Status and Development Trend of Active Sub-arrays Structure Design in Active Phased Array Antenna

Rui Xiao*, Shouli Jiang*, Jianfeng Zhongb
Nanjing Institute of Electronic Technology, Nanjing, China

*Corresponding author e-mail: 250242323@qq.com, *jzl430@163.com, zhongjianfeng712@163.com

Abstract. Active sub-arrays structure design is an important part of phased array radar design. The basic architecture and composition are introduced, especially the different between brick, tile and chip sub-arrays are discussed. Integrated design of radiating unit and sub-array, intelligent health detection system and electromagnetic compatibility, microelectronics and topology optimization design, application of new materials, which considered to be four key technologies, are also pointed out.

1. Introduction

With the development of weaponry technology, the speed and penetration capability of aircraft, missiles and other aircraft have been significantly enhanced. Radar, as the core component of battlefield sensing and detection, undertakes important tasks such as air defense and antimissile early warning. The traditional radar using a mechanical scanning system cannot adapt to the multi-warhead, multi-target, saturated attack combat mode of modern weapons. Phased array radar can take advantage of the characteristics of multiple beams without mechanical rotation to achieve tracking of multiple targets and complete a variety of tasks such as search and guidance [1, 2].

The reason why phased array radar can achieve this function is rely on the active sub-array of a large number of internal, arrayed and integrated with thousands of transceiver modules called T/R components. As the core component of a phased array antenna, the active sub-array is the basic unit for radar transmission and reception in terms of electrical performance; from a structural perspective, the purpose of improving the structural design of the active sub-array is to achieve lightweight and modular array maintain. Discussing the integration form of the active sub-array structure and the key technologies in the future, this will be of great significance for improving radar integration and realizing radar light-weighting.

2. Basic composition of active sub-array

Active sub-arrays belong to the radar antenna front sub-system. From the layout point of view, it is generally behind the antenna radiation unit. The active sub-array can be interconnected with the antenna radiating unit through the array winding layer according to the needs; at the same time, the back end of the active sub-array needs to be interconnected with digital modules, power supply networks, liquid supply networks, etc. to achieve control, radio frequency, power supply, thermal and other interaction.

The composition of the active sub-array includes T / R components, integrated networks, sub-array power supplies, delay components, and sub-array skeletons. Among them, the T / R component is
usually a separately packaged micro-assembly integrated circuit (MMIC) module; the sub-array power supply includes primary and secondary power supplies; the sub-array skeleton often integrates liquid-cooled flow channels or air channels. The sub-array skeleton is not only the structural installation foundation of modules such as T/R components, power supplies, and time-delay components, but also the function of cooling and cooling. This is a typical structure-function integrated component.

Figure 1. Schematic diagram of the composition and position of the active sub-array.

3. Basic classification of active sub-arrays

3.1. Classification by cooling method
According to different classification standards, active sub-arrays can be classified differently. For example, according to the cooling method, active sub-arrays can be divided into liquid-cooled active sub-arrays, air-cooled active sub-arrays, and conductive active sub-arrays. Liquid-cooled active sub-arrays have the highest heat dissipation efficiency, but liquid cooling often requires a separate cooling unit and provides reliable front-surface runner channels. The advantages of air-cooled active sub-arrays and conductive natural cooling sub-arrays are that they do not need to be equipped with additional cooling units, and the heat dissipation effect is generally not as good as that of liquid cooling, which leads to increased system temperature and reduced reliability. Active modules such as components are derated, sacrificing some performance.

Many new cooling technologies have also appeared, such as two-phase flow and spray cooling. These technologies are still in the laboratory stage, and there is still a certain distance from engineering applications. The specific cooling method should be separately distinguished and designed according to the weight requirements of the front and the cooling environment conditions.

3.2. Classification by architecture system
In addition to classification based on cooling methods, more sub-array classifications can be divided into brick-type active sub-arrays and tile-type active sub-arrays according to the architectural form. The typical difference between the two is the arrangement of the T / R components: in the brick sub-array, the T / R components are arranged perpendicular to the antenna array; in the tiled sub-array, the T / R components are arranged parallel to the antenna. Generally speaking, brick active sub-arrays can be subdivided into brick-type active sub-arrays based on two-dimensional directions [3] and blade linear arrays based on one-dimensional integration [4]. The number of sub-array channels is divided according
to the requirements of the array. The general number of channels is 2n, that is, a sub-array often includes 16, 32, 64 channels. The one-dimensional array pattern after sub-array division is:

\[
F(\theta) = (E \cdot A_{SA}) \cdot A_P
\]  

(1)

in the formula:  
E represents the array element pattern;  
A_{SA} represents the array element sub-array pattern;  
A_P represents the array pattern of the terminal array behind the array [5].

