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Review:

Engineering applications and technical challenges of active array microsystems*

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Abstract: In the post-Moore era, the development of active phased array antennas will inevitably trend towards active array microsystems. In this paper, the characteristics and composition of the active array antenna are briefly described. Owing to the high efficiency, low profile, and light weight of the active array microsystems, the application prospects and advantages in the engineering of multi-functional airborne radar, spaceborne radar, and communication systems are analyzed. Moreover, according to the characteristics of the post-Moore era of integrated circuits, scientific and technological problems in the active array microsystems are presented, including multi-scale, multi-signal, and multi-physics field coupling. The challenges are also discussed, such as new architectures and algorithms, miniaturization of passive components, novel materials and processes, ultra-wideband technology, and new interdisciplinary technological applications. This paper is expected to inspire in-depth research on active array microsystems.

Key words: Microelectronics; Heterogeneous integration; Packaging materials; Antenna array microsystems; Multi-functional radar; Communication

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1 Introduction

Most active phased array systems are high-power and functionally complex systems, which are complete systems integrating various circuits, modules, and interconnections. Conventional active array systems have a low level of integration and are easy to implement technically. Although the active phased array systems using the aforementioned integration methods are separate, they have been miniaturized rather than using traditional discrete devices and circuits, resulting in a smaller size and lighter weight.

In the 21st century, active array antennas are the preferred system for a new generation of radar/communication systems. The requirements for their volume, power consumption, performance, reliability, and cost are becoming increasingly stringent, as shown in Fig. 1. Therefore, the active phased arrays are being rapidly iterated and advanced high-density integration technology is being introduced to achieve the characteristics of multi-functional integration, large-aperture and low-profile appearance, broadband wide scanning angle, high efficiency, short development cycle, low cost, and so on (Lu et al., 2021). To achieve this goal, a high level of integration is required, and various functional chips and electronic components should be highly integrated, which will significantly contribute to the development of active array microsystem technology.

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Limited by the traditional relationship between antenna gain and aperture size, the miniaturization of active array systems has focused on reducing the profile thickness of the antenna. In Table 1, the relationship

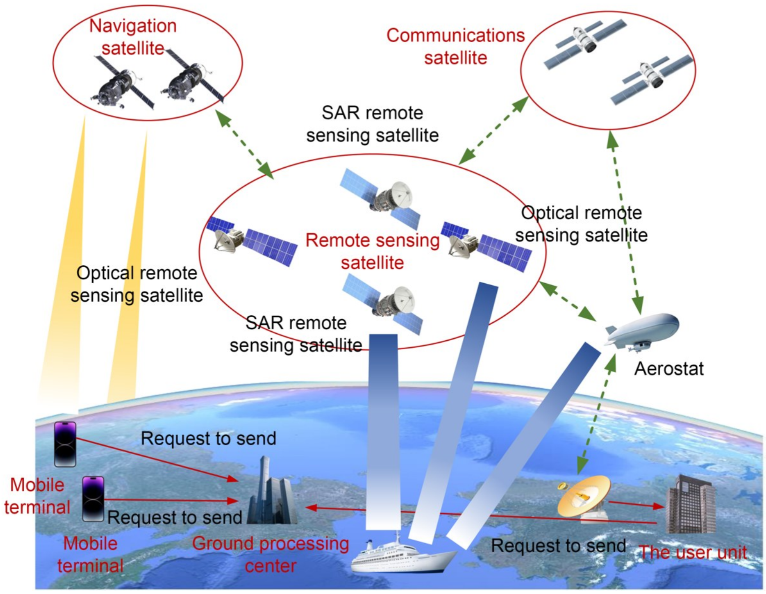

Fig. 1 Applications of active array antennas in radar/communication systems (SAR: synthetic aperture radar)

Table 1 Relationship between active array antennas and radar/communication systems

Feature	System benefit	Mechanism analysis
Broadband, high efficiency, multi-channel, and high power-aperture product	(1) Increasing the radar range, and improving the positional accuracy of detection targets and target resolution accuracy (2) Improving communication for high-capacity data transmission	(1) The power-aperture product is proportional to the radar range (2) Large signal bandwidth is the foundation of high resolution (3) High performance communication through multi-beam, multiplexing, and multi-channel echoes
Multi-band and multi-polarization	(1) Radars obtaining the information of frequency and polarization to improve target detection and recognition capabilities (2) Improving the ability to transmit information, ensuring the integrity of the information transmitted, and enhancing the anti-interference ability	(1) Using the subtle differences in target scattering characteristics under different wave bands and polarization electromagnetic waves to obtain a more complete fusion image of target information
High channel isolation	(1) Reducing the crosstalk of the accompanying signals to the main signal (2) Improving the main polarization/frequency band/the purity of channel information, and improving radar detection performance and communication quality	(1) Reducing polarization, frequency band, and channel coupling is the foundation for improving isolation, such as the distributed feeding of array antennas, which facilitates high isolation among channels
High efficiency, low profile, and light weight	(1) Improving the system sensitivity, and enhancing the adaptability of active array antennas to the space platforms (2) Decreasing the platform development and the launching cost	(1) Effectively using the platform power with high efficiency, and reducing power and thermal design costs (2) Low profile and light weight can facilitate platform loading and help to meet satellite launching envelope requirements

between active array antennas and radar/communication systems is shown. Especially in the ultra-wide band and low-wave bands, the thickness of the antenna profile becomes larger due to the longer wavelength, resulting in significant difficulties for the active array antenna layout. Additionally, due to the high profile thickness of the antenna and the constraints of the launch vehicle envelope, the development of spaceborne large-aperture active array antennas is severely limited, and the high-profile thickness has a negative impact on the aerodynamic shapes of missiles and airplanes moving at high speeds. Therefore, the active array microsystems should focus on low-profile and broadband characteristics.

The active array microsystems share common features with conventional microsystems, including miniaturization, integration, and intelligence (Lu and Wang, 2020). While conventional microsystems aim to reduce their sizes and weights through three-dimensional (3D) reduction, active array microsystems have their own unique architecture and integration methods. To maintain the advantage of antenna gain, the profile thickness and weight of the antenna should be minimized within the given aperture size. Therefore, the active array microsystems focus on improving performance, such as by reducing radio-frequency (RF) loss and profile thickness, to enable large-aperture active array antennas to be foldable and conformal.

2 Principle and structure

As shown in Fig. 2, active array antennas are usually composed of transmitter/receiver (T/R) modules, delay lines, amplifiers, down-converters, high-speed acquisition circuits, excitation up-converters, waveform generators, frequency sources, power combiners, etc. In terms of functional composition, active array antennas are generally classified into passive antenna arrays, passive circuits, active circuits, power supply circuits, and control circuits. The general implementation path of a high-efficiency, low-profile, and light-weight active array antenna is illustrated in Fig. 3. Additionally, multi-functionality, intelligence, low power consumption, and high reliability are crucial research topics.

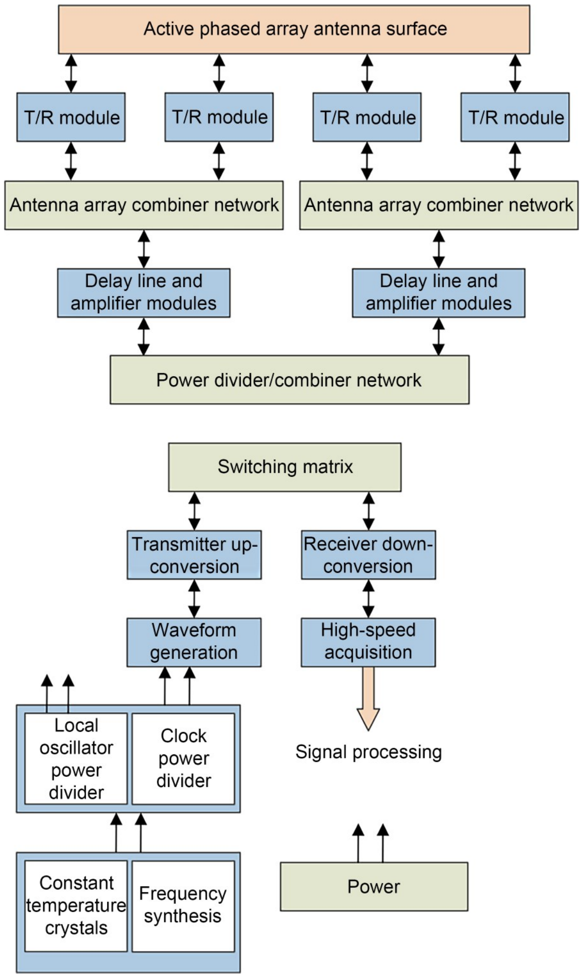

Fig. 2 Functional composition of an active phased array antenna (T/R: transmitter/receiver)

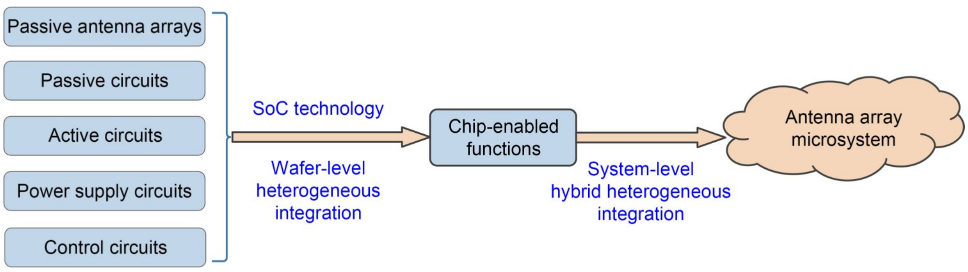

Fig. 3 Implementation path of a high-efficiency, low-profile, and light-weight active array antenna (SoC: system-on-chip)

From an engineering perspective, a typical active array microsystem is usually composed of five transmission flows: the first one is the signal flow, which includes the generation, conversion, amplification, transmission, emission, and reception of signals. The second one is the information flow, including signal flow control, hardware status monitoring, system status monitoring, and compensation. The third one is the power supply flow, which contains voltage conversion, energy distribution, filtering, etc. The fourth one is the force conduction flow, consisting of thermal stress, vibrations, and shocks. The fifth one is the heat transport flow, in which heat transfer, thermal interface matching, heat dissipation, and heat sinking are included.

2.1 Passive antenna arrays

For an antenna array consisting of multiple antenna elements that are arranged with certain layout rules, its bandwidth can be influenced by the mutual coupling between the antenna elements and the parasitic resistance effects of the metal reflector (Langley et al., 1996; Shin and Schaubert, 1999; Hansen, 2003; Munk et al., 2003; Doane et al., 2013; Lu, 2017; Fang et al., 2018; Lu et al., 2019). Due to the incompatibility between the low-profile thickness and large frequency bandwidth of active array antennas, decoupling structures, absorbing materials, and large spacing between the array elements are commonly employed to reduce the coupling effect in the layout of broadband array antenna elements (Hansen, 2004; Moulder et al., 2013; Lu et al., 2020; Qian et al., 2021). Typically, array antennas are equipped with metal reflectors, which can effectively suppress backscatter and improve the gain of the array. However, the bandwidth of the array is seriously limited due to the parasitic reactance caused by the metal reflectors (Lu, 2001; Holland and Vouvakis, 2012; Logan et al., 2018; Lu et al., 2022).

