Jiaguo LU, Haoran ZHU, 2024. Engineering applications and technical challenges of active array microsystems. *Frontiers of Information Technology & Electronic Engineering*, 25(3):342-368. https://doi.org/10.1631/FITEE.2300401

Engineering applications and technical challenges of active array microsystes

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

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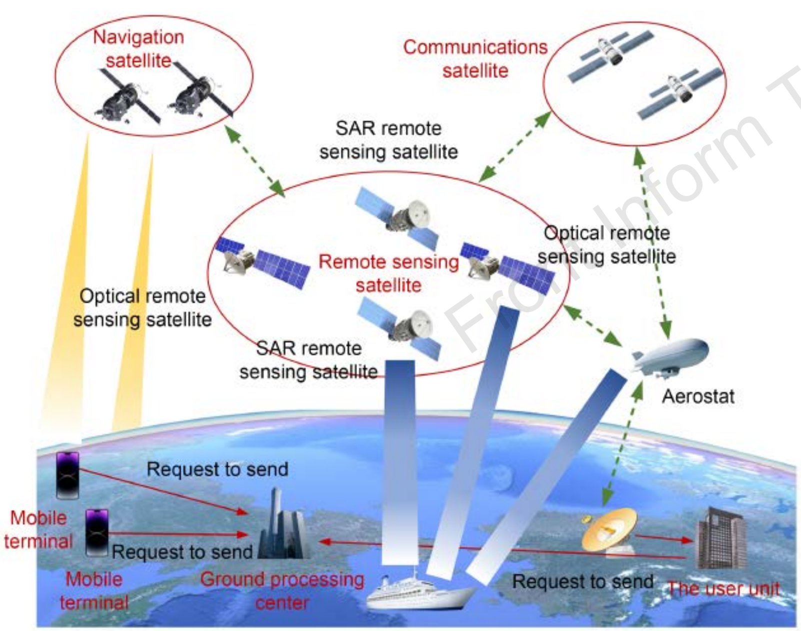
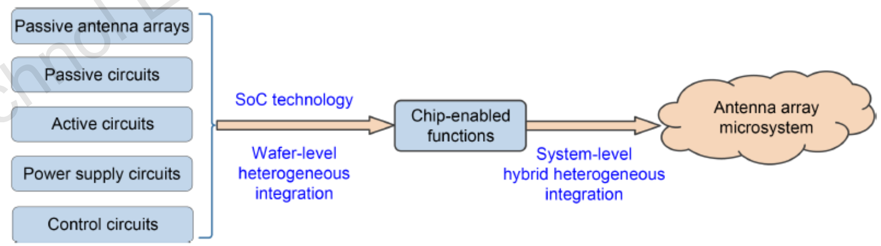
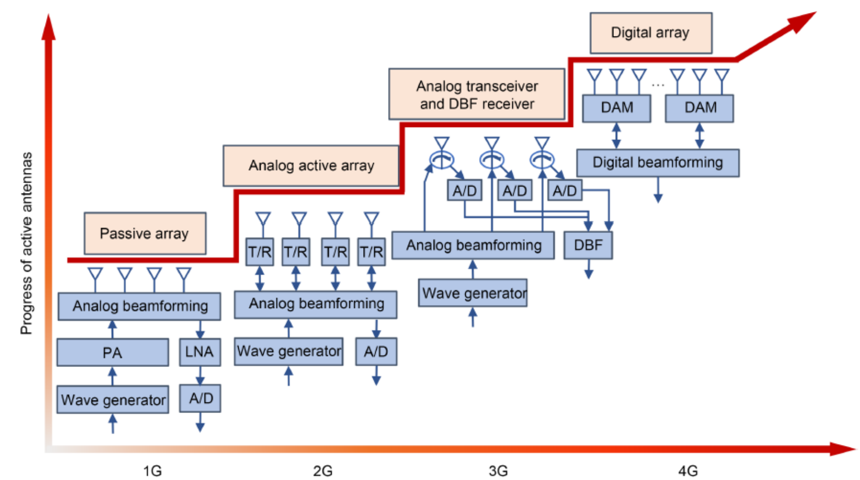
Progress of active array microsystems

- Active array microsystems take characteristics of high-density, multi-functional, large-aperture, low-profile, broadband wide-scanning angle, high efficiency, and low cost
- Active array microsystems are preferred for the new generation of radar/communication systems.







