Jiaguo Lu · Wei Wang ·
Xiaolu Wang · Yongxin Guo

Active Array Antennas for High Resolution Microwave Imaging Radar

国防工业出版社
National Defense Industry Press

Springer

Active Array Antennas for High Resolution Microwave Imaging Radar

Jiaguo Lu · Wei Wang · Xiaolu Wang ·
Yongxin Guo

Active Array Antennas for High Resolution Microwave Imaging Radar

国防工业出版社
National Defense Industry Press

Springer

Jiaguo Lu
Department of Science and Technology
East China Research Institute of Electronic Engineering
Hefei, China

Xiaolu Wang
Research Center for Microwave and Antenna Technology
East China Research Institute of Electronic Engineering
Hefei, China

Wei Wang
Research Center for Microwave and Antenna Technology
East China Research Institute of Electronic Engineering
Hefei, China

Yongxin Guo
Department of Electrical and Computer Engineering
National University of Singapore
Singapore, Singapore

ISBN 978-981-99-1474-6 ISBN 978-981-99-1475-3 (eBook)
https://doi.org/10.1007/978-981-99-1475-3

Jointly published with National Defense Industry Press
The print edition is not for sale in China (Mainland). Customers from China (Mainland) please order the print book from: National Defense Industry Press.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Human beings and the earth they live on are facing severe challenges. The development of advanced earth observation radar technology is of great significance to national security, ecological monitoring, and disaster monitoring. For a long time, active phased array antennas have been hotspots and challenging in the research of the earth observation radar systems. The purpose of writing this book is to enable readers to systematically, comprehensively, and deeply understand and master the basic concepts, working principles, and types of active array antennas, understand and master the working modes, architecture compositions, and analysis methods of active array antennas and the differences with conventional active phased array antennas, as well as the ideas, methods and special considerations in the design and research of active array antennas.

On the basis of discussing and introducing the basic principles of active array antennas, array synthesis and analysis methods, and modeling techniques for antenna radiation characteristics, this book systematically illustrates the architectures, analysis methods, and engineering practices of active array antennas with the goal of being low profile, high efficiency, and light weight to realize broadband, multi-band, multi-polarization, and shared-aperture properties, and studies digital array antennas, microwave photonic array antennas, active package antennas, and other hot technologies.

This book is divided into 9 chapters. Chapter 1 introduces the characteristics of high-resolution microwave imaging radar and active array antennas, puts forward the new concept of "antenna array microsystems," and discusses the outlooks of the new technologies and development directions of active array antennas; Chap. 2 analyzes linear arrays, planar arrays, sparse arrays, and beamforming optimization techniques based on the application scenarios by using microwave imaging; Chap. 3 analyzes the influence of active array antenna error factors, introduces antenna measurement techniques, and provides rapid measurement of microwave imaging radar two-dimensional phased array antennas and precise modeling technology; Chap. 4 starts from the mechanism of antenna instantaneous broad bandwidth, analyzes the configuration methods of real-time delay lines, and introduces the design methods and experimental results of common microwave delay components in detail; Chap. 5 focuses on the research of "tile" array modules, miniaturization of chip transceiver components, and three-dimensional heterogeneous integration methods on the basis of discussing the low profile, high efficiency and light weight of active array antennas; Chap. 6 introduces the requirements and implementation methods of broadband multi-band multi-polarization shared-aperture antennas, focuses on the multi-polarization/multi-band shared-aperture technologies of microstrip patches and waveguide slots antennas, and introduces the triple-band dual-polarization shared-aperture antennas; Chap. 7 analyzes the coupling and mutual interference mechanism of multiple physical quantities at a small scale, studies the parasitic effects between multiple parameters on the basis of introducing the classification of packaged antennas and broadband packaged antenna elements, and explores embedded devices to realize the miniaturization, light weight and high integration of microwave passive devices. Chapter 8 introduces the basic principle of digital array antennas, DDS spectrum characteristic analysis methods, digital signal generation based on DDS spurious suppression, digital sampling, digital down-conversion, and other digital receiving technologies, researches on reducing the noise figure of digital array antenna systems and improving the technical approach to the dynamic range of the system, and proposes a distributed frequency source design idea beyond the traditional frequency synthesizer; Chap. 9 studies and analyzes microwave photonic digital array antennas and optically controlled phased array antennas, and elaborates on the solution to broadband active array antennas. Basic principles and implementation methods of optical real-time delay, microwave signal modulation and demodulation, optical analog-to-digital conversion, and microwave photon filtering.

The authors of this book have published more than 100 academic papers on active array antennas. These papers are the outcomes and findings of the author's research work on active array antennas for more than 30 years. The authors are closely aiming at the frontier of high-resolution earth observation microwave imaging radar technology, have been engaged in the research of synthetic aperture radar systems and active array antennas, and have rich professional knowledge and practical experience. Therefore, this book can be used as a reference for engineering and technical design and scientific researchers engaged in high-resolution synthetic aperture radar, phased array radar, and other new system phased array antenna technologies, and also has reference value for teachers and students of related majors in colleges and universities.

Chapters 1, 7, 8, and 9 of this book were written by Jiaguo Lu, Chaps. 2, 3, and 6 were written by Wei Wang, and Chaps. 4 and 5 were written by Xiaolu Wang. Yongxin Guo revised the full text and translated it into English. The whole book is planned and drafted by Jiaguo Luo and Yongxin Guo. Thanks to National Defense Industry Press and Springer Nature for their support, as well as the responsible editor for their hard work.