In Tables 2 and 3, the operating bandwidth, scanning angle, profile thickness, cross-polarization, and radiation efficiency of the commonly tapered slot and tightly coupled dipole array antennas are compared (Langley et al., 1996; Lu, 2001; Hansen, 2003, 2004; Munk et al., 2003; Holland and Vouvakis, 2012; Moulder et al., 2013; Syed and Neto, 2013; Logan et al., 2018; Novak et al., 2018; Lu et al., 2020, 2022; Qian et al., 2021).

2.2 Passive circuits

Passive circuits are usually combined with active devices to form functional modules in active array microsystems, such as digital, power, and RF modules. These modules include energy storage capacitor arrays, filters, matching networks, resonators, etc., as shown in Fig. 4.

In Table 4, the number of components in six typical microwave transceiver front-end modules is listed; passive components account for more than 70% of the total number of components, over 50% of the total area, and around 40% of the total cost. Therefore, the performance, profile thickness, reliability, and cost of the active array antennas are significantly influenced by the passive components.

Table 2 Characteristics comparison of the tapered slot array antennas

Antenna type	Operating bandwidth (octave)	Scanning angle (°)	Profile thickness* (λ_H)	Cross-polarization (dB)	Radiation efficiency
Vivaldi antenna	≥10:1	≥45	2–3	≤−10	≥50%
Antipodal Vivaldi antenna	≥4:1	≥45	0.5	≤−10	≥70%
Balance antipodal Vivaldi antenna	≥4:1	≥45	0.5	≤−15	≥55%
Banyan tree antenna	≥3:1	≥45	0.5	≤−10	≥90%

* Expressed in electric length

Table 3 Characteristics comparison of tightly coupled array antennas

Antenna type	Operating bandwidth (octave)	Scanning angle (°)	Profile thickness* (λ_H)	Cross-polarization (dB)	Radiation efficiency
Tightly coupled dipole	≥46:1	≥60	≥1	≤−10	≥50%
Integrated with Balen	≥9:1	≥60	About 0.5	≤−10	≥90%
Planar modularity	≥6:1	≥60	About 0.5	≤−10	≥90%

* Expressed in electric length

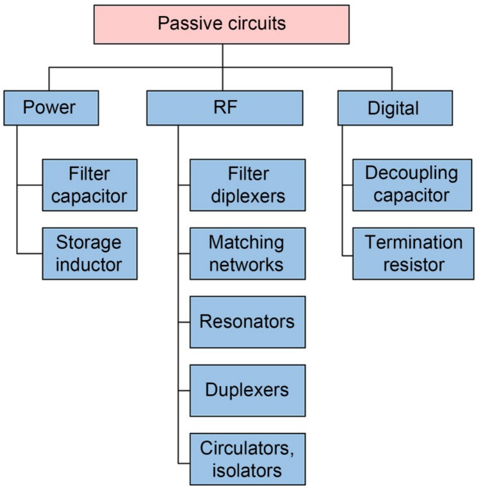

Fig. 4 Types of the common passive circuits (RF: radio-frequency)

Driven by Moore's law, conventional microsystems cannot continue to be reduced in size at the same rate due to the difficulty of miniaturizing passive circuits. For example, the traditional active array antenna is a brick structure, which is integrated with various active functional modules, passive antenna arrays, and passive discrete circuits. This significantly limits the reduction of the profile thickness of the active phased array antenna.

Integrated passive devices (IPDs) have small sizes and a high level of integration (Le Coq et al., 2015; Zheng and Sheng, 2017; Hannachi et al., 2018; Zhu and Wang, 2023b), which provide a better system performance than surface mounted devices (SMDs). It is a lower-cost option compared with the integration of passive components on active integrated circuits (ICs). Embedded IPDs, which integrate stacked passive components with high-density laminates, can effectively reduce system size and parasitic effects, thus improving system performance (Sabharwal et al., 2014; Reiskarimian et al., 2017; Zhu et al., 2018; Shen and Zhu, 2020).

2.3 Active circuits

The active circuits in the active array microsystem are mainly composed of high-efficiency, high-power, ultra-broadband, multi-function, and small-signal multi-functional circuits, including various types of amplifiers and control circuits (Lu et al., 2013). A typical transceiver multi-functional circuit is depicted in Fig. 5.

In high-power circuits, GaN microwave power devices are the third generation of wide band-gap semiconductor devices. Due to the high saturation electron drift rate, GaN high electron mobility transistors (HEMTs) have the advantages of high operating voltage, high operating frequency, high power, etc. The double-field plate structure can be used to reduce the peak electric field at the gate edge of the transistor and improve the uniformity of the channel electric field distribution and the voltage withstanding capability, which can meet the breakdown requirements of high-power switches (Herd and Conway, 2016).

For ultra-wideband multi-functional circuits, power amplifiers, low-noise amplifiers, and high-power switches are integrated into a monolithic ultra-wideband GaN RF transceiver front-end circuit to meet the demand of high power and small antenna element spacing (Cho et al., 2012; Singh and Kukal, 2020). The broadband GaN monolithic microwave integrated circuit (MMIC) T/R module integrates high-power switches to replace the conventional circulator. The insertion loss of high-power switches must be equal to or even smaller than that of the available conventional circulator. Reducing losses that are caused by ohmic contact resistance is essential to improving the performance of switch circuits.

In small-signal multi-functional circuits, for the switch circuit on a multi-functional chip, suitable circuit topologies are selected to effectively extend the operating bands, reduce the insertion loss, and improve

Table 4 Number of components in six typical multi-channel microwave transceiver front-end modules

Serial No.	Number of active chips	Number of passive chips	Number of power modulation chips	Number of resistors and capacitors	Total number	Percentage of resistors and capacitors	Percentage of passive components
1	24	19	25	107	175	61%	72%
2	12	7	10	59	88	67%	75%
3	8	6	8	56	78	72%	79%
4	56	38	75	279	448	62%	71%
5	52	18	22	228	320	71%	77%
6	58	50	45	476	629	76%	83%

the isolation and the power characteristics (Zhu et al., 2021a). For the receiver channel, the traveling wave structure, multi-stage cascade structure, and novel circuit topologies are studied to optimize its noise performance (Bahl, 2009).

2.4 Power supply circuits

Power supply circuits are the essential components in active array microsystems, as they convert the input direct current (DC) voltages to various lower DC voltages of the system. Typically, these circuits consist of switching power transfer and rectifier filter circuits, and provide power supply for chips, modules, and systems. Power conversion circuits integrate power switches, energy storage and transmission circuits, logic control circuits, and passive components to provide one or more energy sources with different voltages and powers (Tang et al., 2019).

As shown in Fig. 6, by means of surge suppression, switching conversion, isolated transmission, rectification filtering, and voltage regulation, the power supply circuit can provide different output DC voltages, such as +28 V, +5 V, and −5 V, to the T/R modules, driving circuits, and array control circuits of the active array antennas.

There are several power supply circuit topologies, including single-ended forward, single-ended backward, push–pull, half-bridge, and full-bridge (Nishikawa et al., 2006; Kapat, 2017; Fei et al., 2018; Li et al., 2018). The characteristics of typical power supply circuits are listed in Table 5. To meet the demand of a smaller size, higher power density, and faster dynamic response characteristics of switching power supplies, the operating frequency of these circuits has shifted from the early tens of kHz to several MHz in recent years.

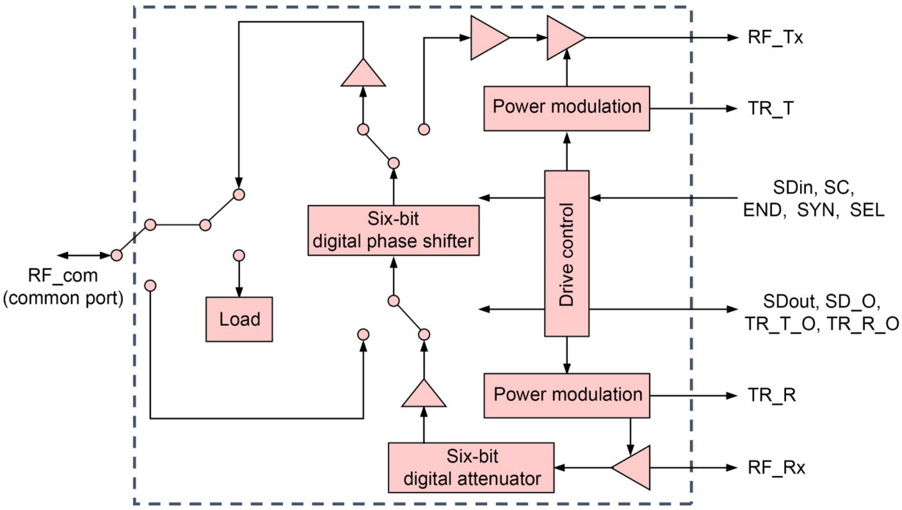

Fig. 5 Composition of a typical transceiver multi-functional circuit

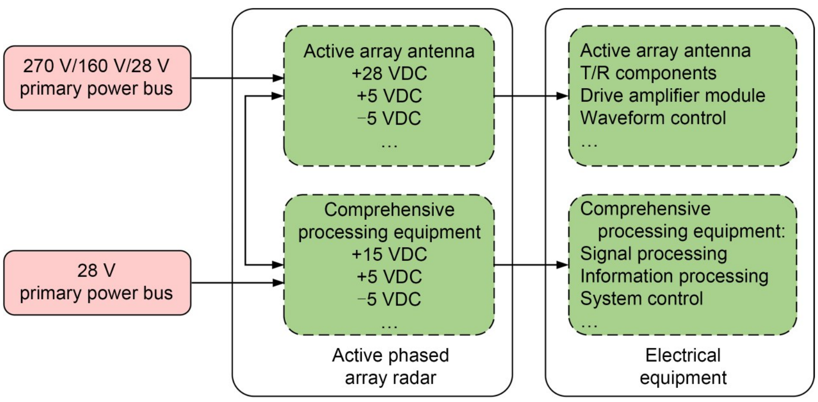

Fig. 6 Typical power supply systems in active phased array radars (T/R: transmitter/receiver)

Table 5 Characteristics comparison of typical power supply circuits

Circuit form	Advantage	Disadvantage
Single-ended forward	Continuous current output and good ripple control	The transformer requires a magnetic reset, and the switching transistor stress is twice of the input voltage
Single-ended backward	Simple design of high-frequency transformers and simple filter circuits	Low transformer winding utilization
Push–pull	Easy to drive switching transistors and easy to be driven	The switching transistor stress is twice of the input voltage
Half-bridge	Simple high-frequency transformer, switching transistor voltage stress equal to input voltage	The supply voltage utilization is low, and it is not suitable for applications with low-voltage input
Full-bridge	Simple high-frequency transformer, switching transistor voltage stress equal to input voltage, high output power, high efficiency	The driving circuit is complex and requires four switching transistors

2.5 Control circuits

As shown in Fig. 7, the control circuit is responsible for the beam control of the phased array antenna, which is employed for the two-dimensional (2D) electronic scanning and beam shaping. The beam control circuit receives beam scheduling instructions from task management and performs the following functions according to the instructions (Charlish et al., 2015): (1) generating antenna beam control codes based on the beam pointing angle and storing compensation codes; (2) completing the distribution and deployment of beam control codes in a given time; (3) switching the beam under the control of timing pulses; (4) providing telemetry functions, such as supply voltage, array temperature, and component BIT; (5) furnishing self-protection functions such as over-pulse width detection and transceiver timing error protection.

