LETTER

Integrated design of X-band phased array antenna with LTCC 3D T/R module

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Abstract In this paper, a novel design scheme of X-band phased array antenna is introduced. The antenna array is mainly composed of the 3D T/R module, which is based on LTCC technology, and the slotted waveguide antenna. The whole system adopts the vertical interconnected three-dimensional multi-layer technology for the spaceborne synthetic aperture radar (SAR) system. 3D T/R module greatly improves the integration of the system by assembling different multifunctional chips into a complete multi-layer LTCC substrate. The slotted waveguide antenna is connected vertically with the T/R module, the power divider, etc, implementing the integrated design. The test results of the antenna system show that the phased array antenna has a good performance in terms of gain, radiating patterns and so on, which provides a new idea for the integrated design of the phased array antenna.

Keywords: phased array antenna, integrated antenna module, slotted waveguide antenna, LTCC, T/R module

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Spaceborne synthetic aperture radar (SAR) has been receiving more and more attention because of its cloud-penetrating and day and night operational capabilities. Nowadays, SAR is widely used in fields of military reconnaissance, civil construction and science research [1, 2, 3, 4, 5].

Active phased array radar has become the mainstream direction of the development of modern radar due to its outstanding technical characteristics and great potential advantages. Active phased array radar has been widely researched in terms of large action distance, strong anti-interference capacity, rapid scanning speed, flexible and variable beam forming, multi-target tracking capability and other advantages as well as the great potential advantages, it is widely applied to military affairs, navigation, communication, weather prediction and other fields [6, 7, 8, 9, 10]. As a key component of active phased array radar, T/R module is mainly used to finish the amplification of the transmitting and receiving signal, phase and amplitude

control of the transmitting and receiving signal, its performance will influence the discovery capacity of the phased array radar system, pointing accuracy, action distance and other tactical indicators [11, 12, 13, 14, 15].

With the development of modern active phased array radar of multiple application platform, more and more strict requirements are put forward for electric property, size, weight and others of T/R module. In actual circuit design, multi-chip module (MCM) [16, 17, 18, 19, 20] form and traditional structural form are difficult to meet this requirement, it is necessary to seek the new design method and design approach. LTCC technology is a multi-layer substrate process technology that appeared in the mid-1980s, it has many design advantages such as flexible design, high frequency, high Q characteristic, large wiring density, great integration and so on, it is a media substrate technology that is especially applicable to MCM assembly, and it is also a hot point of the research and development of high density three-dimensional integration technology at present [21, 22, 23].

In this work, an X-band phased array antenna with low cost and compact T/R 3D module for spaceborne SAR system is devised with a reduced overall implementation cost and rapid prototyping speed. The remainder of this paper is organized as follows: the whole system is briefly introduced in Section 2. The design details of the T/R module and antenna array are given in Section 3. Section 4 shows the simulation and measurement results of the devised system. Section 5 finally gives the conclusion.

2. Active phased array antenna architecture

The main motivation of this work is to design a active phased array antenna with compact T/R 3D module for spaceborne SAR system in X-band. The main electrical and mechanical specifications are listed as follows:

- (1) antenna system: 2-dimensional scanning solid-state phased array
- (2) operation frequency: 9.3~9.9 GHz
- (3) scan range: $\pm 20^\circ$
- (4) polarization: HH
- (5) T/R EIRP: ≥ 22.5 W
- (6) gain: ≥ 26 dBi
- (7) VSWR: ≤ 1.5 dB

Fig. 1 shows the schematic diagram of the proposed phased array antenna system. The active phased array antenna system works in X-band and in the linear polarization operation. The phased array antenna carries out the

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power amplification for the transmitted signals, radiates electromagnetic energy to the airspace, carries out the receiving of the echo signals and the low-noise amplification, and has the two-dimensional beam scanning capability. In the SAR imaging, the antenna adopts two-dimensional extended single-beam transmission, and the 10 receiving channels of the azimuth direction performs independent receiving, implementing the single send and multiple receive working mode.

Fig. 1. Schematic diagram of the proposed active phased array antenna system.

The effective aperture size of the antenna radiation array is 10.0 m (azimuth direction) and 1.997 m (range direction). The antenna, which is divided into 10 independent subarrays along the azimuth direction, in the direction of flight, as the sub-arrays 1–10. Each subarray is divided into three groups, and each group consists of 16 integrated antenna modules. This paper is focus on the performance of the integrated antenna module as shown in Fig. 1. We could estimate good performance of the whole system in advance if we could get excellent measurement of the integrated antenna module. The integrated antenna module is provided with a 1:3 power divider, a 1:3 power combiner, three T/R modules and six slotted waveguide antennas. The T/R module is composed of two channels and each T/R channel excites a slotted waveguide antenna. The integrated antenna module also contains the SMP connector, heat pipe and so on.