Hefei, China
December 2022

Jiaguo Lu

About This Book

This book addresses the “invisible and indistinguishable” technical challenges encountered in the high-resolution microwave imaging radar’s earth observation by focusing on the two elements of “frequency and polarization,” and researching and discussing the analysis, optimization, and design methods of active array antennas for high-resolution microwave imaging Radar. On the basis of discussing and introducing the basic principles, analysis methods, and performance parameters of active array antennas, aiming at low profile, high efficiency, and light weight, it systematically illustrates the realization of broadband, multi-band, multi-polarization, and shared-aperture architectures, analysis methods and engineering practices for active array antennas, studies hot technologies such as digital array antennas, microwave photonic array antennas, and active package antennas, proposes that the advanced stage of “active array antennas” is the new concept of “antenna array microsystems,” and discusses the outlook of the new technologies and development directions of active array antennas.

This book can be used as a teaching reference book for senior undergraduates and postgraduates majoring in radar, communications, microwave, and antennas, and can also be used as a reference for relevant professional scientific research and engineering technicians.

Contents

Acronyms

ADC	Analog to Digital Converter
AGC	Automatic Gain Control
AIP	Antenna in Package
AOC	Antenna on Chip
APD	Avalanche Photo Diode
ASK	Amplitude-shift key
AUT	Antenna under Test
BGA	Ball Grid Array
CDR	Compression Dynamic Range
CGA	Cylinder Grid Array
CPW	Coplanar Waveguide
CWDM	Coarse Wavelength Division Multiplexer
D	Directivity
DAC	Digital to Analog Converter
DAM	Digital Array Module
DBC	Direct Bond Copper
DBF-SAR	Digital Beam Forming Synthetic Aperture Radar
DDC	Digital Down Conversion
DDFS	Direct Digital Frequency Synthesis
DDS	Direct Digital Synthesis
DDWS	Direct Digital Waveform Synthesis
DFB	Distributed Feedback Laser
DNL	Differential Nonlinearity
DTR	Digital Transceiver
DWDM	Dense Wavelength Division Multiplexer
EDFA	Erbium Doped Fiber Amplifier
EIRP	Equivalent Isotropic Radiation Power
FET	Field Effect Transistor
FM	Frequency Modulated
FNBW	First-Null Beam Width
FO-WLCSP	Fan Out-Wafer Level Chip Scale Packaging

FRA	Fiber Raman Amplifier
FSK	Frequency-shift Keying
GMTI	Ground moving target indication
HBT	Heterojunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
HIC	Hybrid Integrated Circuit
HMSIW	Half Model Substrate Integrated Waveguide
HPA	High Power Amplifier
HTCC	High Temperature Co-fired Ceramic
IDS	Interface Data Sheet
INL	Integral Nonlinearity
INSAR	Interferometric Synthetic Aperture Radar
IPD	Integrated Passive Device
ISAR	Inverse-Synthetic-Aperture-Radar
LFM	Linear Frequency Modulation
LGA	Land Grid Array
LNA	Low Noise Amplifier
LTCC	Low Temperature Co-fired Ceramic
MCM	Multi Chip Module
MEMS	Micro-Electromechanical Systems
MESFET	Metal Semiconductor Field Effect Transistor
MIC	Monolithic Integrated Circuit
MIM	Mental Insulator-Mental
MLPCB	Multi-Layer Printed Circuit Board
MMIC	Monolithic Microwave Integrated Circuit
MPL	Microwave Photonic Link
NCO	Numerical Control Oscillator
NEσ0	Noise Equivalent Sigma Zero
NLFM	Nonlinear frequency modulation signal
OEST	Ohmic Electrode Sharing Technology
OTTD	Optical True Time Delay
PA	Power Amplifier
PCB	Printed Circuit Board
PGA	Pin Grid Array
PIN	Positive Intrinsic Negative
PLF	Polarization Loss Factor
PM	Phase Modulation
PSK	Phase-shift Keying
PSO	Particle Swarm Optimization
QFN	Quad Flat No-lead Package
RDL	Redistribution Layer
RF	Radio Frequency
RF-MEMS	Radio Frequency Microelectro Mechanical Systems
RIN	Relative Intensity Noise
RMS	Root Mean Square

SAM	Scalable Array Module
SAR	Synthetic Aperture Radar
ScanSAR	Scanning Synthetic Aperture Radar
SFDR	Spurious Free Dynamic Rang
SIC	Semiconductor Integrated Circuit
SIP	System In Package
SIW	Substrate Integrated Waveguide
SLL	Side Lobe Level
SNR	Signal-Noise Ratio
SOA	Semiconductor Optical Amplifier
SOC	System on Chip
SOI	Silicon-On-Insulator
SPDT	Single Pole Double Throw
SpotlightSAR	Spotlight Synthetic Aperture Radar
SRF	Self Resonance Frequency
STC	Sensitivity Time Control
StripSAR	Strip Synthetic Aperture Radar
T/R	Transmit / Receive
TGV	Through Glass Via
T-SAM	Tile Scalable Array Module
TSV	Through Silicon Via
TTD	True Time Delay
TTDL	True Time Delay Line
UWB	Ultra-Wide Band
VCSEL	Vertical Cavity Surface Emitting Laser
VIC	Vertical Interdigital Capacitor
VSWR	Voltage Standing Wave Ratio
WDM	Wavelength Division Multiplexing
WLP	Wafer level packaging

Chapter 1
Introduction

1.1 High-Resolution Microwave Imaging Radar

Microwave imaging radars can be categorized as either active or passive, with Synthetic Aperture Radar (SAR) being the most common active type. SAR is a typical active sensor and one of the important means for high-resolution earth observation. As shown in Fig. 1.1, the operating wavelengths are usually located in meter wave, microwave, millimeter wave, and submillimeter wave, and the side-view operation mode is generally adopted. Compared with other passive high-resolution sensors, such as visible imagers or infrared sensors, SAR has demonstrated obvious advantages in reconnaissance and surveillance performance. Its main features include (1) imaging is not limited by natural conditions, such as day and night, weather, etc., and can work 24/7 and in all-weather; (2) selecting the appropriate radar working wavelength can penetrate certain shelters to find the target; and (3) radar image resolution has nothing to do with wavelength, flight height, and radar range. Therefore, SAR is an essential milestone in the development of radar. Furthermore, SAR imaging technology enables the radar to determine the position and motion parameters of the observed objects and obtain images of targets and scenes. In addition, the SAR's capability to effectively differentiate moving targets from stationary backgrounds has contributed to its widespread adoption and popularity [1].