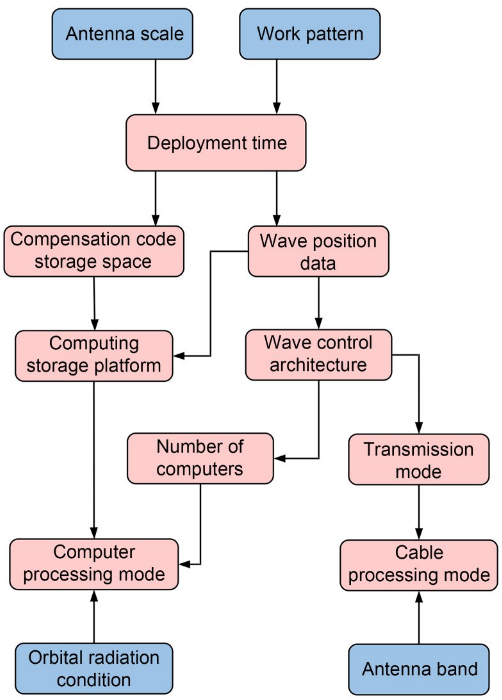

Fig. 7 Operating principle of the antenna beam controller

As the aperture size of the antenna increases, the number of beam positions is also increased to lead a heavier and more power-consuming control circuit. There are several measures that improve the performance of control circuits and reduce their weight and power consumption (Jeauneau et al., 2014; Han et al., 2018): (1) Optimize the configuration of control circuits, such as how to divide the functional modules and how to accomplish the required tasks with a minimum number of modules (at the same time, reliability problems should be considered with system engineering); (2) Improving system integration and vertical interconnection technology can significantly reduce the numbers of connectors and cables, which is one of the important ways to reduce the weight of the control circuit; (3) Miniaturizing control circuits is another approach to reducing the weight and power consumption.

3 Research status and development trends

3.1 Integrated microsystems

As physical sizes approach their limit, the development of semiconductor technology can no longer follow Moore’s law, and semiconductor processes are reaching a bottleneck. In the post-Moore era, various integration technologies, such as system-in-package (SiP), system-on-package (SoP), and 3D heterogeneous integration technology, have been proposed to cope with the physical bottleneck of the semiconductor process. The above technologies extend the functionality of the chip to achieve vertical space utilization in the form of chip stacking. Moreover, 3D high-density integration can be achieved by integrating devices with different functions in the vertical direction (Gupta and Hall, 2000; Baggen et al., 2013; Zhu et al., 2022).

From the perspective of technological evolution, microsystems develop from systems on chips, microwave photonic microsystems, microelectromechanics, and SiP/SoP. Based on the multi-chip module (MCM), several chips of the same or different types of passive circuits are integrated to form more complex microsystems.

In terms of technological developments, microsystem technology is developing towards miniaturization, intelligence, and spectrum expansion utilization. Miniaturization enables the higher integration of multiple application systems, reduces costs and power consumption, and expands the range of applications. Intelligence can allow multiple application systems with high autonomy to be adapted to a wider range of application scenarios and environments, which can greatly expand the field of application and drive innovation on various platforms. Spectrum expansion utilization can help to expand the operating frequency bands of microsystems and improve the performance of electronic information systems (Beer et al., 2012; Zhu and Wang, 2023a; Zhu et al., 2023).

The intelligence of the antenna microsystem combines mainly the active array microsystem itself and external characteristics to optimize the parameters as well as to improve the performance of the antenna system. The principal challenges are as follows:

1. Adaptive beam steering

RF signals are monitored in real time and analyzed to dynamically optimize the system performance. Adaptive beamforming is achieved by integrating adaptive control algorithms in microsystems and adjusting the beam pointing and shape of the antenna array. According to the change of the electromagnetic environment, the position and number of beam zeros are dynamically adjusted.

2. Spectrum sensor and dynamic spectrum management

By using spectrum sensor technology, intelligent signal processing is employed to fully exploit existing spectrum resources, enabling research in cross-band, multi-band, and spectrum-sharing technologies. Receiver performance is improved via the implementation of techniques such as the selective reception of wideband signals, diversity, and signal merging. Moreover, the spectral efficiency is improved through the utilization of multiplexing technology.

In view of the approach to integration, microsystems can realize multiple functions in a single-chip and multi-chip integration by means of 3D through silicon via (TSV). Based on the MCM, package on package (PoP) and 3D heterogeneous integration can be further investigated. Fig. 8 shows the typical integration methods used in microsystems (Babakhani et al., 2006; Baggen et al., 2006; Lau et al., 2018).

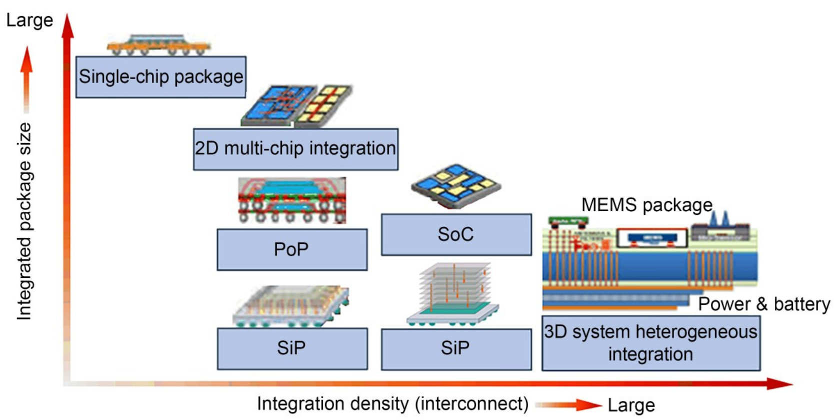

Fig. 8 Typical integration methods used in microsystems (PoP: package on package; SoC: system-on-chip; SiP: system-in-package; MEMS: micro-electro-mechanical system)

Moreover, in consideration of the application requirements, microsystem technology is evolving towards multi-functional integration, 3D stacking, hybrid heterogeneous integration, intelligent sensing, and so on. Microsystem products are also developing from the chip- and module-level to more complex system-level applications. Microsystems can be categorized into three types: system-on-chip (SoC), which is the integration of microsystems on a single chip; system-on-board (SoB), which is the integration of microsystems through hybrid integration and 3D heterogeneous technologies; system-level microsystems, which can perform specific system-level functions, such as the active phased array systems and high-performance computing platforms.

3.2 Active array microsystems

Traditional active array antennas are brick structures, which integrate passive antenna arrays with a variety of functional modules. With the development of semiconductor technology and advanced packaging processes, the technology and architecture of the active array antennas are changing continuously (Fig. 9). The technological evolution paths of several typical architectures are presented in Fig. 10, while the typical performance parameters for X-band active array antennas are listed in Table 6.

The tiled active array microsystems dedicatedly pursue a reduction in profile height and an increase in mass area density efficiency. The system integrates signal generation, frequency conversion, amplification, and transmission circuits, in addition to components related to antenna radiation, heat transfer, and mechanical support structures. Fig. 11 shows the research progress of several different X-band array microsystems.

Fig. 11a shows the initial active array microsystem module. This approach has achieved technical and engineering maturity and is characterized by an MCM

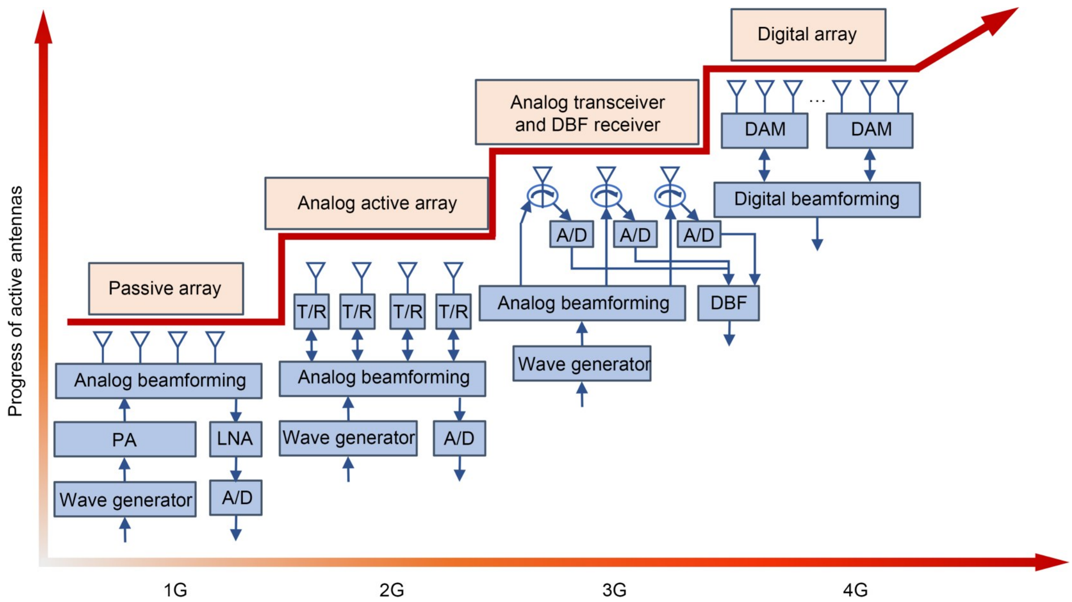

Fig. 9 Technology development route of active array antennas (PA: power amplifier; LNA: low noise amplifier; A/D: analog to digital; T/R: transmitter/receiver; DBF: deblocking filter; DAM: driver amplifier module)

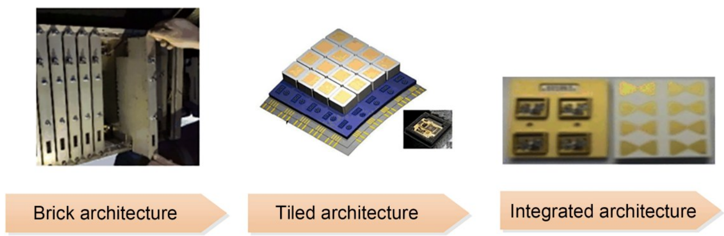

Fig. 10 Technological evolution paths of several typical active array antenna module architectures

Table 6 Performance comparison of several typical architectures for active array antennas

Architecture	Relative bandwidth (%)	Insertion loss (dB)	Profile thickness (mm)	Weight (kg/m^2)
Brick	15	2.0	300	120
Tiled	5	0.5	48	50
Integrated	3	0.3	15	15