Studies have shown that when the number of elements in the sub-array is too small, this is unfavorable to the weighting operation; if the number of elements is too large, increasing the pitch of the sub-array will cause excessively dense grating lobes at the element-level pattern. In the case of the same cell spacing, the number of channels in the sub-array directly determines the number of sub-arrays, the amount of internal equipment, the economy of the sub-array, and the size of the sub-array. Therefore, the determination of the internal channel number of the sub-array is the result of a joint iteration of telecommunication design and structural design.

![Figure 2](image)

**Figure 2.** a) Blade sub-array based on one-dimensional direction [4]. b) Brick sub-array based on two-dimensional direction [7].

When the radar frequency band is increased to Ka frequency band and above, the antenna unit spacing is reduced, and the traditional brick sub-array size no longer meets the requirements. The tiled sub-array is placed on the stack by the internal modules such as T / R modules, which can effectively reduce the thickness of the front and reduce the weight of the front. It should be noted that although tile sub-arrays can partially realize the lightweight of sub-arrays, tile sub-arrays and chip sub-arrays are not the same concept: tile sub-arrays are still tiled stacks based on SOP packaging modules. The sub-array is a system integration based on the micro-system SIP independent packaging module, which has a higher degree of integration and integration. The realization of the chip sub-array depends on the maturity of the packaging process such as chip-based chip T / R components and TSV based on SIP packaging.

![Figure 3](image)

**Figure 3.** Tiled active sub-array [8].
4. Active Sub-array Development Trend
With the development of phased array radar in the past ten years, the internal composition of active sub-arrays has become more and more complex, and digital parts such as frequency conversion modules have been moved forward and integrated into the sub-arrays, which places higher requirements on structural design. The four key technologies of the active sub-array that need to be developed are discussed below.

4.1. Integrated design of radiating unit and active sub-array
In a general sense, the sub-array and the antenna radiating unit are physically separated, and the middle is interconnected by a winding layer. With the development of 5G communication, the research of millimeter wave and terahertz radar has been deepened, and the loss and standing wave degradation caused by the interconnection between the sub-array and the antenna radiating unit through the winding layer are no longer accepted. The antenna radiating unit has the original form of a horn and a metal vibrator, and it is developed to a high-frequency printed board vibrator and a patch antenna. The antenna radiating unit and the sub-array need to realize the transition through integrated design integration and blind plug connectors. This design can reduce antenna weight and thickness. Active sub-array and radiating unit integrated design also need to consider the forward and backward maintenance in advance. Generally speaking, the spherical radome does not have high requirements for the forward or backward maintenance of the sub-array, and both can be implemented; the flat-type radome requires that the sub-array can be designed to perform rearward maintenance from the hatch.

During the integrated design of the radiating unit and the active sub-array, higher requirements are placed on the interconnection method within the sub-array. Conventional SMP, BMA and other blind plug forms, or SMA cable assembly link forms are gradually replaced by SSMP\CSMP, and the use of wool buttons to achieve inter-plane interconnection is gradually being applied. No matter what kind of interconnection is mentioned above, interconnection reliability (especially reliability under comprehensive stress environment) needs to be taken seriously.

4.2. Intelligent health monitoring system and electromagnetic compatibility design
The active sub-array integrates many sensitive modules such as T / R components. The reliability of these modules is largely dependent on temperature. These modules also need to avoid risk factors such as leakage. This means that the health monitoring of sub-arrays and the detection of hidden dangers to avoid greater losses need to be promoted to an increasingly important position. The first is the monitoring and feedback of the sub-array temperature. According to the classic theory of electronic modules, the reliability decreases by 50% during every 10 °C increase in temperature. During the structural design of the active sub-array, the temperature sensor is usually placed in the water inlet and outlet of the sub-array hanger. The temperature and temperature difference of the water inlet and outlet are monitored to adjust the liquid supply situation of the entire array to improve the overall temperature consistency of the array. In addition to the external temperature sensor of the sub-array, the multi-function chip inside the T / R module sometimes integrates the temperature detection function as required. This integration can more accurately reflect the temperature information of the single channel inside the module, and the back-end controller can intuitively read it. Security situation of the entire sub-array and antenna.