Because of the combination of high resolution, penetrability, all-weather, and all-day operation capabilities of SAR, these characteristics have established the vital position of SAR in the fields of intelligence reconnaissance, target reconnaissance, surveillance, and remote sensing technology, making it an indispensable and irreplaceable means of obtaining information on the earth's surface today.

SAR is an advanced surveying and mapping sensor. The surveying and mapping tasks include rapidly drawing and repairing basic surveying and mapping maps (topographic map scales of 1:10,000 and 1:50,000) for overseas areas and "hot spots." Spaceborne SAR is also an accurate and fast surveying and mapping method that processes SAR images to provide surveying and mapping for various purposes.

J. Lu et al., *Active Array Antennas for High Resolution Microwave Imaging Radar*,
https://doi.org/10.1007/978-981-99-1475-3_1

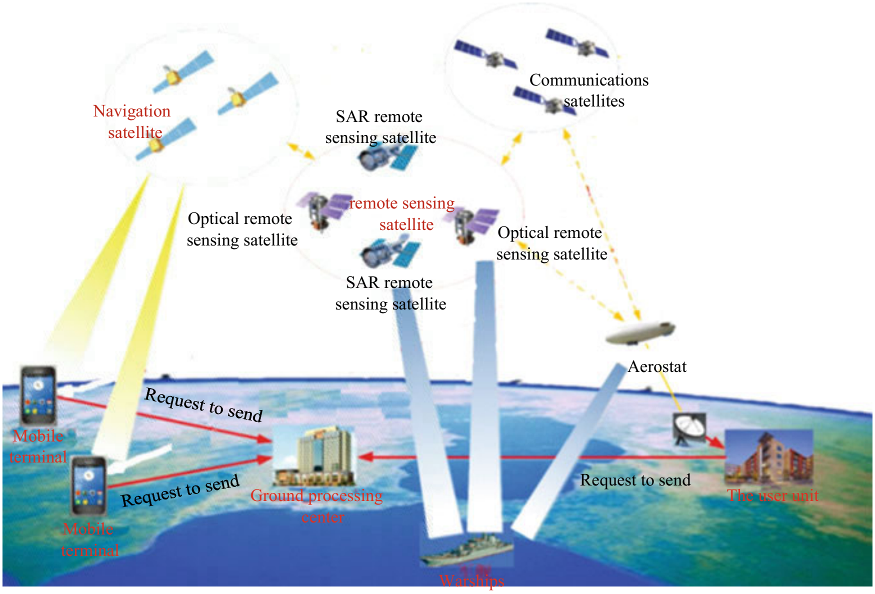

Fig. 1.1 Schematic diagram of high-resolution Earth observation system

As one of the most critical remote sensing and imaging methods, SAR has been widely used in resource and environmental surveys, disasters (flood, drought, storm surge, etc.) and ocean monitoring, agricultural yield estimation, geological, hydrological, and engineering surveys.

SAR is an advanced scientific device that integrates platforms, antennas, RF modules, signal processing, data transmission, image processing, and other modules. In fact, with the development of electronic technology and its application in imaging radar, today's SAR is entirely different from the original. In terms of resolution, SAR has developed from tens of meters to meters and decimeters. From the polarization perspective, it has grown from single to multi-polarization and full polarization. From the frequency point of view, it has developed from meter wave and microwave bands to millimeter wave and submillimeter-wave bands. In terms of applications, it has developed from military use to civilian use and scientific research. From the platform perspective, SAR technology has evolved from being mounted on unmanned aerial vehicles, helicopters, and manned fixed-wing aircraft, to being integrated into satellites and missiles.

How to obtain better images from imaging radar and how to turn images into more useful intelligence [2] require solving the following theory problems:

(1) Improve the individual quality of SAR as soon as possible. First, improve the existing SAR technology, with a particular focus on the realization of high-resolution imaging of small targets in strong interference, scattering, and high-density electromagnetic signals. Given that current SAR technology is a "zero IQ" system, it faces significant challenges in effectively tracking and competing with "smart targets".Therefore, the intellectualization of SAR is imperative.

(2) Maximize the group advantage of SAR combined with other types of sensors. These groups include SAR of different platforms, passive detectors, and other sensors such as infrared, optical, and acoustic. To this end, solving the fusion for the sensors of the same type and multi-type sensors data is necessary.
(3) Strengthen the image intelligence processing capability of SAR. SAR image intelligence processing is to transform massive SAR image data into usable and effective information, and it is the only way to realize the application of SAR technology. However, it is still difficult to quickly and automatically detect and identify the target of interest from SAR images, which seriously affects the application value of SAR technology and has become an urgent problem and bottleneck technology in the application of SAR technology.
(4) In-depth study of the new system and new technology of SAR so that SAR truly becomes the "jewel in the crown." New SAR systems and technologies are fundamental to improving performance, such as digital array imaging radar and optically controlled phased array imaging radar. Effectively solve the core problems of ultra-large instantaneous bandwidth signal generation, amplification, radiation, processing, and image application, especially the high efficiency, low profile, and light weight of large active array antennas, and welcome the new era of imaging/sensing in the network information system.