Principle of active array microsystems

- From the engineering perspective, five transmission flows are attributed to the typical active array microsystems

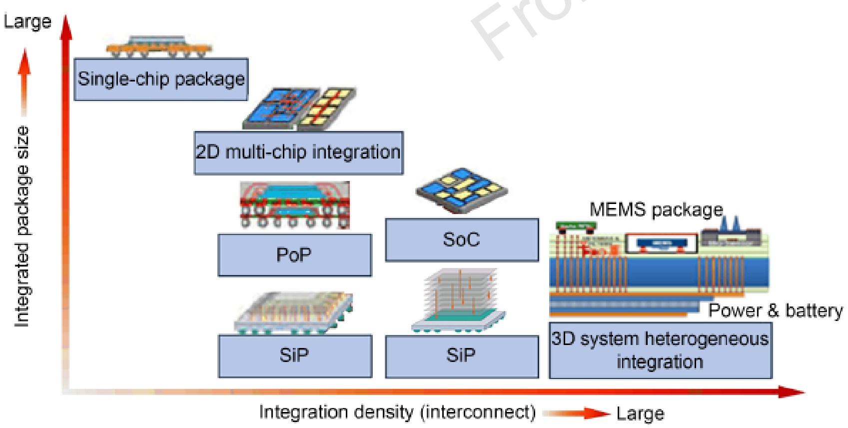
- Signal flow, which includes generation, conversion, amplification, transmission, transmitter, and receiver of the signals.
- Information flow, including signal flow control, hardware status monitoring, system status monitoring, and compensation.
- Power supply flow, which contains voltage conversion, energy distribution and filtering.
- Force conduction flow, consisting of thermal stress, vibrations, and shocks.
- Thermal transfer flow, including heat transfer, thermal interface matching, heat dissipation, and heat sink.

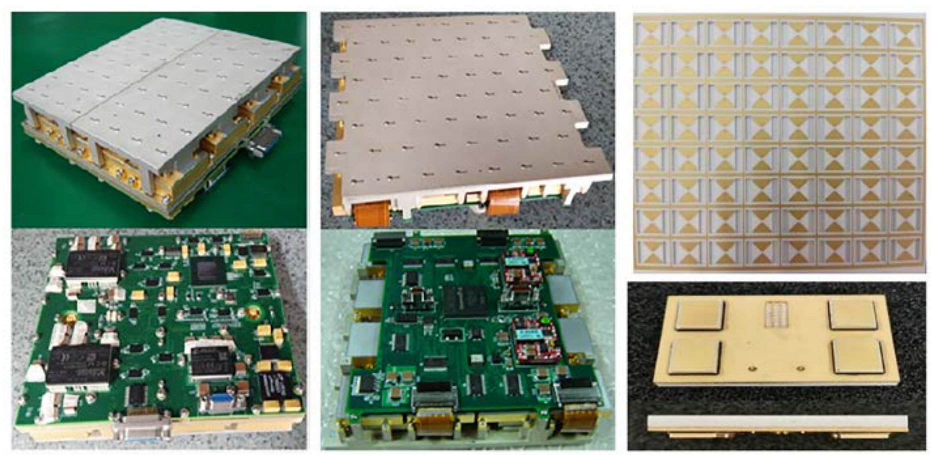
Relationship between active array microsystems and radar/communication systems

