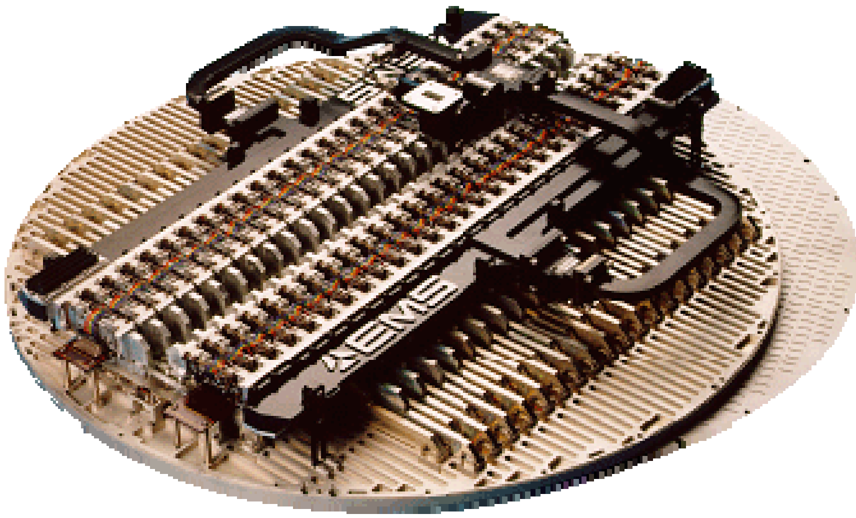

White Paper

Passive Phased Arrays for Radar Antennas

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1 Introduction

Phased array antennas offer many advantages to the radar system designer, such as agile beams, low profile, and scalability. There are two types of phased arrays; passive and active. Passive phased arrays have a central transmitter and receiver, with phase shifters located at each radiating element or subarray. The passive array is the least expensive phased array because of its low number and cost of components[1]. Active arrays use Transmit/Receive (T/R) modules to provide the last stage of amplification for transmitted signals, the first stage of amplification for receive signals, and provide both amplitude and phase control at each radiating element. The use of T/R modules in active arrays provides the advantages of amplitude control, low loss, and graceful degradation over passive arrays. Given these advantages, one could assume that all phased arrays in development are active. In fact, despite the large investment that the U.S. Government has made in the development of T/R modules beginning in 1964, the high cost and low efficiency of the modules has proven to be an obstacle to development of active phased array antennas. For example, the United Kingdom's ASTOR (Airborne Stand-Off Radar) program, which is expected to have initial operational capability in 2007 and full fleet in operation in 2008, is an airborne, ground-surveillance radar which employs a passive phased array design. Raytheon chose to use phase shifters, rather than T/R modules, citing concern over size, weight, power and technical risks. Another example is the AN/SPQ-9 Surface Surveillance and Tracking Radar, developed by Northrop Grumman Norden Systems. It is a track-while-scan radar which uses a phased array for a gunfire control system on U.S. Navy surface combatants. The antenna provides for three beams, and it will be installed on cruisers, destroyers, amphibious ships and aircraft carriers. A final example is the Joint Surveillance Target Attack Radar System (JSTARS), an airborne phased array used in a synthetic aperture radar. It is a long-range, air-to-ground surveillance system designed to locate, classify and track ground targets in all weather conditions, and it provides the combatant commanders with the best situational awareness data available. This paper outlines the problems inherent in active phased array antennas, and discusses the advantages of passive phased array antennas for radar systems.