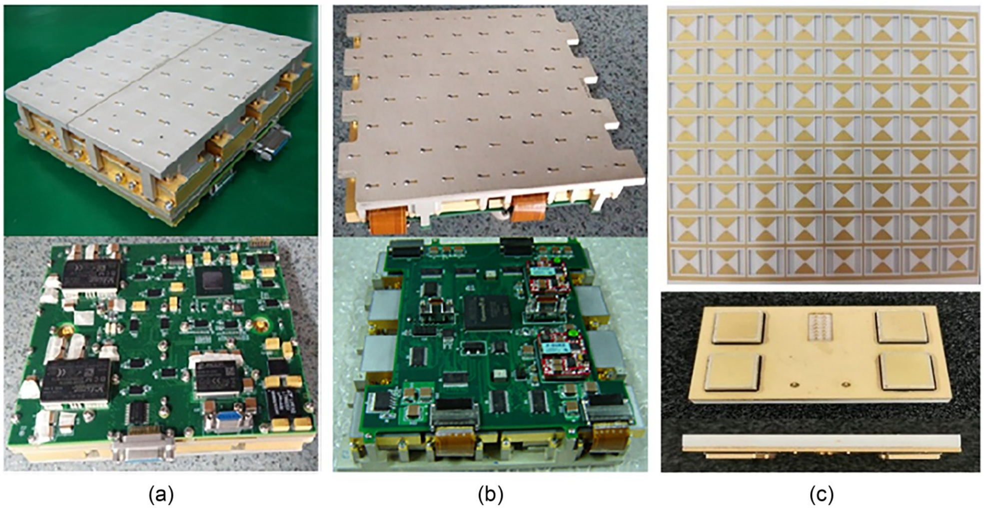

Fig. 11 Research progress of X-band tiled active array microsystems: (a) the profile thickness is about 60 mm, and the mass surface density is lower than 80 kg/m^2; (b) the profile thickness is about 35 mm, and the mass surface density is lower than 33 kg/m^2; (c) the profile thickness is about 15 mm, and the mass surface density is lower than 16 kg/m^2

integration strategy. The digital–analog hybrid circuits, such as power supply modulation, control storage, tantalum capacitance, and resistor components, are harmoniously integrated using multi-layer printed circuit board (PCB) technology. Subsequently, these circuits are cascaded with antenna modules through subminiature version A (SMA) connectors. This technology has found successful applications in high-power electronic systems employed in ground-based and airborne platform radars.

Fig. 11b shows a typical hybrid integrated active array microsystem architecture. The corresponding functional circuits are designed according to the characteristics of different materials. Digital control circuits, high-power amplifier circuits, T/R modules, and heat dissipation modules are integrated through SiP technology, which can form an integrated active array microsystem. It is suitable for small unmanned aerial vehicle (UAV) borne radar systems and missile-borne guidance radar systems.

To meet the requirements of lighter, denser, and more complex functions, 3D hybrid high-temperature co-fired ceramic/low-temperature co-fired ceramic (HTCC/LTCC) and silicon-based packaging integration technologies are further applied. Different functional circuits are stacked vertically through micro-bumps, TSV, ball grid arrays, re-distributed layers, and other processes, which can effectively reduce the interconnection loss of high-density signals. Finally, a lightweight active array microsystem with integrated software and hardware, low cost, and high integration is realized.

Fig. 11c shows the most recent advancement, a 3D hybrid HTCC/LTCC active array microsystem module. Based on the multi-layer heterogeneous ceramic co-firing technology, antennas, active multi-function RF chips, and high-speed digital control chips are embedded in HTCC/LTCC using micro-assembly technologies such as 3D chip stacking. To ensure efficient heat dissipation, microfluidic channels are incorporated into the multi-layer ceramic substrate. This innovative approach can effectively address the requirements of compact and light-weight radar/communication systems for micro platforms, and is also suitable for the development of electronic information systems for spaceborne aircraft.

With the development of micro- and nano-scale theories, and the benefits from the electromagnetic field, microelectronics, optoelectronics, materials, and thermodynamics, a 3D hybrid heterogeneous integration can be realized to integrate an active array antenna, an active transceiver channel, a power divider/combiner, a frequency synthesizer, a beam controller, a power supplier, and a thermally conductive structure in distributed and open architectures (Fig. 12).

3.2.1 From independent design reintegration to system integration design

Active array microsystems are different from conventional ones in design routes. With the advancement of technology, it is possible to move beyond module-level integration to the chip level, directly combining passive circuitry and passive antennas into active array microsystems, with great progress in the integration, reduction of profile thickness, and improvement of performance parameters (Fischer et al., 2014; Lu, 2019).

The design route of active array microsystems is characterized by two typical features: multidisciplinary co-design and system integration design. The former involves the combination of various design aspects, such as electrical characteristics, system configuration, mechanical structure, and thermal designs. The latter emphasizes collaborative design by different levels, with a system designer as the primary designer and technical support from other designers. This approach eliminates the hierarchical design approach and emphasizes the importance of system integration.

Independent design is not preferred for active array microsystems. Integration design reduces the profile thickness, the length of interconnection, the number of relay points, and the length of the signal transmission path in the system. The smaller interline capacitance is achieved by shorter wires, reducing the interline crosstalk of the signal.

3.2.2 From staged test and alignment in traditional development to accurate system simulation

The active array antenna is a complex piece of electronic equipment (Zhu et al., 2013), which covers multiple disciplines, including electromagnetic fields, temperature fields, and displacement fields. The traditional active array antenna architecture is designed by discrete integration of single-functional modules, and the cross-coupling of multi-physics fields is weak. The conventional design includes multi-module independent design, combined installation, debugging test, local alignment/adjustment, and so on.

In active array microsystems, a large-scale antenna and many micro-sized chips are integrated in a single package to form an integral module. In this module, multiple signals are transmitted from one transistor on a chip to another transistor on another chip and then to the system. The signal can be transmitted only when the appropriate power is supplied to each transistor.

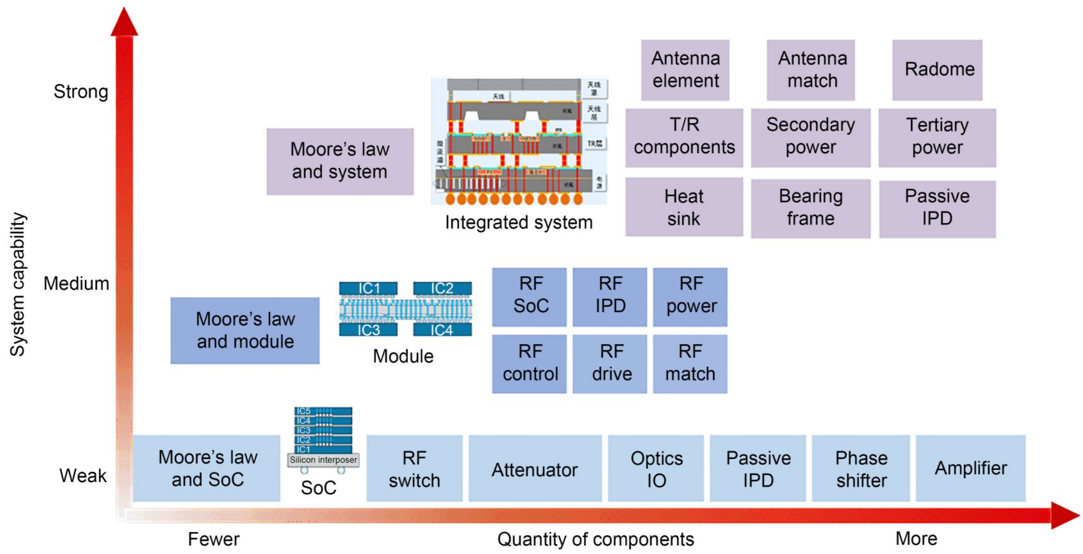

Fig. 12 Relationship between Moore's law and integrated microsystems (SoC: system-on-chip; RF: radio-frequency; IC: integrated circuit; IPD: integrated passive device; IO: input/output; T/R: transmitter/receiver)

However, this power supply distribution poses a number of challenges. The transmission path and resistances from the power supply to the transistors are different, causing different voltage drops. Moreover, the signal distribution introduces several problems, such as “crosstalk” between signal lines, as well as signal distortion, reflection, and alternation.

For antenna microsystem modules, coupling and entanglement effects are observed between the radiated electromagnetic fields of the large-scale packaged antenna and the chips of different scales and functions. In particular, as the operating frequency of analog/RF circuits increases towards millimeter wave and terahertz and the operating rate of high-speed digital circuits is continuously accelerated, the electromagnetic coupling and multi-physics field coupling problems caused by the high integration of the 3D heterogeneous integration are becoming serious.

In summary, the application theory, accurate simulation analysis, and integral design of the active array microsystems are a critical problem and will become a hot research topic.

3.2.3 From customized product to standardized antenna modules

In conventional radar/communication systems, active array antennas are developed especially to match their corresponding system, and different antennas are customized for individual customers. Multiple sets of active array antennas are shared only in terms of technology. However, as performance requirements and operating environments become more challenging, radar/communication systems are becoming increasingly complex, leading to longer development cycles, higher development and production costs, and greater technical risks.

To address this situation, an important approach for large-aperture active array antennas is to construct standardized and scalable microsystem modules. The scalable array module (SAM) is the most basic building component of an antenna array, and makes it easy to build a larger-size active array antenna. The independent active array microsystem module can be modularly combined in the horizontal or vertical direction according to the application requirements, which can be freely expanded into ground, airborne, and spaceborne radar/communication active array antennas.

4 Engineering applications

An active phased array system can achieve greater functionality, higher performance, and better environmental adaptability with a smaller size, lighter weight, and lower power consumption. It can be used for reconnaissance, interference, detection, communication, and imaging. The architectures of hardware and software are becoming more complex, the frequency band coverage is wider, and the commonality is becoming lower. As a result, the cost of phased array systems for radar, electronic warfare, communication, and other functions is increasing, and the volume and weight also grow.

The technical advantages of microsystem engineering applications of active array antennas are as follows:

1. Power consumption

Three-dimensional ICs are beneficial for compressing wire lengths and reducing the longest path in the network. Shorter wire lengths are advantageous for reducing the average load capacitance and decreasing the number of transfer points in long connections, which can reduce the power consumption of the interconnectors. Compared to 2D ICs, the compression of the average interconnect length in 3D ICs can improve the wiring efficiency by 15% and reduce the total power consumption by more than 10%.

2. Anti-interference

In 3D ICs, the reduction of interconnect lengths and load capacitance can decrease the noise introduced by synchronous switches, thus enhancing anti-interference capabilities. Shorter wires introduce smaller interline capacitance, leading to less interline crosstalk in the signal. The use of fewer transfer points and shorter global links can reduce the probability of introducing noise and jitter, thereby improving the overall signal integrity.

