![Figure 1. Structural diagram of 3D integrated tile T/R module](image)

As can be seen from figure 1, the chips with various functions are assembled in layers, and the signal transmission between different layers is realized through vertical interconnection holes, which greatly reduces the longitudinal size and improves the integration. The tile T/R module is 20% ~ 80% smaller than the existing brick T/R module, the thermal path is shortened, the heat dissipation efficiency is improved accordingly, and has higher reliability. Although it is more difficult to realize miniaturized tile T/R modules, it has great advantages in reducing production cost, reducing size and weight, and is easy to realize large-scale multi-channel module array [7]. Based on the above advantages and the practical application requirements of modern radar array, T/R module is gradually developing from brick structure to tile structure [8].

3. Reliability design criteria

The number of T/R modules used in phased array radar is generally very large. In order to improve the reliability of the whole system, the reliability of core modules must be improved. Each function of the T/R module depends on a variety of different electronic circuits, so the cognition of circuit design reliability must be improved. According to experience, reliable circuit design technology mainly includes the following aspects: simple scheme, mature technology, inheritance of experience, correct selection and use of components, over stress design, tolerance design, overvoltage, overcurrent and overheat protection, EMC design, thermal design, etc.

This paper does not discuss the widely used circuit design requirements such as simplified design,
redundant design and derating design, but focuses on reliability design and simulation technologies such as EMC design, thermal design and antistatic design. It is designed from the aspects of EMC, thermal stress and antistatic, and combined with simulation, test verification and other methods to improve the reliability of tile T/R module.

4. Reliability design scheme

4.1. EMC design

The early design of microwave modules mainly focused on logic and function. Even if there were EMC problems, they could be simply solved by isolation, filtering and grounding. However, there are EMC problems in the layout, wiring, through-hole distribution and packaging mode of high density packaging T/R modules. The EMC of products must be fully considered in the design work. Due to the complexity of EMC problems, the traditional EMC problems are mostly found by the test after product design and production, and then corrected afterwards, resulting in the improvement of design cost and the growth of research and development cycle. Serious EMC problems will even lead to irreparable product design failure.

With the development of T/R module technology, the EMC problem of modules is becoming more and more complex. The structure of 3D high density integrated modules is more complex, the circuit layout is more compact, and the problem of EMC is more prominent, which needs further analysis and design. Especially in the 3D integrated tile T/R module, the signal transmission between module substrates adopts interlayer vertical interconnection, the high-frequency transmission performance is not easy to guarantee, and the connection reliability is poor. The vertical interconnection between microwave signal layers not only needs to achieve the integrity of microwave signal transmission, but also needs to ensure the structural integrity, do not produce high-order modes and radiation effects, or do not inhibit its ability to spread to the outside world, so as to protect the normal operation of other devices in the module. Therefore, vertical interconnection is one of the key technologies to realize tile multi-channel T/R modules. Table 1 shows several common millimeter wave vertical interconnection methods and performance comparison [9].

Table 1. Comparison of various microwave vertical interconnection technologies

| Transmission line type | Irregular waveguide | Quasi coaxial line | Plane transmission line | Planar line coupler |
|------------------------|---------------------|--------------------|-------------------------|---------------------|
| High frequency transmission performance EMC | Excellent | Good | Normal | Poor |
| Contact mode | Mechanical contact | Good Mechanical contact, elastic crimping or bonding of outer conductor; Elastic crimping or bonding of inner conductor | Poor Elastic crimping or bonding | Bad Mechanical contact of ground plane, non-contact of conduction band |
| Connection reliability | Excellent | Poor | Poor | Good |
| Miniaturization | Excellent | Excellent | Good | Normal |
| Mass production | Excellent | Poor | Normal | Excellent |

It can be seen from table 1 that various vertical interconnection modes cannot fully meet the integration requirements of tile modules. Due to the influence of spatial coupling and surface wave of dielectric substrate, the EMC of open planar transmission line structure is poor. The closed structure of coaxial type is conducive to improve the EMC of signal transmission. Therefore, in the design of vertical interconnection between tile T/R module layers, in addition to good high-frequency performance, simple structure and process and easy realization, metal shell should be selected for shielding as much as possible to maintain good EMC performance, so as to ensure that the signal is not subject to external interference and leakage. In T/R module, the discontinuity of transmission line
will be amplified and propagated through cavity resonance effect, which is easy to cause electromagnetic interference to various devices in the module. Therefore, improving the transmission of microwave signal and restraining the propagation of high-order modes have very positive significance for the design of module EMC.