3. Module design

3.1 LTCC 3D T/R module

In general, T/R module includes transmission channel, receiving channel as well as power supply. T/R module has the independent transmission channel including single or multistage power amplifier circuit, and its independent receiving channel includes single or multistage low noise amplifier circuit and power amplitude limit protection circuit [24, 25].

X-band T/R module is adopted by two-channel integration design. Module is composed of divider network, two transmitting channels and receiving channels, power management circuit and logical control circuit, the working

principle of the module is shown in Fig. 2. Each channel can be independently controlled, every T/R channel includes one transmitting circuit and one receiving circuit, which can achieve transmitting and receiving mode. Another characteristic of the design principle of this paper shows a single signal is coupled on the output terminal of each channel, taken as the calibration signal, this calibration signal can effectively verify if each channel of T/R module is normal in actual work.

Fig. 2. Diagram of the proposed X-band T/R module.

As shown in Fig. 3, the gain of the receive chain of the T/R module is 31.4 dB, and the noise figure mainly depends on the first stage amplifier and the components before it, which includes the amplitude limiter, the circulator and the coupler. According to the calculations, the noise figure of the receive chain is 2.84 dB. The calculation formulas of the gain and the noise figure are as follows.

$$G_{SYS} = G_1 + G_2 + \dots + G_n \quad (1)$$

$$F_{SYS} = F_1 + \frac{(F_2 - 1)}{G_1} + \frac{(F_3 - 1)}{G_1 G_2} + \dots + \frac{(F_n - 1)}{G_1 G_2 \dots G_{n-1}} \quad (2)$$

The transmission power of the T/R module mainly depends on the last stage power amplifier. The last stage power amplifier is stimulated by 19 dBm input signal, therefor the output power of the power amplifier is 44.6 dBm, and the final output power is 43.8 dBm.

Fig. 3. Basic system specification distribution diagram.

Fig. 4 shows the exploded view of the assembled T/R module. The multilayer board is inserted and fixed to the cavity, and a metal plate is placed on top of it for mechanical protection. Four SMP connectors and a 21-pin low-frequency socket are designed at the two sides of the module.

Fig. 4. Exploded view of LTCC 3D T/R module.

3.2 Slotted waveguide antenna design

According to the overall technical requirements of the system, the antenna array is H polarized, with the signal bandwidth of 600 MHz. In order to realize the beam scanning and keep a higher radiation efficiency, the waveguide radiation array is used to optimize the input VSWR and realize the average in-band radiation efficiency of more than 80%. The waveguide radiation array is made of aluminum alloy, an integrated structure is realized, which contains the waveguide array, the T/R module and the power divider. The antenna array adopts the slotted waveguide array [26, 27, 28, 29, 30], each waveguide is composed of 16 radiation slots, and two adjacent radiation slots are in two reversed directions with each other so as to achieve mutual cancellation of cross polarization. Single slotted waveguide antenna simulation is shown as Fig. 5. The antenna array adopts the double resonator structure. The antenna array is shown in Fig. 6, when viewed from the top. The proposed antenna array is designed individually and connects with the T/R module via SMP.

Fig. 5. Single antenna simulation. Fig. 6. Array antenna structure.

3.3 Thermal management

Proper thermal design is of crucial importance for spaceborne application in which unwanted heat should be dissipated efficiently. In the spaceborne environment, the heat in the equipment can only be dissipated by thermal radiation. In order to avoid heat accumulation, it is necessary to spread the heat temperature as flat as possible on the antenna array. In the integrated antenna module, the most heat-consuming part is the power amplifier chip in the T/R module. In order to effectively dissipate the heat generated

by the power amplifier chip, the devised module uses heat pipe to quickly remove the heat generated by the chip, and coats the thermal conductive silicone grease on the surface of the T/R module to reduce the thermal resistance, thus effectively dissipating the heat.

For better demonstration, thermal simulations are conducted in ANSYS Icepak to validate the above design considerations. Fig. 7(a) shows the simulated temperature distribution of the module. In the practical application of the phased array antenna, there is a temperature environment control system. The minimum temperature of the environment is -20°C . The simulation is based on the real application scenario. The peak chip temperature is around 68°C . Fig. 7(b) depicts the transient thermal analysis result. When the module works for five minutes, the maximum temperature can be achieved in roughly 300 seconds after module starts up, fully validating the effectiveness of heat design. Then the temperature slowly drops to -20°C after the module shuts down.

Fig. 7. Thermal simulation results (a) module temperature distribution (b) transient thermal response.