3. Logic extensions

The fan-out rate of metal-oxide-semiconductor field-effect transistors (MOSFETs) is limited by the gain of the wire’s parasitic capacitance, which is fixed for each cycle. The capacitance of external wires significantly affects the increased load on the internal logic gate. With 3D ICs, the interconnecting load is reduced, enabling the drive of more logic gates and achieving a larger fan-out.

4. System performance

In the 3D structure, passive and active chips can be stacked to reduce the size and weight of the device, which can reduce the thickness of the active array antenna. The total area occupied by the chip device and metal interconnects can be reduced, providing more space for the rational layout to optimize the electromechanical and thermal synergies of the system.

4.1 Applications in multi-functional airborne radars

Active phased array systems are widely used on both small and large platforms, including unmanned and manned aircrafts. General aircraft platforms require multiple antennas for functions such as detection, communication, navigation, and guidance, which results in the increased number of payloads and increased cost of the aircraft platform (Lu et al., 2000; Lu, 2015).

Table 7 presents the standard requirements for active array microsystems for multi-functional airborne radars. To reduce weight, facilitate loading on airborne platforms, and even conform with the aircraft fuselage, it is necessary to solve the problem through an active array system with high efficiency, large bandwidth, and low profile. Such a configuration serves as the foundational architecture that can be readily reassembled and repurposed. This approach can realize small and thin appearance, high power on ultra-wide bandwidth, aperture distribution, resource configuration, and function reconfigurability.

For small platforms such as unmanned aircrafts, if a pair of antennas can be functionally reconfigured to achieve multiple antenna functions, the cost and load of the platform will be significantly reduced. Functionally reconfigurable active array microsystems, especially the low-cost ones, are of significant importance for practical engineering applications and are one of the main hotspots and difficulties of current research. An active array microsystem co-formed with the unmanned aircraft fuselage is shown in Fig. 13.

Multi-functional airborne radars are generally used for simultaneous search and tracking, multi-area search, multi-target tracking, high-resolution imaging of stationary and moving targets on the ground, and simultaneous multi-regional imaging. To conveniently reduce weight and payload on airborne platforms, and conform to the airplane fuselage, the airborne radars are pursuing high efficiency, large bandwidth, and low profile. A multi-functional airborne

Table 7 Relationship between the multi-functional airborne radar system and active array antennas

Application	Typical status	Performance bottleneck	Requirement
Detecting surveillance UAVs over a wide area	Unmanned control, low-orbit close detection, navigation	Small platform, low cost, reducing platform load, one pair of antennas capable of realizing multiple antenna functions	Reconfigurable, conformal arrays, low cost
Air early warning	Multi-area search, multi-target tracking, high-resolution imaging of moving targets	Multiple modes of radar/communication/electronic countermeasure working at the same time, the detection power being limited, and the power consumption and volume being difficult to meet	Large bandwidth, low profile, high efficiency
Multi-functional airborne fire control radar	High power, simultaneous search and tracking	High power and high efficiency being limited by the platform area, and the detection power being limited	High efficiency, high power, multiple functions

UAV: unmanned aerial vehicle

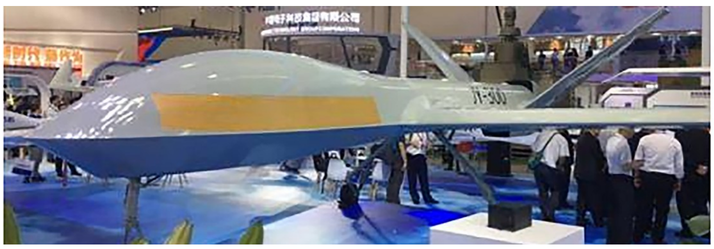

Fig. 13 A conformal active array microsystem with the unmanned aircraft fuselage

radar operating in the P–L band is depicted in Fig. 14, with dimensions of 9.0 m×0.7 m and a profile thickness of 65 mm.

4.2 Applications in space-based imaging radars/communications

The active array antenna is an essential component of a multi-functional satellite radar/communication system, and its performance has a direct impact on the latter (Lu et al., 2015). Table 8 illustrates the relationship between the spaceborne radar system and the active array antennas. We can see that spaceborne imaging radar systems have a shared requirement for active array microsystems. Spaceborne imaging radars generally require a large instantaneous bandwidth to improve multi-target imaging recognition and anti-interference capabilities. The above problems need to be solved by analyzing the system indicators such as low profile, high efficiency, and light-weight antennas. At the same time, it is necessary to investigate the electromechanical thermal multi-physics modeling and the analysis of active array microsystems. Finally, the problems of the efficient integration of mechatronics and the thermal integration of antenna microsystems (including RF, analog, digital, power supply, etc.) are solved.

The schematic diagram of the "HISEA-1" satellite is shown in Fig. 15. The profile thickness of the active array microsystem is 68 mm, and the mass density is 28.2 kg/m^2.

Technologies, such as high thermal conductivity materials, semiconductor integrated circuits, and 3D hybrid heterogeneous integration, are the basis for the research of broadband multi-polarization, multi-band shared-aperture, and flexible large-aperture active array microsystems.

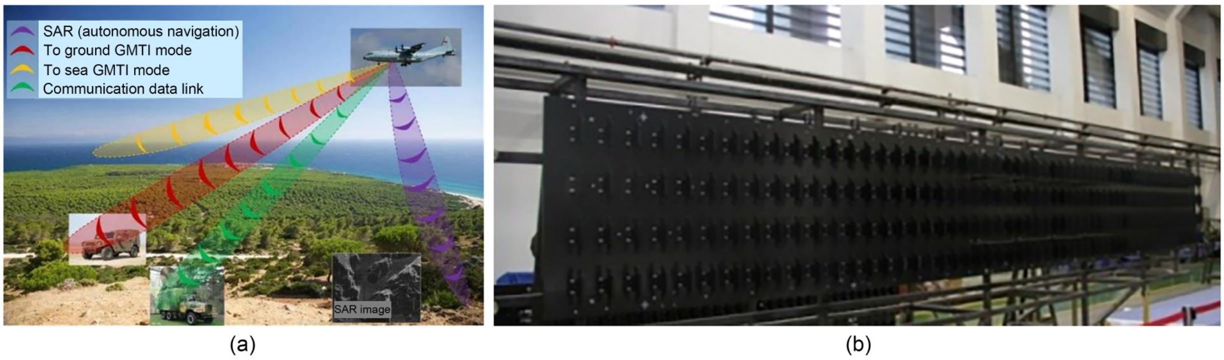

Fig. 14 Multi-functional airborne radar: (a) diagram of simultaneous multi-tasking; (b) photograph of a multi-functional active array microsystem (SAR: synthetic aperture radar; GMTI: ground moving target indication)

Table 8 Relationship between the spaceborne radar system and the active array antennas

Application	Typical status	Performance limit	Requirement
Low-orbiting satellite SAR	The satellite SAR in orbit operates for no more than 30 min per revolution (each lap time is about 90 min)	Limited energy on the satellite, inefficient antenna systems, and inadequate thermal control	Improving antenna efficiency, increasing antenna aperture, reducing system weight
Low-orbiting satellite early warning radar system	Multi-target surveillance of satellite early warning detection radars in the air and sea surface	The detection performance of the satellite radar is limited, and the power consumption and antenna profile thickness are difficult to meet	Light weight, low profile, high efficiency
High-orbiting communications satellite system	High orbit, large-aperture antenna, high data rate for multi-user simultaneous communications	Limited space on the ground side of the satellite and the inability to share transceiver antennas	Multi-load, multi-frequency, multi-function

SAR: synthetic aperture radar

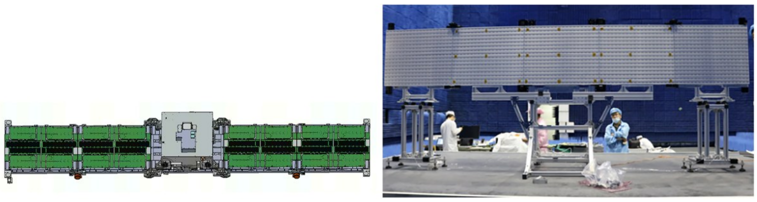

Fig. 15 Schematic diagram of the "HISEA-1" satellite: (a) diagram of the antenna in its unfolded state; (b) photograph of an active array system

4.3 Applications in communication systems

From the perspective of communication technology development and communication system platform, the 4G (including its predecessors) or 5G era is dominated by terrestrial communication. The 6G (or post-5G) era will develop towards air-space integrated communication on airborne or spaceborne platforms. For user terminals (especially mobile phones) and spaceborne platforms, how to achieve light, small, and thin active array antennas is a key topic.

Fig. 16 shows the millimeter-wave mobile phone terminal antenna based on LTCC, which has the functions of millimeter-wave antenna and virtual equivalent non-millimeter-wave antenna (Huang and Lu, 2021, 2022). The millimeter-wave antenna in package acts as a non-millimeter-wave antenna (mm-Wave AiP as non-mm-Wave antenna, AiPaA), without additional module volume. The module size of the AiPaA is 19.39 mm×4.18 mm×1.36 mm and can be used to satisfy the main popular frequency band requirements for the 5G millimeter-wave (n257, n261, n260, and the Chinese 5G millimeter-wave bands) and non-millimeter-wave (n78 and n79 dual bands).

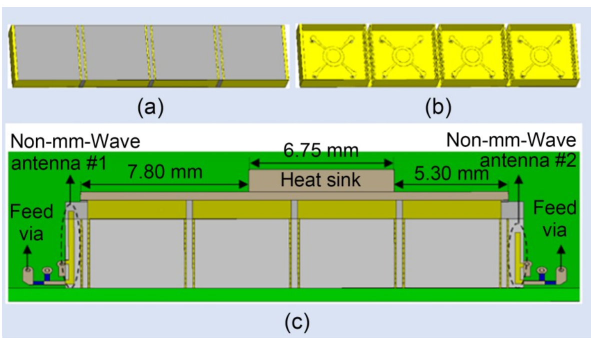

Fig. 16 Mobile phone 5G millimeter-wave antenna in package as a non-millimeter-wave antenna (AiPaA): (a) the shape of the antenna; (b) internal configuration of the antenna; (c) schematic diagram of the antenna (reprinted from Huang and Lu (2021), Copyright 2021, with permission from the authors, licensed under a Creative Commons Attribution 4.0 License)

Table 9 shows the shared requirements for active array microsystems within commercial communication systems. The development trend of commercial communication systems is the integration of passive antennas and active RF systems, and the pursuit of high-performance/high-reliability/low-cost commercial active arrays. It is necessary to explore new antenna and active circuit configurations, and the communication background environment is mostly noise mixed with multiple interferences and intermodulation. Low-noise performance is no longer a priority, and intermodulation interference and volumetric power cost become the key bottlenecks in products. Therefore, exploring a simple circuit structure and realizing monolithic integration are the top priorities for the large-scale application of electronic systems.