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

Development tendency

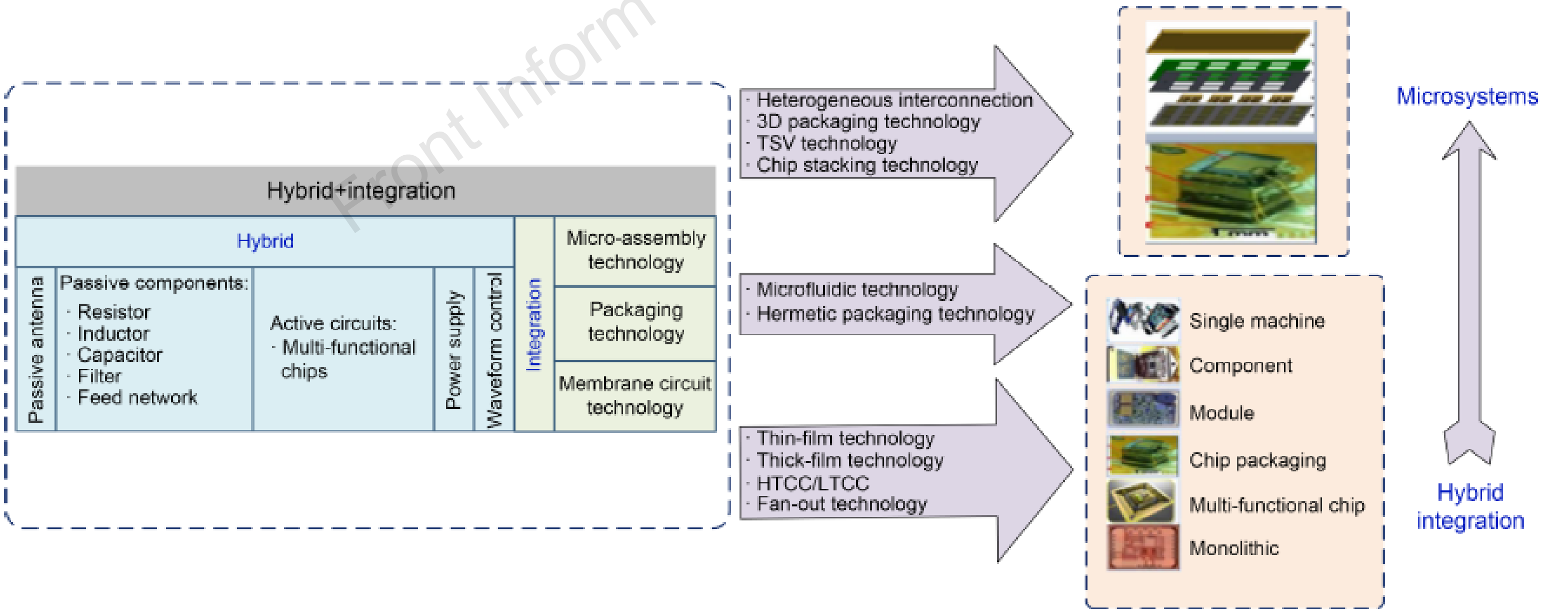
- In consideration of the application requirements, microsystem technology is evolving towards multi-functional integration, 3D stacking, hybrid heterogeneous integration, and intelligent sensing.
- Based on multi-layer heterogeneous ceramic co-firing technology, antennas, active multifunction RF chips, and high-speed digital control chips are integrated, while microfluidic channels are incorporated to ensure efficient heat dissipation.
- The profile thickness can be reduced to 15 mm, and the mass density of less than 16 kg/m^2.





Motivation

- 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
- For active array microsystems, it is necessary to analyze the mechanisms through the accurate modeling of multi-scale, multi-signal, and multi-physics coupling.



“Triple coupling” problem in active array microsystems

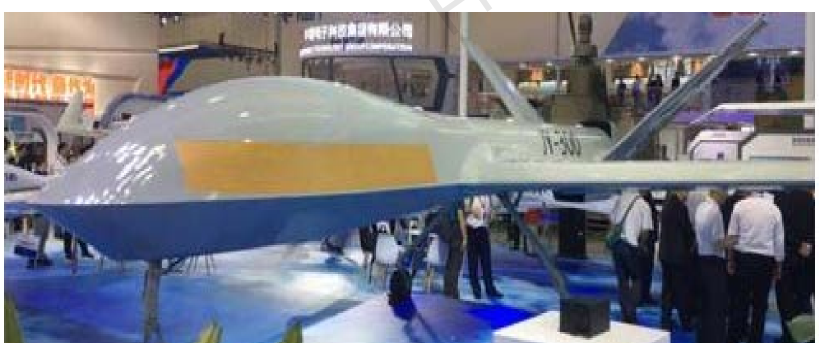
Coupling problem	Basic concept	Physical implication	Physical model	Contribution
Multi-scale coupling	Active array microsystems are composed of multi-scale circuits such as nanoscale integrated circuits, micron-scale die circuits, millimeter-scale passive circuits, and macroscopic passive antennas at 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

