Review of the Evolution of Phased-Array Radar

Yuhang Wei [*]

Electronic information Engineering College, Beijing Jiaotong University, Beijing, China, 100091

ABSTRACT: Ever since the human race discovered how bats locate, it has never stopped exploring the use of various waves to analyse and determine the position of objects to be detected. This paper describes the development of radar detection technology since World War II by investigating and analyzing the development of equipment technology in various countries' militaries, and analyzing the bottlenecks of existing technology, pointing out the possible future direction of development. This paper concludes that the most likely breakthrough direction for the new phased array radar is a breakthrough in materials science (SiC-GaN) technology, which will enable the phased array module to be fully digitalised.

1. INTRODUCTION

The technology of phased arrays has been continuously explored since it was introduced in 1900. The phased array technology was theoretical until 1940, when in the Second World War, the American Lincoln Laboratory first controlled the direction of the signal waves by mechanically controlling the movement of the elements.

Over the 80 years of its development, phased array radar has gone through three main phases: passive, active and digital. Faced with the air defence requirements of the Second World War, Britain first built the first radio detection station on the East Coast in 1937. In the 1960s, the Advanced Research Projects Agency (ARPA) began the world's first technology development programme for a passive phased-array radar, which demonstrated a two-position, electronically controlled, computer-controlled phased-array radar [1]. With the US military race against the Soviet Union, the military demanded higher power radars. The Defense Advanced Research Projects Agency's (DARPA) microwave and millimeter wave monolithic integrated circuit program [2] first established advanced tools such as GaAs circuit integrated chips, multi-chip fabrication processes, precise computer control and circuit modeling tools. DPRPA [3] carried out simulation-based methods to replace models of traditional design solutions, so design times were greatly reduced. Beginning in the 1990s, the Active phased array radars were deployed in a new generation of military systems because of the efficiency of their design. After the 1990s, the military again demanded higher levels and higher power from radar systems.

By investigating and analyzing the development of military equipment technology in various countries, this paper analyzes the bottleneck of existing technology, and describes the development of radar detection technology since World War II. The main significance of this paper is to extrapolate the history of phased-array radar development by revisiting the history of phased-array radar development to infer several highly likely future directions: circuit layout and material optimization. The current development of integrated circuits has reached a bottleneck, while breakthroughs in materials chemistry are still very promising.

2. PASSIVE PHASED ARRAYS

Passive phased array radar transmitters were first widely adopted by the military in the 1970s for their relatively low cost and high reliability. Passive array architectures require the use of low-loss beamformers and phase shifters, as there is a lot of loss in the output path of the signal. Passive phased array radars have only one central transmitter and one receiver. The high frequency energy generated by the transmitter is automatically distributed by computer to the individual radiators of the array, and the reflected signal from the target is uniformly amplified by the receiver. Passive phased array radar has only one transmitter and one receiver, so if it is damaged, it will not work.

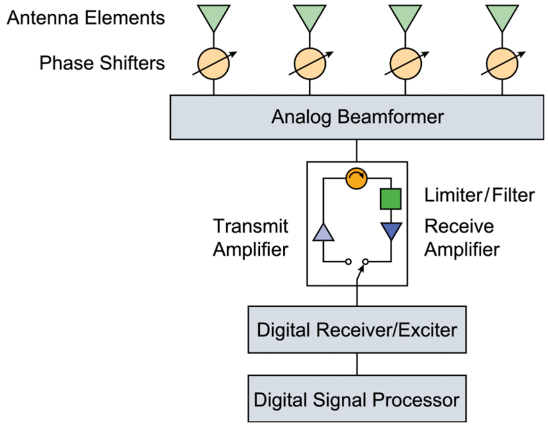

Figure 1 Passive phased array architecture [1]

---

*Corresponding author. Email: 19721024@bjtu.edu.cn

3. ACTIVE PHASED ARRAY RADAR

To overcome the RF losses introduced by passive phased arrays, transmit and receive amplifiers can be distributed over each element of the array. The advantage of this approach is that the RF losses are much lower. This change reduces the noise figure of the array by a factor of two or more, resulting in increased sensitivity and a longer operating range. The second advantage is that the array of the active phased array architecture allows the possibility of failure due to the loss of the transmit amplifier at the element level. If the failures are distributed randomly throughout the array, up to 10% amplifier loss can be tolerated while maintaining acceptable array performance.

With the end of the Second World War and the advent of the computer age, Dolph [5] posted a paper on controlling the beamwidth of arrays with a reduction in amplitude. He mapped the array factor of a linear array to the Chebyshev polynomial in order to obtain equal peak partial levels at a specified level below the peak of the main beam [6]. In 1958, Houston Aircraft Manufacturing invented a new planar array design that could be computer-controlled in elevation and azimuth for scanning purposes, which was eventually placed on the main mast of the world's first nuclear-powered cruiser, the cruiser Long Beach. As seen in fig.2, its active phased array was large, and this array was known as the billboard radar.