5 Analysis of electromagnetic coupling problems

In integrated microsystems, it is generally difficult to eliminate or reduce electromagnetic coupling by conventional methods such as capacitive decoupling, metal shielding, and microwave absorbing material wrapping. Thus, it is necessary to analyze the mechanisms through the accurate modeling of multi-scale, multi-signal, and multi-physics coupling. In particular, for active array microsystems, the presence of electromagnetic coupling is inevitable, including the internal electromagnetic coupling of the microsystem and the influence of open electromagnetic fields. The performance of the active array microsystem is significantly affected by the existence of these electromagnetic coupling phenomena. The electromagnetic coupling relationship is shown in Fig. 17.

Table 9 Relationship between the communication terminal and the active array antennas

Application	Typical status	Performance limit	Requirement
Cell phone	The antenna belongs to electrical antennas and is separated from the active circuit, the frequency band is increasing, the space is small, and the nearby metal parts have a great impact on the antenna radiation	The antenna radiation efficiency is low, the bandwidth is limited, the radiation difference in the outer half space is large, and the radiation intensity in the inner half space is large	Improving antenna efficiency, reducing the antenna size, improving radiation directionality, coexistence of mm-Wave and non-mm-Wave antennas
Handheld satellite communication terminal	For positioning, navigation, and communication, the multi-polarized multi-antenna design enables expansion of system capacity, versatility, and bandwidth	Compactness, small size, and high efficiency of complex systems such as multi-antenna, multi-polarization, and multi-RF	Multi-band, wideband, miniaturization, characteristics reconfigurable
Airborne communication terminal	From reflective surface antennas to active phased array antennas, the transceiver antennas are set independently, the beam scanning angle is large, and the scanning speed is high	The transceiver antenna cannot be shared, the large-angle scanning loss is large, and the antenna profile is high, making it difficult to adapt to multiple airborne platforms	Large scanning angle, high efficiency, low profile, low cost

RF: radio-frequency

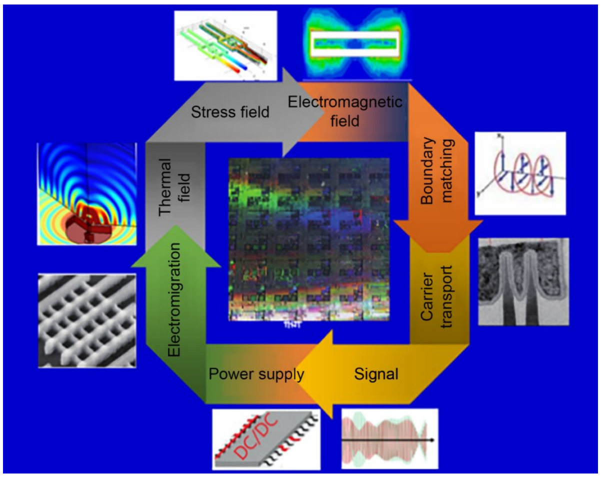

Fig. 17 Schematic diagram of the electromagnetic coupling relationship

The basic concepts, physical implications, and physical models of, and contributions to the research on active array microsystems of the "triple coupling" problem are listed in Table 10.

5.1 Multi-scale electromagnetic coupling

In active array microsystems, large-scale antennas and micro-sized chips are integrated in the same package, resulting in coupling and entanglement effects between the radiated electromagnetic fields of the large-scale packaged antenna and the different scales and different functional chips. The multi-scale coupling phenomenon of the active array microsystem is shown in Fig. 18. As can be seen from the figure, microsystems are usually composed of numerous semiconductor chips, devices, support materials, connection materials, etc. For example, a silicon chip is made up of billions of interconnected segments on a micron scale, the size of which is much smaller than the size of a wavelength, a bump pitch close to 100 μm, and a heat dissipation of tens of watts per square centimeter. In contrast, PCBs contain thousands of interconnections on a 100-mm scale, with connectors spaced close to 1 mm apart, multiple connections soldered at one point, and heat dissipation of several milliwatts of joule heat per square centimeter.

Multi-scale problems refer to the analysis and simulation of electromagnetic fields, in which the objective is not only to have a larger electrical size, but also to include microstructures that have an impact on the performance and functionality of the system (Iwamoto et al., 2012). For multi-scale problems, many of the original electromagnetic simulation methods and software are no longer suitable. Microstructures may produce quantum effects, which challenges the simulation and analysis of multi-scale problems in traditional

Table 10 Analysis of the "triple coupling" problem

Coupling problem	Basic concept	Physical implication	Physical model	Contribution
Multi-scale coupling	Active array microsystems are composed of multi-scale circuits such as nanoscale integrated circuits, micron-scale die circuits, millimeter-scale passive circuits, and macroscopic passive antennas at the meter scale, with coupling problems among them	Nonlinear responses at different scales are stimuli for responses at other scales. Microscopic quantum effects, macroscopic coupling, and entanglement effects during high-density integration are serious	$E=\frac{p^2}{2m}+v(r)$, where E is the wave function, p is momentum, m is mass, and $v(r)$ is the potential field of non-relativistic particles in motion	Suppressing self-excitation of the chip; reducing noise signals; improving electromagnetic compatibility; optimizing link matching; improving signal integrity; extending chip life
Multi-signal coupling	Active array microsystems can generate, convert, amplify, and transmit multiple signals such as digital, analog, RF, and power, with coupling problems among them	In the process of signal generation, transformation, amplification, and transmission, the power switching, impedance adaptation, and loop oscillation can cause coupling among digital, analog, and RF signals	$P=\sum_{k=0}^{n}\sum_{j=0}^{n}p(j,k)+\sum_{j=0}^{n}\mathrm{ps}(j)$, where P is the total signal energy, $p(j,k)$ is the signal intrinsic or coupling energy, and $\mathrm{ps}(j)$ is the energy loss	Improving active standing waves; enhancing antenna efficiency; improving multi-signal routing; broadening antenna bandwidth; improving signal-to-noise ratios; reducing cross-polarization
Multi-physics coupling	Stress from non-uniform thermal expansion, mismatch of thermal transport paths and interfaces, and mismatch of signal transport paths in active array microsystems result in severe electrical properties, thermal and stress coupling and interaction	The different thermal dissipation of the devices causes an uneven thermal distribution in the microsystem, resulting in changes in the displacement field and changes in signal amplitude, phase, time delay, and spectral characteristics in the channel	$f(u_i, s, m_j)=0$, where u_i is the field variable, s is the field source, m_j is the physical property variable of the material, and f is the differential operator	Reducing the weight and the thickness of the antenna profile; decreasing the difficulty of thermal control; improving the reliability

RF: radio-frequency

electromagnetics. Therefore, it is necessary to develop efficient methods for solving multi-scale electromagnetic problems.

The objective of solving multi-scale problems is not limited to including large electrical dimensions, but also involves analyzing multiple structures that impact the system performance and functionality, such as nanometer-scale chips, micrometer- to millimeter-scale TSVs and microspheres, and the millimeter- to meter-scale antenna radiation elements, heat sinks, and PCBs. Therefore, research must be conducted on the characterization of multi-scale physical properties, the mechanism of multi-scale electromagnetic wave action, the nature of abnormal electromagnetic compatibility phenomena, energy-efficient RF integrated circuits, and multi-scale coupled directional suppression.

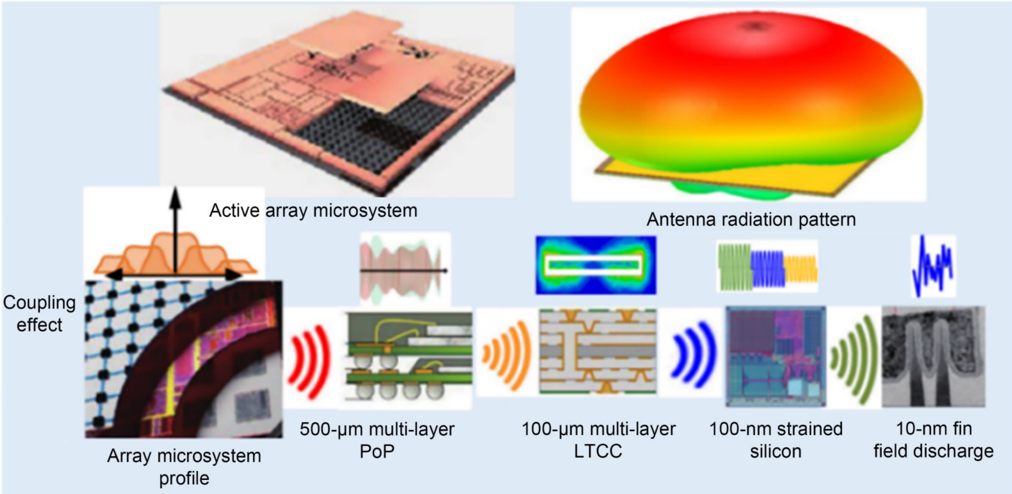

Fig. 18 Schematic diagram of the multi-scale coupling phenomenon (PoP: package on package; LTCC: low-temperature co-fired ceramic)

5.2 Multi-signal electromagnetic coupling

Multi-signal electromagnetic coupling problems are commonly encountered in active array microsystems. Multi-functional chips are heterogeneously integrated in the 3D RF microsystem, and the 3D interconnection lines, such as ball grid arrays, micro-bumps, and vertical vias, provide multiple electromagnetic coupling paths. These interconnection lines are especially affected by high-frequency electromagnetic fields and high-speed signal parasitic reactance, and the electromagnetic noise is coupled and radiated inside the structure of the packaged multi-signal transmission network. In microsystem integration, the backward near-field radiation of the antenna can cause crosstalk to the active sensitive chip inside the package via multi-dimensional interconnected feeding structures. Additionally, the impedance mismatch of the active interconnect chip can affect the antenna in terms of load traction.

Serious electromagnetic coupling problems arise from the high-speed digital, RF, and analog signals between different functional chips. The impedance matching of interconnected lines is affected by different interconnected signal lines, such as ball grid arrays, micro-bumps, and vertical vias, due to high-frequency parasitic effects at increased operating frequency bands. The impedance discontinuity structures, such as inductors, gaps, and interconnecting wires, can deteriorate the noise signal in the coupling transmission of the power distribution network (PDN). The RF-sensitive chips can trigger the self-excitation of the amplifier and cause a phase lock loop, resulting in multi-signal coupling problems.

In summary, there are several problems in active array microsystems, such as impedance mismatch during transmission, harmonic generation during nonlinear signal transformation, and crosstalk among multiple signals. As shown in Fig. 19, serious electromagnetic coupling problems can be observed with the high-speed digital and RF/analog signals in an active array microsystem (Zhu and Mao, 2013; Zhu et al., 2013, 2019, 2021b).