1.2 Development of Antenna Technology

Antennas and signal processing are the two core units of an electronic information system. The system of the high-resolution SAR antenna determines the radar system. Usually, the antenna accounts for about 90% of the cost, weight, and power consumption in an active phased array radar. The rapid progress of the antenna technology has promoted the development of radar system technology. Some say that if the painter Vincent van Gogh used his hands to create a masterpiece that amazed the world, then the antenna engineer used his wisdom to draw a pleasing radiation pattern in cyberspace [3], as shown in Fig. 1.2. It allows human beings to perceive and utilize information.

An antenna is a converter that converts the guided waves on the transmission structure into space free waves. The essence of antenna radiation is the problem of the macroscopic electromagnetic field. Electromagnetic waves are transmitted from the feed port of the antenna to the antenna radiation unit through the feeder. The prerequisite for an antenna to convert electromagnetic guided waves into space electromagnetic waves is to satisfy the boundary conditions of Maxwell's equations. The differential form of Maxwell's equations is usually composed of the full current law (Eq. 1.1), Faraday's law of electromagnetic induction (Eq. 1.2), the principle of magnetic flux continuity (Eq. 1.3), and Gauss's law (Eq. 1.4), which describe the changes in the electromagnetic field in space.

$$\nabla \times H = \frac{\partial D}{\partial t} + J \tag{1.1}$$

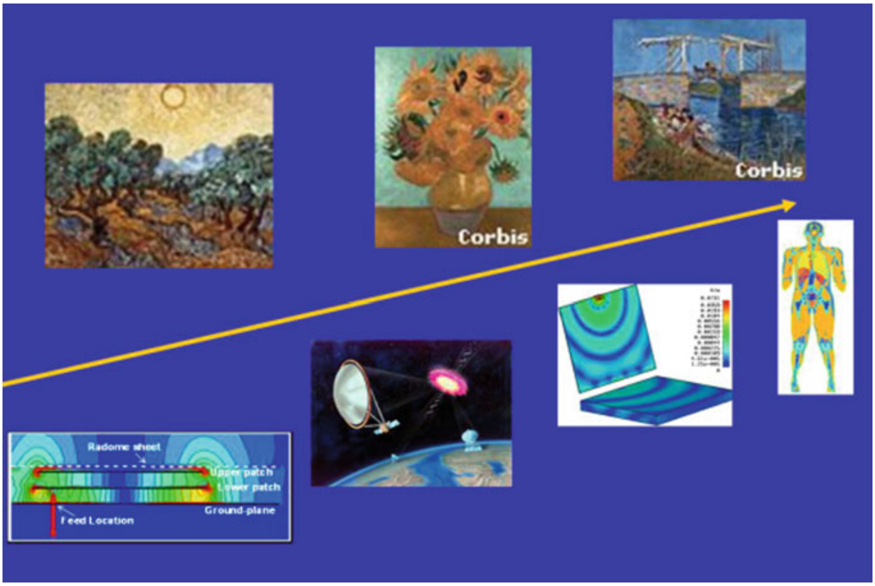

Fig. 1.2 The radiated electromagnetic field of the antenna

$$\nabla \times E = \frac{\partial B}{\partial t} \tag{1.2}$$

$$\nabla \cdot B = 0 \tag{1.3}$$

$$\nabla \cdot D = \rho \tag{1.4}$$

Equation 1.1 indicates that the magnetic field strength H's curl equals the full current density at this point (the sum of the conduction current density J and the displacement current density $\frac{\partial D}{\partial t}$). That is, the vortex source of the magnetic field is the full current density, and the displacement current can generate the magnetic field as well as the conduction current. Equation 1.2 indicates that the electric field strength E's curl equals the negative value of the time rate of change of the magnetic flux density B at this point. That is, the vortex source of the electric field is the time rate of change of the magnetic flux density. Equation 1.3 indicates that the magnetic flux density B's divergence always equals zero. That is, the B line has no beginning and no end. Finally, Eq. 1.4 is a generalization of Gauss's law of electrostatic field. That is, under time-varying conditions, the divergence of electric displacement D is still equal to the density of free charge bodies at this point.

When analyzing antenna radiation, because the time-varying charge and current are difficult to determine, and the electromagnetic field excited by the radiation source also affects the boundary conditions of the radiation source, solving Maxwell's equations will lead to mathematically complex problems. Therefore, an approximate solution method is often used in practice. The antenna radiation problem can be decomposed into two relatively independent problems, namely, determining the current distribution on the antenna and solving the spatial radiation field characteristics, that is, solving the problem of the external field of the antenna.

As a transmitting and receiving equipment of electromagnetic wave signal, an antenna directly affects the quality of the electromagnetic wave signal. Therefore, an antenna occupies a significant position in the electronic information system. An antenna system with a reasonable structure and excellent performance can not only minimize the requirements of an electronic information system for other parts of the system and save the overall cost of the system, but also improve the performance of the entire electronic information system. In modern electronic information systems, by processing the received signal, a phased array antenna can respond quickly to the environment, control its beam to point in the desired direction, and simultaneously aim its beam null direction to the unwanted interfering signal so as to maximize the signal-to-noise ratio of the desired signal. For example, with the development of modern cities and the increasing number of high-rise buildings, the electromagnetic environment in which an antenna is located is increasingly complex. Therefore, in order to improve the signal quality of electronic information systems, especially mobile communication systems, the research and development of active array antennas have attracted much attention.

As early as 1887, to verify Maxwell's electromagnetic wave theory, Hertz designed a transmitting antenna composed of a metal rod, a metal plate, a metal ball, and an induction coil, which was the first antenna for humanity. Since this antenna's generation, the antenna's development can be roughly divided into four historical periods.