In addition to temperature detection, multiple leak detection sensors will be integrated in the sub-arrays of the blindly inserted interconnects, which can detect early and detect the presence of water in the array in time to avoid short circuits caused by leaks or water. At present, leak detection is generally collected through leaks, and only when there is fluid accumulation. In this case, the sub-array leakage has occurred for some time and may have caused losses. Therefore, where to arrange in the sub-array and through what kind of structure to achieve rapid collection of leaks to reach the alarm threshold as soon as possible, this tests the experience and wisdom of the sub-array structural designer. Temperature and leakage are typical health monitoring items. Now when the radiating unit is integrated with the sub-array, in order to monitor the deformation of the antenna radiating unit, mechanical and deformation
monitoring sensors are also integrated inside the sub-array. It is common to attach strain gauges. Through the monitoring of stress and strain, it is timely found whether the sub-array has abnormal damage during the service process, and real-time electrical signal compensation based on the deformation of the array is realized through back-end control according to this [9].

4.3. Application of micro-system and topology optimization in sub-array design
In recent years, micro-systems have received extensive attention in the design of phased array radars [10], and the core of which is the integrated implementation of 3D heterogeneous heterogeneity [11]. In the active sub-array, the module system-level package (SOP) such as T / R components is developed to a micro-system-based sub-array system-level package (SIP). The sub-array-level SIP system integration is different from the SOP package of the component: the SIP-based integration method is for the pursuit of functional and application integrity, which is consistent with the sub-array's complete telecommunications and structural function requirements, especially the sub-array and patch antenna units Integrated design.

The large number of applications of TSV technology in micro-system architecture put forward higher requirements for thermal stress modeling and topology optimization, and thermal simulation and optimization represented by micro-channels [12].

5. Conclusion
In this paper, the common architecture, classification, and composition of current phased array radar active sub-arrays are introduced, and the trend of subsequent sub-array structure design is proposed, and the matters needing attention are summarized. The structural design of the phased array radar active sub-array needs to be involved in the initial arrangement of the antenna array. It is determined together with the array scheme, and the optimal cooling form and layout scheme are selected. At the same time, the electromagnetic compatibility of each internal module is considered in advance. As the main hardware component of the antenna array, the active sub-array is not only a mechanical arrangement in the integrated design, but also needs to solve the problems of heat, force and electromagnetic compatibility. The design attention points and ideas mentioned in the article are not only applicable to the current brick, tile, or chip sub-arrays, but also have reference for the sub-array and front design of the highly integrated micro-system architecture.

References
[1] Fan H T, Yan J. Development and outlook of active electronically scanned array guidance technology, Acta Aeronautica et Astronautica Sinica, 2015, 36(9):2807-2814.
[2] SHAO Chunsheng. Study Status and Development Trend of Phased Array Radar, Modern Radar, 2016, 38(6):1-4+12.
[3] Tang Baofu, Zhong Jianfeng, Gu Yeqing. Design of Active Phased Array Radar Antenna, first, Xi’an, 2014( in Chinese).
[4] Cui Min, Zhang Juan, Design of a C-band Transmitting-receiving Sub-array System, Fire Control Radar Technology, 2014, 43(2):72-76.
[5] Arik D. Brown. Electronically Scanned Arrays: MATLAB Modeling and Simulation, CRC Press: New York, 2010.
[6] CHEN Jian-feng, WU Hai. Research into Subarray Division Technology Based on Overlapped Subarray Architecture, Shipboard Electronic Countermeasure, 2016, 39(1): 95-98.
[7] Gu Ye-qing, Yao Ye, Wang Chao, Integration Design of Active Phased Array Antenna, Electro-Mechanical Engineering, 2016, 32(6):29-32,40.
[8] Li Gang, Li Tao, Research on Smart Skin Technology of Tile Radar in Helicopter, Fire Control Radar Technology, 2018, 47(01): 28-31.
[9] Tang Baofu, Gu Yeqing, Wang Chao, A Study on the Applications of Intelligent Structure in Phased Array Antenna, Modern Radar, 2014, 36(11): 8-11.
[10] Tang Weiqiang, Applications of Microsystem Technologies in Radar System and Related
Oversea Research Status, Electro-Mechanical Engineering, 2016, 32(6): 21-23+28.

[11] QIN H, YAN Z, SU D, et al. Electromagnetic susceptibility analysis method for 3D TSV ICs, Journal of Beijing University of Aeronautics and Astronautics, 2017, 43(12): 2406-2415.

[12] Ran Hong-lei, Peng Hao, Huang Jie, Research on TSV Technology in 3D Packaging Microsystem, Electronics Quality, 2018, 12, 111-115