Engineering applications of active array microsystems

Multi-functional airborne radar

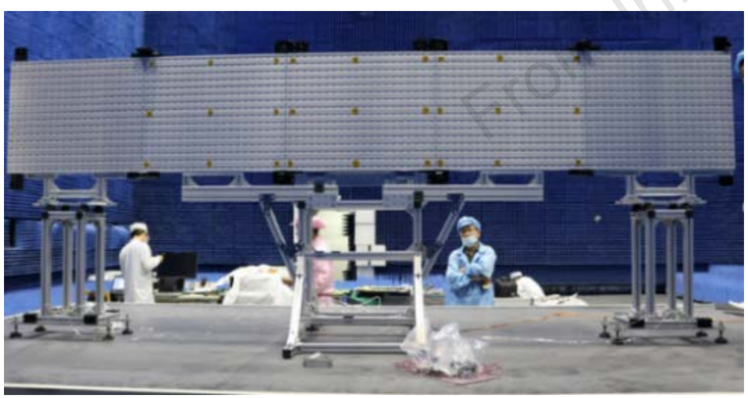
- Active phased array systems are widely used on both small and large platforms, including unmanned and manned aircrafts.
- To reduce weight and facilitate loading on airborne platforms, it is necessary to design active array microsystems with high efficiency, large bandwidth, low profile, aperture distribution, resource configuration, and function reconfigurability.
- The multi-functional airborne radar operates in the P–L band, with dimensions of 9.0 m×0.7 m and a profile thickness of 65 mm.

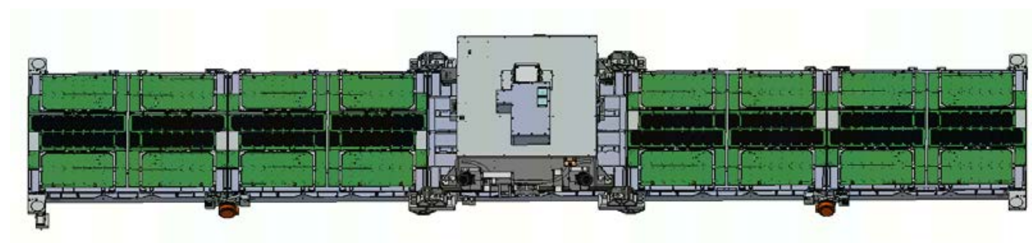


Engineering applications of active array microsystems

□ Space-based imaging radar/communications

- Spaceborne imaging radar generally requires a large instantaneous bandwidth to improve multi-target imaging recognition and anti-interference capabilities.
- The corresponding active array microsystems should take the characteristics of low profile, high efficiency, and light weight.
- In the “HISEA-1” satellite, the profile thickness of the active array microsystem is 68 mm, and the mass density is 28.2 kg/m^2.





Schematic diagram of the “HISEA-1” satellite

Future outlook

Active array microsystem	Outlook
New architecture software-defined functions	• Software defined • Intelligent active array microsystems
Miniaturization of passive components	• Integrated passive devices (IPDs) • Integrating passive components and active devices with advanced packaging technique
Novel materials and processes	• Novel materials for dielectric, conductor, interconnection, filling, packaging, and thermal interface • Novel integration process of wafer-level packaging, through-silicon via, stacked dies, wire bonding, flip chip, micro-bumping
Ultra-wideband technology	• Tradeoff among the broadband radiation, low profile, and high integration array antennas • Linear wideband power amplifiers
Cross-domain application of new technologies	• Integration of MEMS and optical devices • Wavelength division multiplexing technique for increasing bandwidth capacity

Jiaguo LU, Research Fellow and the doctoral supervisor serving in the University of Science and Technology of China and Anhui University. He has been Vice Chief Engineer and Vice President of East China Research Institute of Electronic Engineering, President of East China Research Institute of Microelectronics, Member of National High-tech R&D Program of China (863 Program), Expert of National Reconnaissance Early Warning System and Spacecraft Payload, Member of Radar Sub-council and Microwave Sub-council of China Institute of Electronics (CIE), and Vice Chair-person of Antenna Sub-council.

Prof. LU has performed the research on microwave imaging radar and antenna technology for a long time. He has recognized and addressed the emerging issues in the development of high resolution, multi-polarization and multi-band microwave imaging radar and active array antennas by means of microwave electro-magnetic fields, making systematic and creative contributions in imaging radar and antenna technology.

Prof. LU has won one Second Prize of National Science & Technology Progress, and dozens of Special Prize, First Prize and Second Prize of National Defense Science & Technology Progress. He has authored three publications and more than 80 papers in core journals, holding more than 40 invention patents.

Haoran ZHU received the Ph.D. degree at electrical engineering at Shanghai Jiao Tong University, China in 2014. From June 2014 to September 2017, Dr. ZHU was a Senior Engineer with the Research Department of Micro-system, East China Research Institute of Electronic Engineering. He is currently a full Professor of the School of Electronic and Information Engineering, Anhui University. From February 2019, he is a Research Fellow of the Department of Electrical Computing Engineering, National University of Singapore. His recent research interests include the 3D integration technologies of antenna and RF circuit systems, signal integrity and power integrity analysis of high speed mixed-signal systems, and miniaturized microwave integrated passive circuits.