1.2.1 Wire Antennas

In the early twentieth century, most research was on conducted wire antennas. Since the longer the wavelength, the smaller the attenuation in the propagation signal, the wavelengths used to achieve long-distance communication were above 1000 m. In this period, various asymmetric antennas appeared, such as inverted L-shaped, T-shaped, and umbrella antennas. Since the height of an antenna is limited by its structure, the size of an antenna is much smaller than its operation wavelength; this type of wire antenna belongs to the category of electrically small antennas. Later, due to the discovery of the existence of the ionosphere and its reflection on short waves, the research field of the short-wave band and medium-wave band wire antennas was opened up. At this time, an antenna size can be compared with its wavelength, which promotes the rapid development of antennas. During this period, tower broadcasting antennas, and other forms of antennas and antenna arrays, such as dipole antennas, loop antennas, long wire antennas, in-phase horizontal antennas, Yagi antennas, diamond antennas, and fishbone antennas, appeared. These antennas have higher gain, stronger directivity, and a wider frequency band than the initial long-wave antennas. During this period, theoretical work on antennas was also developed. Pocklington established the integral equation for wire antennas, proving that thin wire antennas' currents are approximately sinusoidally distributed.

1.2.2 Planar Antennas

During World War II, Radar greatly promoted microwave antenna technology development. Several theoretical frameworks for planar antennas were established, such as geometric optics, physical optics, and aperture field theory. At that time, due to the urgent need for warfare, antenna theory was not yet complete. Therefore, experimental research became an essential means of developing new antennas. Concepts such as testing equipment and error analysis were established, and methods such as field and model measurements were proposed. A large number of reflector antennas were used in radar systems. The primary beam electric scanning antenna appeared in this period to quickly capture targets.

From the end of World War II to the 1970s, antennas for microwave relay communication, troposcatter communication, radio astronomy, and television broadcasting have been extensively developed. Especially, the successful development of satellites and intercontinental missiles requires antennas to have high gain, high resolution, circular polarization, and broadband performance and to have fast beam scanning and precise tracking capabilities. During this period, the development of antennas was unprecedentedly rapid. On one hand, large-scale ground station antennas were constructed and improved, including the emergence of Cassegrain antennas, the correction of main and sub-reflectors, and the application of beams waveguide technology and high-efficiency antenna feeds such as corrugated horns. On the other hand, due to the advent of new phase shifters and computers and the need for simultaneous search and tracking of multiple targets, electronically scanned antennas have received renewed attention and have been widely used and developed. Furthermore, during this period, breakthroughs were also made in the research of broadband antennas, and broadband or ultra-broadband antennas such as equiangular helical antennas and log-periodic antennas appeared. At the same time, the statistical theory for analyzing antenna tolerances and the comprehensive theory for antenna arrays were developed.

1.2.3 Planar Array Antennas

In the 1980s, with the development of radar and communication technology, antenna frequency reuse, orthogonal polarization, fast beam scanning, and multi-beam antennas began to receive attention. Ground-based large-scale phased array radar and microwave synthetic aperture imaging radar and other technologies have entered the stage of practical research, and planar array antenna technology has developed rapidly. It began to be applied to ground intelligence radar and airborne radar. On the other hand, it began to study large-scale active phased array radar on the ground. Each antenna element of an active phased array radar antenna array contains active circuit modules. A transmit/receive (T/R) module is the critical component of an active phased array radar, which largely determines its performance. A T/R module with an integrated transceiver includes a transmitting branch, a receiving branch, a radio frequency switch, and a phase shifter. Each T/R module has a high power amplifier (HPA), filters, a limiter, a low noise amplifier (LNA), attenuators and phase shifters, a beam control circuit, and so on. It can be seen that the amount of equipment and cost of an active phased array radar that uses two-dimensional phase variation to control beam scanning are considerable. Among the phased array radars, passive phased array radars, used for satellite measurement and control and long-range detection of strategic targets such as ballistic missiles, came out the earliest. In contrast, active phased array radars appeared relatively late.

With the development of electronic information systems toward millimeter and submillimeter waves with shorter and shorter wavelengths, new millimeter wave antennas such as dielectric waveguides, surface waves, and leaky wave antennas have appeared. In addition, antenna arrays were developed from linear arrays to circular arrays and from planar arrays to conformal arrays. At the same time, due to the need for anti-interference, the ultra-low sidelobe antenna has been significantly developed. Furthermore, due to the emergence of high-speed and large-capacity computers, the method of moments and geometric diffraction theory have been applied in the simulation calculation and design of antennas to solve many simulation analysis problems that could not be solved or were difficult to be solved in the past.

The antenna structure and process technology also made significant progress during this period. In terms of antenna measurement technology, microwave anechoic chamber, near-field measurement technology, the use of celestial radio sources to measure antenna technology, and the establishment of an automatic measurement system controlled by a computer, etc., appeared in this period. The application of these technologies solves the measurement problem of large antennas and improves the accuracy and speed of antenna measurement.

1.2.4 Active Array Antennas

In the past 20 years, with the development of interdisciplinary fields, such as integrated circuits, microsystems, new materials, and other fields, the active phased array antenna technology has been developed in terms of integration, digitization, multiple function, high frequency, and ultra-wide bandwidth. Different from a traditional active phased array antenna, a distributed miniature transceiver unit is directly connected to the back of each antenna element. A miniature transceiver unit includes

Power Amplifier (PA), LNA, attenuator, phase shifter, and duplexer. Sometimes traditional frequency source, signal generator, RF signal receiving/transmitting channel, and digital-analog/analog-digital converter are also integrated into an active antenna module to realize a unified integration of antenna, RF and beam control in the electronic information system. We call this active phased array system as an active array antenna. Compared with traditional active phased array antennas, radio frequency systems, and modules, a large number of distributed, miniaturized, highly integrated, low-power active and passive chips have been adopted, and heterogeneous structures and heterogeneous 3D integration have been implemented in their internal structure. The active array antenna of this structure can reduce the feeder connection's power loss and give the system a higher signal-to-noise ratio, better impedance matching, and a wider frequency band.