With the development of computer technology and the improvement of electromagnetic simulation analysis software, the data obtained by electromagnetic simulation have been very consistent with the actual experimental data. The electromagnetic simulation results have high guiding value for the design. Using electromagnetic simulation software, the EMC problem of the product can be roughly estimated in the product design stage, which is very helpful to solve the EMC problem, so as to improve the product performance, save the cost, shorten the research and development time and improve the success rate of product development. Using electromagnetic simulation software to simulate and analyse the EMC of newly designed products has become a necessary step in the process of product design. Since the modelling and simulation of T/R module electromagnetic microwave related disciplines involve different professional technologies and methods, it is necessary to pay attention to the characteristics of different technologies and the coordination of processes from the basic workflow. The general electromagnetic simulation workflow is shown in Figure 2, and the main links are as follows:

1. According to the simulation input data (such as PCB layout file, cavity view, etc.), build the basic 3D physical model of T/R module. On this basis, make professional processing of the model based on the professional characteristics of electromagnetic microwave simulation, and build the 3D electromagnetic model;
2. For the 3D electromagnetic model, set the necessary excitation, boundary conditions and simulation frequency, and perform iterative optimization of mesh dissection;
3. Perform 3D electromagnetic simulation of T/R module, and obtain the electromagnetic field distribution and other data of different frequency points in the module cavity under signal excitation;
4. According to the simulation input data (such as circuit system principle, device index, S parameters, etc.), build the basic T/R module circuit system model, and combined with the passive 3D structure S parameter model obtained by the 3D electromagnetic simulation of T/R module, build the field-circuit combined T/R module circuit system model;
5. Perform field-circuit combination collaborative simulation of active-passive/3D structure, and obtain the index data of T/R module microwave circuit system considering the actual 3D electromagnetic characteristics.

![Figure 2. Electromagnetic simulation workflow](image)

4.2. Thermal design

The thermal design of micro tile T/R module is an important link throughout the whole process of reliability design. The purpose of thermal design research is to control the product temperature within the specified range, minimize the temperature difference inside the product and ensure the normal operation of the product. By selecting materials and devices and taking reasonable process measures, the heat generated by components is effectively transmitted to the shell to ensure that the junction
temperature or maximum temperature of power devices with large calorific value is controlled within the allowable temperature range, so as to make the heat source layout uniform and avoid local heat source concentration. At the same time, minimize the impact of environmental temperature change on product performance, improve product life, eliminate quality hidden dangers and improve reliability.

After the thermal design is completed, the analysis model is built by using the finite element analysis software for thermal simulation. The junction temperature is one of the important indicators to judge the thermal performance of the chip. Untimely chip heat dissipation will lead to excessive junction temperature [10]. Through the thermal design of the circuit, reducing the junction temperature of the semiconductor chip can better improve the reliability of the circuit.

For example, the GaN chip parameters of a T/R module are as follows: the thermal resistance is about 4°C/W (as shown in table 2), the working voltage is +28V, the pulse width is 200μs, the duty cycle is 30%, and the test platform temperature is +70°C. The process ensures that the lifetime of GaN chip is 1 million hours at 225°C junction temperature; the junction temperature below 150 °C is recommended. When the module works at +28V, the output power is about 3.5W and the dynamic working current is 125mA (30% duty cycle). Therefore, the thermal power consumption of GaN chip is calculated as: 28V*0.125A-3.5W*30%=2.45W; GaN chip temperature rise: 4°C/W*2.45W=9.8°C.

| Name        | Material Science | Thermal Conductivity (W/m K) |
|-------------|------------------|------------------------------|
| Chip        | GaN              | Thermal resistance 4°C/W     |
| Shim        | MoCu             | 170                          |
| Box body    | 6061Al           | 154                          |
| AuSn Solder | Au50Sn50        | 4 (worst condition)         |
| PbSn Solder | Pb63Sn37         | 50                           |

For the above thermal design, the thermal design method is verified by the thermal simulation software to make the thermal design of the product meet the product requirements. The ambient temperature is 70°C, and the thermal simulation is carried out according to the material properties in table 2, the simulation results are shown in Figure 3. The maximum temperature of the chip bottom is 78 °C, and the maximum temperature rise of the chip is 8 °C, which is lower than the design temperature rise, indicating that the structure of the T/R module has good heat dissipation capability.

4.3. Antistatic design

The damage of electrostatic discharge to T/R modules is often hidden and developmental, that is, electrostatic damage is sometimes difficult to find, and will be exposed after a certain time of accumulation, resulting in the complete failure of components on the module circuit board. Therefore,
it is particularly necessary to take antistatic measures in advance for antistatic design. The antistatic design consists of a series of links, including components design, circuit design, components selection, procurement, packaging, transmission, storage, transportation, testing, assembly, operation and use, and each link should be considered.

For example, in addition to meeting the conventional anti-static requirements for a certain type of T/R module, the following measures are taken in circuit design and structural design:

1. Devices with high electrostatic sensitivity shall be selected as far as possible during device selection, and the protection grade shall be at least 1A;
2. Maintain well connection between the module power ground and the box body to provide electrostatic discharge circuit;
3. Protect internal devices by controlling input port connected in series with current limiting resistor, use decoupling capacitor to fully filter in the power input terminal, and add diodes to improve the antistatic ability;
4. The bottom layer of the circuit board is a large area metal layer, which is connected with the box body to form an effective electrostatic discharge path;
5. Place the electrostatic sensitive devices between interstage circuits in the circuit layout, and avoid placing the electrostatic sensitive devices at the input, output and power terminals;
6. Rationalize the structural design and layout, and avoid the design of sharp corners, narrow seams, shell openings, etc.

5. Conclusion
Active phased array radar and communication system are developing towards miniaturization, high working frequency, high integration and low cost, which puts forward higher and higher requirements for the development of T/R module. However, the miniaturization and high integration of T/R modules have brought more serious and complex reliability problems such as EMC and heat dissipation, which seriously restricts the development of T/R modules. Therefore, it is of great research significance to analyse and improve the reliability of 3D high density packaging T/R modules.

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