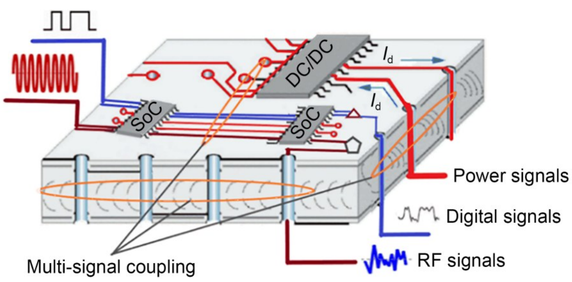

Fig. 19 Schematic diagram of the multi-signal coupling phenomenon (SoC: system-on-chip; DC: direct current; RF: radio-frequency)

Usually, the electrical analysis of the designer focuses on signal integrity, power integrity, electromagnetic radiation, and magnetization in microsystem integration. The multi-physics field analysis of digital or analog circuits focuses on electrical and thermal interactions or, in some RF applications, on physical shape changes. Fig. 20 illustrates the schematic diagram of the generation and coupling of signal integrity (SI), power integrity (PI), and electromagnetic interference (EMI) in microsystems.

The simulation analysis of the system design process should include the parasitic effects of interconnections across different levels of chip, device, and component, as well as modeling the interaction of all elements of the integration. However, the current simulation and analysis methods focus on the independent units of the microsystem rather than on its system level. As a result, these methods are limited in diagnosing problems related to the performance in hardware. Therefore, research is needed on a unified characterization of multi-signal electromagnetic properties, a multi-signal coupling mechanism, new methods for multi-signal coupling analysis, signal integrity, noise suppression, and the optimization of the system's signal-to-noise ratio.

5.3 Multi-physics field coupling

In active array microsystems, multiple physical fields, such as electromagnetic, thermal, and stress, are coupled to each other. With increasing signal processing speeds, high-speed signal wavelengths are comparable to the geometry size of the system or the circuit components within it. Therefore, the analysis and design of the electrical characteristics of the system must be based on the microwave electromagnetic field theory, and Maxwell's equations must be solved under 3D multi-layer complex boundary conditions. Moreover, due to the high-density integration of chips and components, thermal problems of system-level packaging are becoming more and more serious. To obtain the temperature distribution in the system and to analyze and solve various thermal problems, it is necessary to solve the heat diffusion equations (Ghosh and Joshi, 2014; Jia et al., 2016; Monier-Vinard et al., 2017; Zhang et al., 2018).

Due to the significant increase in the power density of active RF circuits in packages, the 3D distribution of heat and stress exhibits time-varying characteristics and interacts with electromagnetic problems. The uneven temperature distribution can affect the noise and efficiency of RF amplifiers in multi-signal circuits, as well as the delay and jitter characteristics of high-speed digital signals. Additionally, due to the thinning of the chip packaging and the widespread use of TSV, the mechanical support within the 3D stack expands non-uniformly thermally, resulting in discontinuous stress field distribution, which reduces mechanical reliability and affects the electrical performance of the system. As shown in Fig. 21, the electromechanical–thermal coupling phenomenon of active array microsystems is analyzed. Conventionally, electromagnetic and thermal fields at the chip level, particularly at the package level, are analyzed separately. The electrical and thermal characteristics of the system are independently processed and analyzed.

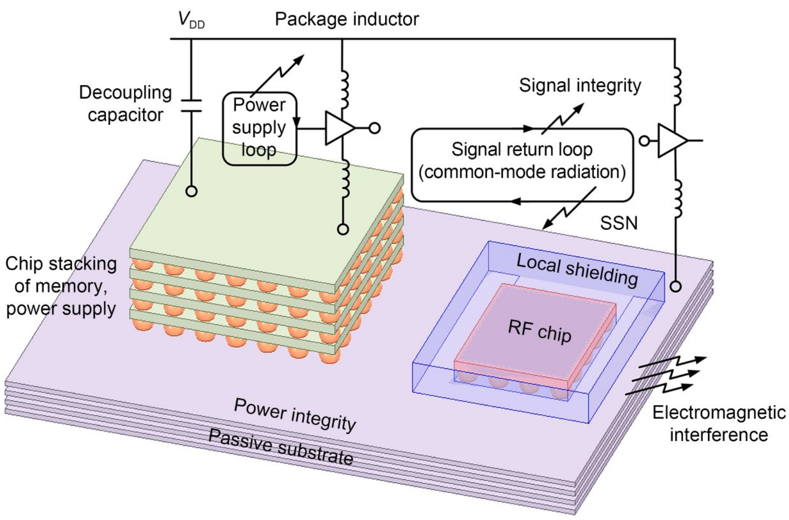

Fig. 20 Schematic diagram of the generation and coupling of signal integrity, power integrity, and electromagnetic interference (RF: radio-frequency; SSN: simultaneous switch noise)

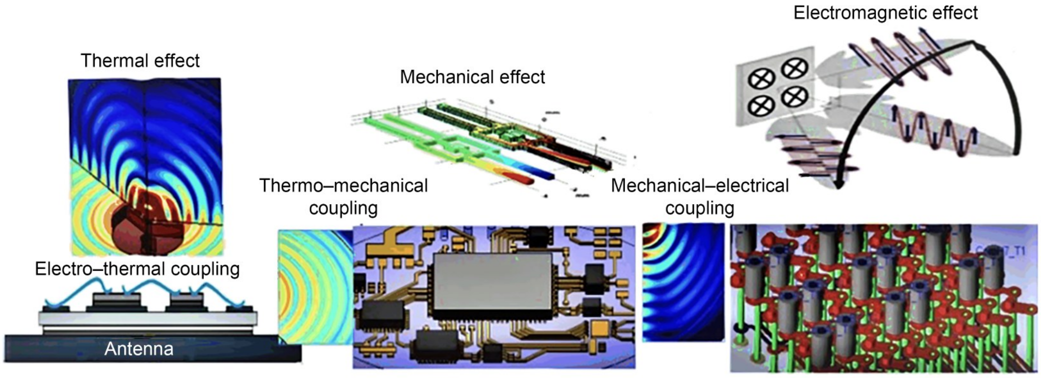

Fig. 21 Schematic diagram of the electromechanical–thermal coupling phenomenon

However, the thermal field distribution is closely related to the electromagnetic field distribution. The heat source distribution is determined by the electromagnetic field distribution, which, in turn, affects the distribution of the electromagnetic field. This leads to a mutually coupled process until equilibrium is reached. This coupling between electromagnetic and thermal fields is reflected in Maxwell's equations and the intrinsic parameters of the medium, particularly the conductivity of the conductor as a function of temperature, which is a function of the electromagnetic field in the heat diffusion equations. Thus, given the characteristics of the active array microsystem, the coupling relationship between electromagnetic and thermal fields must be considered, and co-analysis and co-modeling of these fields are a key scientific problem to be solved. Research is necessary for the unified characterization of multi-physics fields, multi-physics coupling mechanisms, cross-scale and cross-level accurate modeling, field–path co-simulation, and error model building and validation.

The above problems are fundamental challenges in the research process of active array microsystems, which require more attention being paid to the mechanism analysis, modeling, and simulation investigation, as well as to engineering applications.

6 Technical implementation challenges

Antenna array microsystems are rooted in the micro-nano scale theory and evolved on the basis of electromagnetic fields, microelectronics, optoelectronics, materials, and thermodynamics. In a distributed and open architecture, antenna arrays, active transceiver channels, power distribution/combination networks, frequency synthesizers, beam controllers, receivers, power converters, and thermally conductive structures are integrated in a 3D hybrid heterogeneous architecture by hybrid heterogeneous integration techniques, as shown in Fig. 22. The hardware includes deep cross-fertilization, architecture optimization, and functional hardware chipping, and is high-density. The low-consumption vertical interconnection of signals enables a light-weight antenna system with integrated hardware and software, scalability, up−down compatibility, collaborative resource allocation, intelligence, reliability, multi-functionality, and high integration, at a low cost.

From the perspective of antenna system and architecture, active array antennas can be divided into active phased array antennas, digital array antennas, and microwave photonic array antennas. The architectures of the different antenna arrays are shown in Fig. 23.

Active phased array antennas are widely used in radars for their advantages of multi-target, long range, high reliability, and high adaptability, although the amount and cost of the equipment can be considerable. These antennas have the ability to switch beams quickly and control direction, allowing for beam forming and steering, and are increasingly used in communications. As radar frequency bands become wider and array sizes increase, the development of active array microsystems is moving towards multi-functionality, low cost, high efficiency, and light weight.

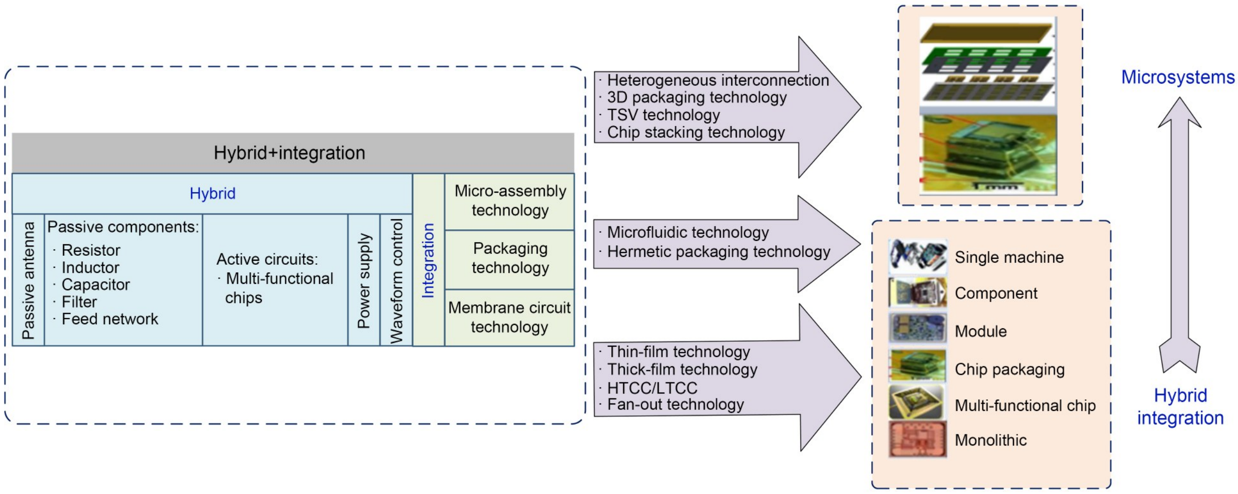

Fig. 22 Schematic diagram of the array microsystem integration process (TSV: through silicon via; HTCC: high-temperature co-fired ceramic; LTCC: low-temperature co-fired ceramic)

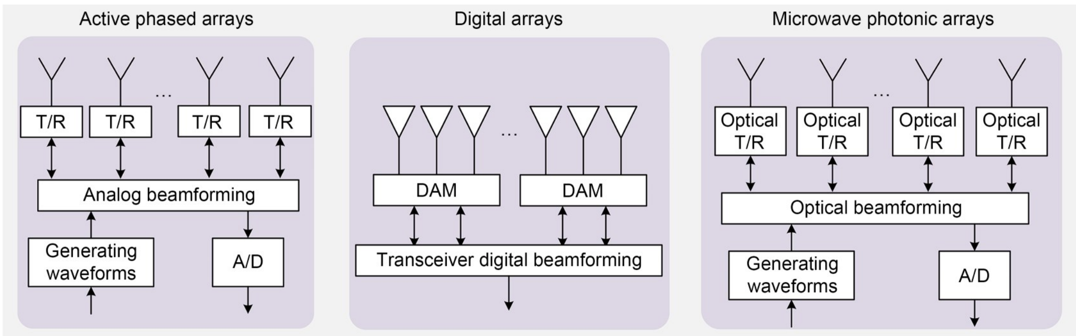

Fig. 23 Basic composition of common active array antennas (T/R: transmitter/receiver; A/D: analog to digital; DAM: driver amplifier module)

Digital array antennas have been successfully applied in early warning detection radars, providing multi-dimensional information in the space, time, and frequency domains. The performance of the radar system is enhanced while the composition is simplified, making it a trend in their development. If digital arrays are applied in synthetic aperture radar (SAR) technology, it can effectively resolve the conflict between high resolution and wide observation bandwidth in traditional spaceborne SARs. This will enable high-resolution wideband imaging and simultaneous multi-mode and multi-task operation, and changes the radar signal waveform during beam scanning, thus reducing the intercept probability. However, there are still challenges that need to be addressed for active array microsystems, including the high-density integration of broadband data acquisition, transmission, and processing modules.