A traditional radar system comprises antennas, transmitting, receiving, signal processing, data processing, system monitoring, and other subsystems. The emergence and development of active array antennas have changed the form of electronic information systems. For example, a radar system comprises only three parts: an active array antenna, connecting cable, and a general digital processor [4]. High-density, high-efficiency, high-power, and multi-functional active array antennas are closely related to develop new semiconductor devices, materials, and advanced integration and packaging technologies.

1.3 Active Array Antennas

Phased array antennas are divided into passive array antennas and active array antennas. Active phased array radars have become a mainstream radar development, including high-resolution SARs. In high-resolution SAR, an active array antenna is the only choice to effectively alleviate the contradiction between high resolution and wide swath. The large aperture, low profile, high efficiency, and light weight of the antenna are eternal pursuits of antenna engineers. Figure 1.3 shows a schematic diagram of a large active array antenna for the spaceborne SAR. The large aperture of the antenna is the most direct way to obtain the high-power aperture product of the radar. Due to the rocket's launch envelope limitation, a larger antenna aperture can be obtained with a lower antenna section thickness. The high efficiency of the antenna enables the antenna to achieve two-way effects of transmission and reception. Therefore, antenna efficiency is an essential parameter that spaceborne SAR prioritizes. The phased array radar technology can meet the requirements of various advanced radars and has excellent potential to improve the "four countermeasures" capability of the radar in modern warfare. In addition, the development of computers, integrated circuits, and hybrid integration technology has laid a solid foundation for developing and applying active array antenna technology.

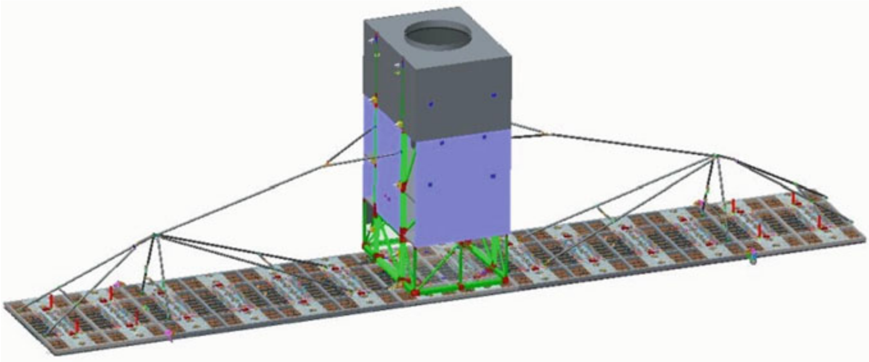

Fig. 1.3 Large aperture spaceborne active array antenna

1.3.1 Characteristics of Active Array Antennas

Active array antenna technology is applied to SAR, which is especially suitable for multimode fast switching to realize multiple functions of SAR and enable a radar to have the ability of rapid response, self-adaptation, and fault weakening. According to the characteristics of SAR and the development of technology, the following characteristics of active array antenna technology are most worthy of attention:

(1) **An active array antenna is a critical way to improve the performance of SAR**

High resolution, multimode, multi-polarization, and multi-band are essential development directions of synthetic aperture imaging radar. Active array antennas have significant advantages in high-resolution imaging and multimode realization.

SARs with different loading platforms have different requirements for effective radiated power. Reasonable realization of effective radiated power is the basis of radar work. Therefore, we must pay attention to the product of antenna aperture and average transmit power, that is, the antenna size is as large as possible, and the transmit power is as large as possible. As we all know, the azimuth resolution of SAR is half of the azimuth size of the antenna. Therefore, a smaller antenna size is better. On the other hand, a large antenna aperture is an important way to reduce the cost of SAR. Therefore, achieving high resolution and using a large antenna aperture is a contradiction. An active array antenna effectively alleviates this contradiction. When the resolution is low, the large aperture of the antenna can be effectively used. On the other hand, when the resolution is high, the antenna beam can be broadened by phase weighting, equivalent to shortening the antenna aperture.

Compared with a conventional vacuum tube or solid-state transmitter-based SAR, an active array antenna-based SAR system can reduce the loss of transmitting and receiving feeder, realize signal power synthesis in space, and improve the effective radiation power of radar. At the same time, for the active array antenna, the low noise amplifier is generally placed behind the antenna element, which reduces the noise of the receiving system and improves the sensitivity of the radar receiving system. The active array antenna is the main measure to achieve a high signal-to-noise ratio and sensitivity of SAR.

Compared with a mechanical scanning antenna, an active array antenna has the characteristics of flexible beam scanning, no inertia, and fast speed. It shows unparalleled advantages when the SAR works in multiple modes. Especially for the spaceborne SAR, an active array antenna dramatically improves the range imaging width of the ScanSAR mode, the implementation of spotlight mode, and the beam pointing accuracy. Active array antenna beam scanning is flexible, inertia-free, and fast, which enables the SAR to achieve precise motion compensation, thereby improving the quality of radar imaging and ensuring the realization of high-resolution imaging.

(2) **An active array antenna is beneficial to improving the anti-jamming capability of SAR**

The purpose of SAR is to obtain the intelligence information of the selected area, and the purpose of jamming the radar is to prevent, confuse or delay obtaining the information of the selected area. For intelligence or tracking radars, the effectiveness of jammers is generally measured by the reduction in the radar's search or tracking range. For SAR, a jammer is to prevent the reconnaissance of image information in an area, and the effectiveness of a jammer is generally measured by the sensitivity reduction of the SAR.