In 1957, the bypass flap eliminator was invented at General Electric. They were designed with a small auxiliary omni-directional antenna pointed in the same direction as the main antenna to eliminate the residue of interference. In 1968, Widrow and Mantey [7] used the adaptive technique of the Least Mean Square (LMS) algorithm for automatic adjustment. The difference between the GE algorithm and the LMS algorithm is that the GE method is suitable for radar detection, while the LMS method is suitable for communication system.

Figure 2 Nuclear Powered Cruiser USS Long Beach

4. SOLID-STATE TRANSMIT AND RECEIVE MODULES

In the early 1990s, Lincoln Laboratory worked with the U.S. Air Force and Navy to develop a program for the development of space-based radar modules. The goal of the program was to produce a module with higher hardware requirements using MMICs and new materials for digital circuitry that would allow it to accurately control the phase over the expected temperature range, and Figure 8 briefly illustrates the configuration of this module. This system is currently used in commercial satellite communication systems [9].

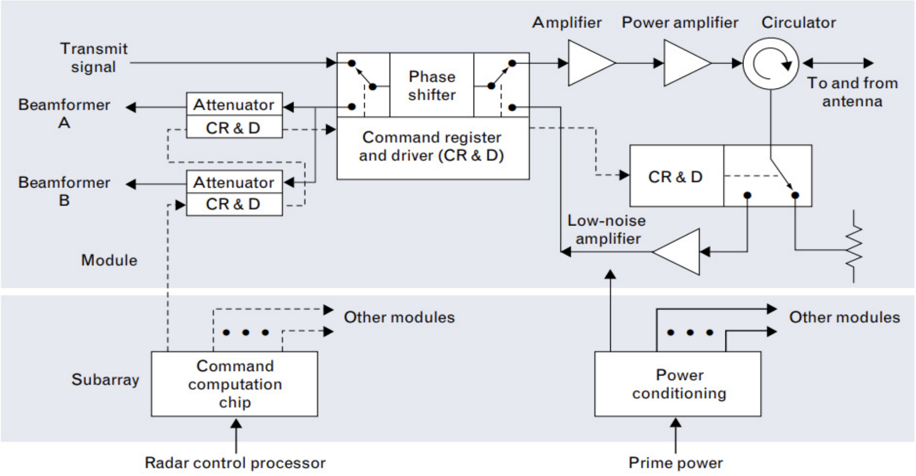

Figure 3 Diagram for desired L-band transmit/receive module for space-based radar applications [8]

The module contains switches that select either the transmit or receive paths. The receive path contains two attenuators to illuminate two displaced phase centers, represented by beamformers A and B. The transmission path includes a phase shifter and a power amplifier to achieve the transmission power level required by the radar.

5. EVOLUTION OF SOLID-STATE ACTIVE COMPONENTS

The feasibility of an all-solid-state phased array was proposed and demonstrated in the 1960s by Mel Vosberg. Early phased arrays were based on variable phase shifters in conical tube waveguides and high-power vacuum tubes.

But with the large number of applications containing integrated circuit arrays, compact size, low weight, low cost and high reliability have become the most important advantages of these circuits.

In the 1960s the technology for manufacturing monolithic silicon was not mature and the early level of materials and processing technology was very limited, resulting in low production yields and inadequate performance of monolithic components. Therefore, it is very necessary to combine integrated circuit with traditional components. Transistors, switches for dipole phase shifting circuits and passive components were all on a ceramic substrate and connected to the integrated circuit with wires. In the 1970s, several companies in the USA and West Germany, with the support of the Ohio Air Force Base in the USA, built the first experimental airborne radar.

6. GAAS MONOLITHIC INTEGRATED CIRCUITS

GaAs is recognized as the most promising substrate material because of its high carrier mobility and is therefore suitable for signals at high frequencies, particularly in the microwave (1GHz-30GHz) and millimetre wave (30GHz-300GHz) frequency ranges. The highest possible frequency and short wavelength to achieve high resolution requirements will be required, while low frequency signals have a better basis for high power search and surveillance related functions.

Back in the late 1960s, Texas Instruments reported on the initial implementation of frequency components for microwave and millimetre wave. In the same year, low-noise field-effect transistors and microwave amplifiers were similarly demonstrated at the IBM laboratory in Zurich, Switzerland [10].

These pioneering efforts provided the way for many subsequent difficulties to be solved. Higher frequencies include the advantage of narrow waves for radar, improving the high resolution of the radar signal. But these theoretical breakthroughs also placed more stringent demands on the GaAs manufacturing process, which was also required in the optical, metallurgical, and photolithographic processes.

The electrical inertness of the epitaxial layers on the surface of semi-insulated GaAs as a base is very beneficial for low insertion losses and also reduces low coupling losses between closely spaced circuit elements. Detailed measurements of the dielectric constants of GaAs have been carried out at Lincoln Laboratory. These results show that when the fabrication process is good, these materials will actually negate the loss characteristics we are concerned about due to frequency variations. As the quality of components becomes higher and higher, the need for higher substrate performance to achieve electrical isolation of electrical components emerges. To achieve this vision, GaAs can be passivated by proton bombardment to create crystal defects and thus semiconductor properties.