Fig. 8 shows the exploded view of the integrated antenna module and Integrated design has been realized.

Fig. 8. Exploded view of the integrated antenna module.

4. Simulation and measurement results

Fig. 9 shows the photograph of the integrated antenna module. To demonstrate the functionality of the proposed phased array antenna, a prototyping system is manufactured and tested. As the photograph shown, the devised systems are measured in a microwave anechoic chamber. The required configuration commands are sent to the systems through a remote-controlled laptop.

Fig. 9. Photograph of the integrated antenna module

Simulation and optimization of the slotted waveguide antenna has been carried out by means of the HFSS software, and testing of the voltage standing wave ratio of the phased array antenna has been measured with the Agilent vector network analyzer. As shown in Fig. 10, within the range of working frequency 9.3–9.9 GHz, the VSWR in the simulation and the measurement is less than 1.5, and the test results are in good agreement with the simulation results. Slight difference is shown between the results of the simulation and the results of the test. An analysis has been performed and the possible causes have been found, which may be the deviations with the connector on the feeding and the uncertain factors during the manufacturing. Such deviations and uncertain factors are inevitable and have very small effect on the performance of the phased array antenna.

Fig. 10. VSWR of the proposed phased array antenna (simulated and measured results).

In this paper, the nearfield planar measurement system is used. The nearfield planar measurement is carried out in nearfield area of antenna radiation. In the area of three to five wavelengths of the antenna radiation, the amplitude and phase data of the antenna radiation in this area are measured. Through strict mathematical calculation, that is, the nearfield-farfield transformation, the farfield pattern of the integrated antenna module is achieved. In the measurement process of the integrated antenna module, the ampli-

tude and phase compensation of the receiving test are calibrated, then the receiving pattern test results are achieved. Because the launch power is saturated, only the phase compensation calibration is done, then the launch pattern test results are achieved.

The simulated and measured radiation patterns of the integrated antenna module at the center frequency 9.6 GHz, at different steering angles are plotted in Fig. 11. In these cases, it could be seen that the proposed phased array antenna can steer the beams from -20 degrees to 20 degrees. It could be seen that the measured radiated patterns are in good agreement with the simulated data. And, at both of transmitting and receiving states, the proposed phased array antenna keeps almost the same radiation patterns.

Fig. 11. Electronically 2D patterns of the phased array antenna at 9.6 GHz. (a) AZ_0° ; (b) AZ_{20° ; and (c) AZ_{-20° .

The simulated and measured gains at the operating frequency band 9.3–9.9 GHz of the antenna is as shown in Fig. 12. The measured gain varies from 26.5 to 27.5 dBi. Slight difference is shown between the results of the simulation and the results of the test. An analysis has been performed and the possible causes have been found, which may be the uncertain factors during the manufacturing. Such uncertain factors are inevitable and have very small effect on the performance of the phased array antenna.

The measured gains at the operating frequency band 9.3–9.9 GHz of the T/R module is as shown in Fig. 13.

Fig. 12. Gain of the phased array antenna (simulated and measured results).

Fig. 13. Gain measurement results (a) receiving channel (b) transmission channel.

The measured saturated output power at the operating frequency band 9.3–9.9 GHz of the T/R module is as shown in Fig. 14. The measured EIRP of the whole system is as shown in Fig. 15.

Fig. 14. Saturated output power.

Fig. 15. EIRP measurement.

Table I shows the performance comparison of the proposed X-band phased array antenna in similar works in literature. The proposed X-band phased array antenna is integrated with 3D T/R module which is more compact than those in [31, 32, 33]. The proposed connection mode of the X-band phased array antenna adopts SMP which has better insertion loss than SMA and RF cable in [31, 32, 33]. SMP is also very convenient for application. Thermal

Table I. Comparison with similar works in literature.

Ref.	f_c (GHz)	Bandwidth (MHz)	T/R module	Connection mode	Thermal Management
[31]	2.705	10	2D	RF cable	Cooling plate
[32]	9.6	80	2D	SMA	Cooling plate
[33]	3	1000	2D	SMA	stirling cooler
This work	9.6	600	3D	SMP	Heat pipe

management of [31, 32] adopts cooling plate and [33] adopts stirling coller. The heat pipe used in this paper realizes low cost and convenience.

5. Conclusion

An X-band phased array antenna based on LTCC 3D T/R module and slotted waveguide antenna array has been introduced in this work. X-band two-channel T/R module based on LTCC substrate technology has been devised, and the small size, low cost characteristics have been achieved. Besides, a slotted waveguide antenna was designed and connected to the proposed T/R modules to form a complete phased array antenna. Measurement results showed very good phased array antenna performances.

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