In order to improve the anti-jamming capability, the commonly used technical means include high effective radiated power, low or ultra-low sidelobe antennas, large time-bandwidth product signals, and dual/multistatic radar systems. These techniques are crucial to improve the radar's ability to anti-interference. In addition, active array antennas are beneficial to improve the total antenna radiation power and form high-gain, low-sidelobe antennas. Spatial filtering technology can also achieve adaptive antenna zeroing and suppress interference and clutter. At the same time, it is also conducive to realizing signal energy management, rational use of signal energy, and improving radar anti-jamming self-defense distance.

(3) **An active array antenna is conducive to the standardization and modularization of SAR, thereby reducing cost and improving reliability**

The improvement of radar performance requirements and the deterioration of the working environment make the composition of the radar system more and more complex, the development cycle prolonged, the development cost increased, and the technical risk increased. To adapt to the evolving needs of modern radar systems, researchers have focused on strengthening the research on basic radar technologies, such as simulation technology, special testing equipment, new processes, structures, and materials. However, another promising solution to address these needs is the use of active array antennas. An active array radar can use many consistent standard components (such as T/R modules), which is conducive to standardization, modularization, and lower production costs.

Microelectronics technology is one of the effective measures to reduce the volume and weight of radar, and it is an important condition to ensure that the radar can normally work in harsh environments. Microelectronics technology is also significant in improving system reliability and signal and data processing speed. It is also a key measure to reduce the production cost of an active array radar. In addition, the development of microelectronics has facilitated the rapid miniaturization of a series of components.

Despite the many advantages of active array antennas, the decision to use them in practical applications should be based on the specific needs and requirements of the application. Firstly, we should focus on analyzing radar tasks. Secondly, we should analyze the cost of using active array antennas and consider technical risks, development cycles, and the impact of production costs. Then a reasonable choice can be made.

Active array antenna technology is indeed a technology that will give SAR a "new life." Moreover, with technological progress and large-scale use, its cost is more affordable. However, there are still many challenges in terms of its technology, which mainly lie in:

(1) The use of large-scale active array antennas in space pays more attention to the low profile, high efficiency, and light weight performance of the antenna, and it is necessary to solve the problem of effective integration of electromechanical and thermal integration of the antenna (including radio frequency, analog, digital, power supply, etc.).
(2) In the case of wide-band and wide-angle scanning, it is necessary to solve the problems of mutual coupling between antenna elements and the "dispersion" of the beam in space and time.
(3) Active array antenna multi-channel technology is one of the most effective methods to alleviate the contradiction between high resolution and wide swaths of SAR. In a wide frequency band, it is necessary to solve the consistency and stability of the amplitude and phase of multiple receiving channels.
(4) An active array antenna needs to solve the monitoring and compensation of signal amplitude and phase in the static state, meanwhile solve the real-time measurement of antenna array deformation and real-time compensation of signal amplitude and phase in the dynamic situation (in flight). However, these real-time measurements and real-time compensations under dynamic conditions are extremely difficult.

In addition, technologies such as high thermal conductivity materials, semiconductor integrated circuits, and three-dimensional hetero-heterogeneous hybrid integration need to be developed simultaneously.

1.3.2 Semiconductor Integrated Circuit Technology

The rapid progress of semiconductor integrated circuit (SIC) and packaging technology has extensively promoted the development and advancement of active array

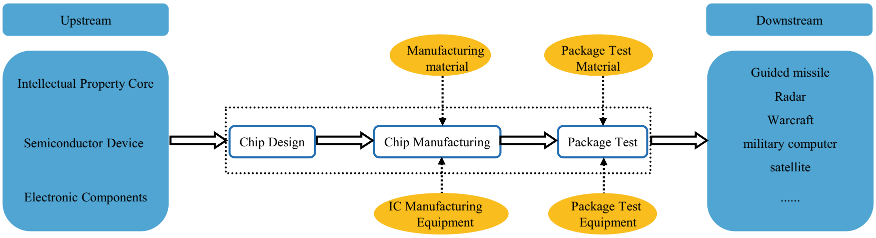

Fig. 1.4 Integrated circuit industry chain

antennas. The relationship between SIC and electronic information-related industries is shown in Fig. 1.4.

The core of an active array antenna is to change the antenna from a passive system to an active system. Therefore, an active antenna contains a large number of active circuits, and most of them are microwave active integrated circuits. At the same time, due to the arraying and expansibility of the antenna system, the scale of the antenna array of this system is huge, and the number of channels of the antenna array has reached thousands. Moreover, it is under development toward digitization. In general, an active phased array antenna system is a planar structure. Therefore, low profile, high efficiency, and light weight are significant for high-resolution SAR active array antennas. The microwave integrated circuit is the key to realizing these characteristics of an active array antenna.

Microwave integrated circuits (MICs) are a type of integrated circuit that utilizes advanced RF complementary metal oxide semiconductor (CMOS), silicon germanium (SiGe), gallium arsenide (GaAs), and other semiconductor processes to process microwave and analog signals. This processing includes amplification, transformation, calibration, comparison, and transmission of signals at microwave frequencies. A microwave system in radar is mainly composed of a microwave transceiver channel, modulation and demodulation circuit, and microwave signal generation. With the development of microwave integrated circuit technology and digital technology, the integration degree of microwave chips is getting higher and higher. An integrated circuit combines multiple components on a chip, improving the chip's performance and reducing cost. The multi-functional microwave single-chip can integrate small-signal downstream (receiving) and upstream (transmitting) circuits. The downstream circuits include low-noise amplifiers, frequency mixing, gain control, and even high-performance Analog to Digital Converter (ADC). The upstream part of the circuit also includes signal generation, frequency mixing, power amplifier, etc. The improvement of the performance and reliability of the multi-functional microwave integrated circuit chip and the cost reduction have greatly promoted the improvement of the sampling frequency and bandwidth of the radar microwave signal.