7. ARRAY CALIBRATION & TESTING

Due to the array arrangement of phased array antenna, multiple channels need to be accurately calibrated to determine whether they can point to the correct direction, and can be used to control the wave measurement level of the radar antenna. The airborne phased-array radar contains thousands of receiving and transmitting devices, and these obviously require computers to assist with flight calibration. Such technology requires the inter-coupling of internal arrays to transmit and receive signals from the elements in the array.

The signals measured between all pairs of elements in the array [11] are allowed to give a complete picture of the relative amplitude and phase corresponding to each signal in the array beamformer. The two systems can therefore be simply calibrated. In addition to this well-known method, there are many other methods such as adaptive rejection techniques [12], compensation for changes in the radiation pattern of the array elements [13] and the influence of the viewing angle radiation elements [14].

8. DISCUSSION

In summary, the future breakthroughs in phased array technology are in two main areas. Firstly, they are the breakthroughs in phased array models, which are difficult to achieve in the short term. Secondly, they are the advances in materials science, through breakthroughs in semiconductor materials to achieve better electrostatic isolation. It can be predicted that in the near future, low-cost solid-state array modules, broadband analog and digital converters will bring great prospects. In the past seven decades, the development of phased array radar is just the tip of the iceberg. In this era, phased array radar technology is just getting started.

9. CONCLUSION

Technology has shifted from the development of electronic beams after the end of World War II to various phased arrays to meet the needs of various ground and air radars, and phased arrays are also considered to be an essential key component in modern and future warfare. With the development of the times, the challenges and difficulties of phased arrays in military and civilian systems are increasing. The European Union, the United States, and many other countries have made significant contributions to phased array radar capabilities.

The limitation of this paper as it currently exists is that it does not touch on the current state of existing developments, as these relate to defence technology, which is top secret in any country's Ministry of Defence. And there is no way to experiment with many of the existing theoretical models one by one to see if they work. Future research will combine a large number of experimental data to further infer the development direction of technology at the level of data analysis.

REFERENCES

1. J. S. Herd and M. D. Conway, “The Evolution to Modern Phased Array Architectures,” in Proceedings of the IEEE, vol. 104, no. 3, 2016, pp. 519-529.
2. E. D. Cohen, “Military applications of MMICs”, IEEE 1991 Microwave and Millimeter-Wave Monolithic Circuits Symposium. Digest of Papers, 1991, pp. 31-34,
3. D. C. Barton, “MAFET thrust 1 program to develop MW/MMW design tools”, IEEE Aerospace Conference Proceedings Dig., 1998, pp. 239-248.
4. M. Rosker et al., “The DARPA wide band gap semiconductors for RF applications (WBGS-RF) program: Phase II results”, Proc. CS MANTECH, 2009, pp. 1-4.
5. Dolph, C. L.. A current distribution for broadside arrays which optimizes the relationship between beam width and side-lobe level. Proc Ire, 35(6), (1946) pp. 335-348.
6. R. L. Haupt and Y. Rahmat-Samii, “Antenna Array Developments: A Perspective on the Past, Present and Future,” in IEEE Antennas and Propagation Magazine, 57(1) (2015) pp. 86-96, doi: 10.1109/MAP.2015.2397154.
7. B. Widrow, P. E. Mantey, L. J. Griffiths and B. B. Goode, “Adaptive antenna systems,” in Proceedings of the IEEE, 55(12), 1967, pp. 2143-2159, doi: 10.1109/PROC.1967.6092.
8. Fenn, A. J., Temme, D. H., Delaney, W. P., & Courtney, W. E. The development of phased-array radar technology. Lincoln Laboratory Journal, 12(2) (2000) pp.321-340.
9. J.J. Schuss, J. Upton, B. Myers, T. Sikina, A. Rohwer, P. Makridakas, R. Francois, L. Wardle, W. Kreutel, and R. Smith “The IRIDIUM® Main Mission Antenna Concept,” 1996 IEEE Int. Symp. on Phased Array Systems and Technology, 15–18 Oct. 1996, Boston, pp. 411–415.
10. W. Bächtold, W. Walter, and P. Wolf, “X and Ku Band M.E.S.F.E.T.,” Electron. Lett. (UK) 8(2), 1972, pp. 35–37
11. H.M. Aumann, A.J. Fenn, and F.G. Willwerth, “Phased Array Antenna Calibration and Pattern Prediction Using Mutual Coupling Measurements,’’ IEEE Trans. Antennas Propag. 37 (7), 1989, pp. 844–850.
12. H.M. Aumann and F.G. Willwerth, “Phased-Array Calibration by Adaptive Nulling,” Technical Report 915, Lincoln Laboratory, 1991, ESD-TR-91-047, DTIC #ADA238562.
13. H.M. Aumann and F.G. Willwerth, “Phased Array Calibrations Using Measured Element Patterns,” 1995 IEEE Antennas and Propagation Soc. Int. Symp. Digest 2, Newport Beach, Calif., 18–23 June 1995, pp. 918–921.
14. H.M. Aumann and F.G. Willwerth, “Application of Beamspace Techniques to Phased Array Calibration and Fault Compensation,” 1991 Antenna Measurement Techniques Assoc. Symp., Boulder, Colo., 7–11 Oct. 1991, pp. 10B/9–13.