Microwave photonic array technology is a new approach that combines the microwave photonic technology and phased array technology, and has potential applications in the generation, transmission, and processing of microwave signals. By modulating microwave signals to optical carriers and using optical fibers for long-distance transmission, it has attracted the attention of the radar community. Optical fibers are used as data and signal transmission lines, and optical true delay lines are used to form the optical beamformer in radar systems. In the optically controlled phased array radar, the RF signal is modulated onto the optical carrier and transmitted by different optical paths to the antenna element for beam formation and control in the optical domain. The application of microwave opto-electronics is used in radar systems, which can use the optical path system to control the amplitude and phase distribution of the antenna array, and thus the distribution of the RF signal from the antenna elements. This is an important research area with the potential to enhance the performance of radar systems.

The basic principle of active array microsystems is to enhance performance and functionality by integrating various advanced technologies from a micro perspective, with the aim of achieving breakthroughs in macroscopic performance and functionality. To promote the development of active array microsystem technology, multiple functional module microsystems are integrated to improve their performance and enhance the functionality of radar and communication systems.

Active array microsystems are usually composed of numerous semiconductor chips, devices, supporting materials, connecting materials, etc. Challenges have been raised in areas such as the multi-disciplinary intersectionality of electromagnetism/optics/force/thermology/materials, the ambiguity of vertical synergistic integration of materials/components/units/subsystems/systems, and the special coupling at microscale. Several cutting-edge scientific and technical issues for antenna array microsystems were described in Lu and Wang (2020).

6.1 New architectures and software-defined functions

There are many types of active phased array antennas. From the perspective of operating frequency, they can be classified into microwave frequencies (P, L, C, S, X, and Ku), millimeter-wave frequencies (Ka and D), and terahertz. Depending on the operating bandwidth, there is narrowband (≤1%), broadband (1%–25%), and ultra-wideband (≥25%). For different operating polarizations, there is single polarization, dual polarization, and circular polarization. From the point of view of loading platforms, there is ground, shipborne, airborne, and spaceborne platforms. In terms of functions and performance, there are different aperture sizes (small, medium, and large) and different types of arrays, such as receive-only or transmit-only arrays, as well as arrays that can transmit and receive. These arrays can also have different configurations, including single-channel transmit and single-channel receive, single-channel transmit and multi-channel receive, and multi-channel transmit and multi-channel receive. Moreover, arrays can have conventional sidelobe levels (≤−20 dB), low sidelobe levels (≤−30 dB), and ultra-low sidelobe levels (≤−40 dB) for both conical and shaped beams.

According to the system function and performance, research has been conducted on the architecture and software-defined functions of active array antennas. A systematic perspective has been taken to analyze the system layout, signal flow, power supply flow, control flow, heat transfer flow, and force conduction flow, as well as other aspects related to the system architecture. This is combined with research on components, functional modules, materials, and the integrated process, as shown in Table 11. With the help of software-defined functional technology, the functions and performance of active array microsystems can be adjusted and enhanced through software defined in a given hardware architecture.

6.2 Miniaturization of passive components

In antenna array microsystems, passive circuits are usually integrated with active circuits to form functional modules, such as digital, power, and RF modules, which include antennas, decoupling arrays, filters, matching networks, resonators, etc. Driven by Moore's law, the integration of digital and microwave active circuits is increasing. Due to the difficulty in miniaturizing passive components, the size of active array

Table 11 Elements for active array antenna integration

Element	Parameter
Performance	Rate, delay, TFLOPS, insertion loss, isolation, dynamic range
Energy/power	Energy per bit, TFLOPS per joule, leakage power
Interface	Signaling protocol, error correction, interconnect length, ESD protection
Thermotics	Junction temperature, total device power, power density, thermal testing standards
Electricity	Power supply loss, conversion loss, noise, harmonic noise
Reliability	Mean time between failures, radiation hardness, derating level, product life

TFLOPS: times of floating-point operations per second; ESD: electrostatic discharge microsystems cannot be reduced to the same scale. The miniaturization of passive parts has become crucial for the development of active array microsystems.

The key to the integrated passive devices in active array microsystems is how to embed them effectively within 2.5D adapter boards, fan-out distribution layers, or high-density organic carrier boards, and how to control them efficiently to ensure long-term reliability. Micro-nano structural materials and substrate-compatible thin film processes can make thin-film-integrated passive components smaller and thinner. By integrating passive components and active devices into advanced substrates through ultra-short interconnects with one another, ultra-small 3D heterogeneous integrated module-level microsystems can be achieved.

6.3 Novel materials and processes

Despite the small size and high density, materials used in the 3D integration of active array antenna microsystems face the challenge of thermal conductivity. To overcome this shortcoming, the multi-layer HTCC integrated package is manufactured with the help of power ceramic materials. For example, aluminum nitride (AlN) not only retains the advantages of a ceramic integrated package, but also significantly improves the thermal conductivity of the package, thereby further improving the density of the package integration. It is necessary to develop new materials with larger than 200 W/(m·K) thermal conductivity. New material or process applications, such as nanomaterials, graphene, local potting technology, and micro-integrated heat pipes, will help antenna microsystems develop to a large size, with multiple dimensions, multiple cavities, and high integration. The functional materials commonly used for system integration are shown in Table 12.

A large number of conventional complementary metal oxide semiconductor (CMOS) circuits, SiC circuits, GaAs circuits, SiGe circuits, optoelectronic circuits, micro-electro-mechanical system (MEMS) devices, and various passive components are integrated into a single package to achieve the functionality of active array microsystems. As the substrate area is limited, assembly is moving towards multi-layer and multi-dimensional configurations, enabling higher assembly density and more space for hybrid integration. However, this also poses new challenges, such as ensuring chip inspection validity, improving the yield of multi-chip primary assembly, and addressing environmental experimental stress.

Additional integration processes are being studied, such as wafer-level packaging (WLP), TSV, stacked dies, stacked packages, stacked wafers, embedded substrates, and IPDs, with key technical processes including wire bonding, flip chip, micro-bumping, etc.

6.4 Ultra-wideband technology

The active array microsystem is dedicated to enhancing both target detection capabilities and communication capacity, while improving spectrum utilization and increasing the efficiency, flexibility, and adaptability of the system. Key performance metrics for active array microsystems encompass high signal-to-noise ratios, extensive scanning angle, superior efficiency, and robust reliability.

Table 12 Functional materials commonly used for system integration

Functional material	Function	Key parameter	Materials used
Dielectric material	Connections and supports	Low dielectric constant, low loss tangent	Fluoropolymers, epoxy-based polymers
Conductor material	Transmission of signals and energy	Low resistance	Copper, tungsten
Interconnect material	Chip-level and board-level interconnects, such as solder	High thermal conductivity, low process temperature	Eutectic solder, such as tin-silver, tin-lead, nano-silver paste
Filling and packaging material	Stress management and encapsulation for physical and chemical protection	Low shrinkage, low CTE, suitable modulus, low curing temperature, excellent adhesion	Epoxy-based materials with fillers
Thermal interface material	Thermal management	High thermal conductivity, good adhesion to substrate and mold	Phase change material, silver epoxy

CTE: coefficient of thermal expansion

A critical consideration in this context is the balance between antenna bandwidth and profile height. How to effectively solve the contradiction between broadband radiation characteristics and low profile and the high integration of ultra-bandwidth antennas is an urgent problem. To solve the issue of the low profile of ultra-wideband antenna, it is necessary to investigate the mechanism of the weak frequency response characteristics of wideband antenna and a new strongly coupled antenna configuration.

Multi-band, multi-polarized common antenna aperture is an important path by which to reduce the number of antenna units. A new approach for multi-band, multi-polarization antennas is explored, which improves the isolation of multi-polarization components, suppresses out-of-band electromagnetic components, reduces antenna profile height, and supports the design of multi-band, multi-polarized broadband common-aperture antennas.

The design of wideband amplifiers in active circuits requires a combination of linear performance, efficiency, stability, nonlinear distortion, material selection, and manufacturing techniques. To improve system efficiency and signal quality, it is necessary to investigate the high efficiency of linear amplifiers, the clutter suppression of frequency conversion circuits, signal transmission impedance matching, and high-frequency switching technology.

6.5 Cross-domain application of new technologies

To promote the development of active array microsystems, there is a need to focus on the integration of MEMS and optical devices. For instance, the wavelength division multiplexing (WDM) principle can be applied to transmit different colors of light on the same fiber, thereby increasing the bandwidth capacity and inspiring new ideas for potential functions.

The application of MEMS and optical devices will be more challenging. For example, some MEMS devices require multi-dimensional assembly with high accuracy in three directions (*XYZ*), flatness, rotation, and consistency of assembly stress, curing stress, applied stress, and screening stress. Additionally, MEMS devices are sensitive to resistance and should be provided in large vacuum packages. Photoelectronic devices, including lasers, require a consistent optical path of fibers, lenses, and optical devices. Assembly or subsequent stress affecting the optical path can lead to a significant drop in coupling, and the corresponding assembly process must be designed systematically with high consistency. In particular, micro-nanoscale adjustment is necessary when coupling to achieve assembly accuracy of ($3\sigma\pm1$) μm on some devices.

7 Conclusions

In the post-Moore era, active array microsystems face challenges that require solving coupled science and technology problems, such as multi-scale, multi-signal, and multi-physics fields. These challenges can be overcome by improving chip performance and multi-functional, 3D heterogeneous integration. Engineering implementations should pay attention to new architectures and algorithms, the miniaturization of passive components, new materials and processes, and new interdisciplinary technologies. In the future, active array microsystems are expected to make significant progress in profile thickness and weight, performance, and intelligence. The progress will be essential in accelerating the development of a new generation of higher-performance electronic information systems.

Contributors

Jiaguo LU designed the research. Jiaguo LU and Haoran ZHU processed the data. Haoran ZHU drafted the paper. Jiaguo LU helped organize the paper. Jiaguo LU and Haoran ZHU revised and finalized the paper.

Conflict of interest

Both authors declare that they have no conflict of interest.

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