Developing semiconductor materials and process levels is the basis and prerequisite for the rapid development of integrated circuits. A generation of materials and a generation of processes will produce a generation of devices and a generation of circuits. Silicon (Si) has always been the dominant material in semiconductor technology. In recent years, integrated silicon (CMOS and BiCMOS) RF technology has greatly progressed. However, many applications can only use the compound semiconductors such as indium phosphide (InP) and gallium nitride (GaN).

In the semiconductor industry, silicon (Si) and germanium (Ge) are generally referred to as first-generation semiconductor materials, while Gallium Arsenic (GaAs), Indium Phosphide (InP), and their ternary and quaternary alloys are called second-generation semiconductor materials. Wide-bandgap (E_g > 2.3 eV) semiconductor materials have developed very rapidly and become the third generation of semiconductor materials, mainly including silicon carbide (SiC), diamond, and Gallium Nitride (GaN). Wide-bandgap semiconductor devices, as the third generation of semiconductor devices, will effectively improve the power level, radiation resistance, high junction temperature, and other capabilities of current microwave devices. InP devices are very suitable for the high-end millimeter-wave band and solve the solid-state problem of current millimeter-wave devices. Improving Microelectromechanical Systems (MEMS) devices and RF-MEMS devices technology mainly applies switches, phase shifters, attenuators, and so on. GaAs is a reasonable microwave transmission medium material, which is very suitable for the substrate of monolithic microwave integrated circuits. Because of the general promotion of GaAs technology, the development of monolithic microwave integrated circuit technology is promoted.

The development of multi-chip integration technology can integrate different types of semiconductor devices (silicon and compound semiconductors) and passive components (including filters and antennas) on a single substrate, and passive components are embedded in multiple stacks to achieve high Q value and miniaturization. Short-distance interconnects enable higher performance and denser circuits than traditional printed circuit boards and have been achieved in recent years in multilayer substrate materials and integration and assembly technologies, including laminates, ceramics, and integrated passives. In addition, the tremendous progress of an integrated circuit has led to the continuous improvement of integrated circuit density and system performance. However, as frequencies increase, interconnect losses between multiple integrated circuits increase rapidly, while multi-chip integration typically lacks the geometric and interconnect definition to achieve high-density integration. This requires the study of new technologies to solve the parasitic effects of micro-scale interconnection.

In the wafer-level heterogeneous integration (small chip, wafer bonding, and epitaxy transfer) approach, Si and compound semiconductor devices are integrated after the respective processes of Si and compound semiconductors are independently completed. This poses minimal risk to existing manufacturing processes and provides tight vertical integration between compound semiconductor (InP) and Si (CMOS and BiCMOS) devices. Among them, small chip integration can integrate various semiconductor chips on a complete CMOS wafer, such as gallium nitride High Electron Mobility Transistor (HEMT), indium phosphide double heterojunction bipolar transistor (HBT), and Si MEMS. In addition, this bonding method breaks the chip size reduction barrier for compound semiconductor technology.

Moore's law is approaching the physical limit [5]. Before the von Neumann architecture has not changed, the contradiction between the slowdown of chip performance improvement and the geometric progression of data demand became increasingly prominent. Under the circumstance that the chip volume cannot be further reduced effectively, multi-layer and three-dimensional heterogeneous integration (including new materials, thermal management, modeling, circuit/system design) technology is an important research topic that will promote the understanding and expectations of active array antennas.

1.3.3 *Hybrid Integrated Circuit Technology*

Hybrid Integrated Circuit (HIC) technology uses thick/thin-film technology, micro-assembly technology, and packaging technology to integrate semiconductor chips, passive components, etc., and is one of the main approaches to achieve miniaturization and light weight of electronic equipment. Figure 1.5 is a schematic diagram of the relationship between monolithic and hybrid integration. Monolithic integration is an eternal pursuit, and hybrid integration is a further and higher stage of monolithic integration. Hybrid integration technology involves a complex multi-level and multi-disciplinary technology system. It can be divided into a series of basic theories, manufacturing practices, and application technologies such as design technology, multi-layer interconnect substrate technology, micro interconnects technology, high air-tight packaging technology, and reliability evaluation and applications, involving electromagnetism, materials science, mechanics, physics, chemistry, and microelectronics, and many other disciplines.

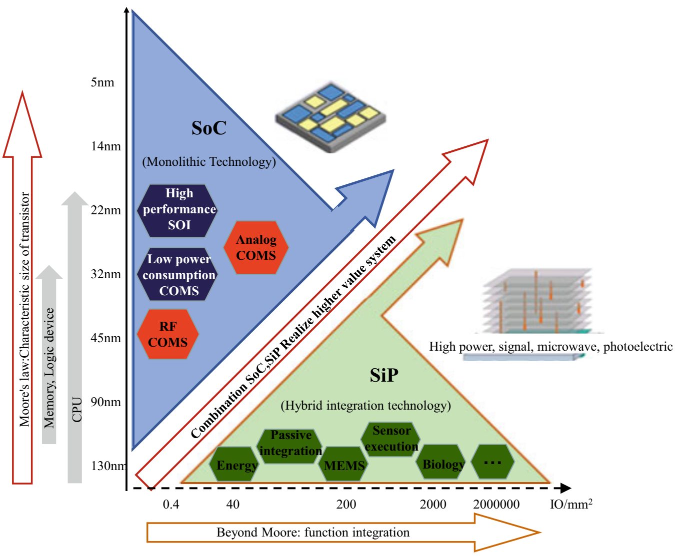

Fig. 1.5 Hybrid and monolithic integrations