2 Types of Phased Arrays

The two types of phased arrays are shown in Figure 2-1. The right side of the figure is a passive phased array. It is similar to a mechanically scanned antenna, in that it has a central transmitter and receiver along with a central feed network. Unlike a mechanically scanned antenna, it has an electronically controlled phase shifter immediately behind each radiating element. The phase shifters allow the beam to be steered electronically. On the left side of

[1] D. Parker & D. C. Zimmermann, "Phased Arrays - Part I: Theory and Architectures," IEEE Trans. Microwave Theory and Tech., vol. 50, pp.678-687, 2002.

the figure is an active phased array block diagram. Note that it has a T/R module placed immediately behind each radiating element. Both these arrays offer several advantages over mechanically steered arrays. They have excellent beam agility, they are very reliable since they have no moving parts, and they minimize radar cross section. In the passive phased array, the only active elements are the phase shifters, which are extremely reliable. Furthermore, if they fail randomly, up to 5% of the phase shifters can fail before the antenna's performance degrades enough to require replacement of the phase shifters.

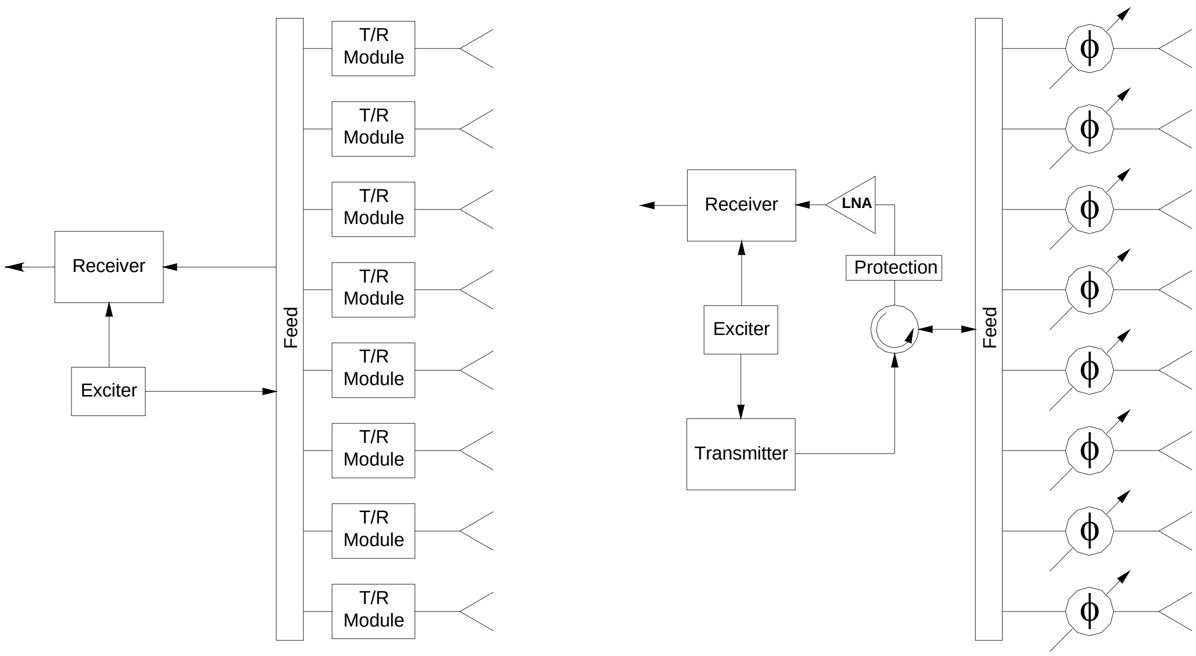


Figure 2-1: Block diagrams of active and passive phased arrays

3 Active Phased Arrays

3.1 *Typical T/R Module Components*

3.1.1 Block Diagram

The RF block diagram of a typical T/R module is shown in Figure 3-1. As the figure shows, amplitude and phase control are provided by a variable attenuator and a variable phase shifter. Since these components are placed at the input to the high power amplifier (HPA) and the output of the low noise amplifier (LNA), they have minimal impact on the radiated power and noise figure of the module. A switch follows these components to provide selection between transmit and receive functions. At the other end of the module, a circulator acts as a duplexer for transmit and receive. The remaining elements are the HPA and LNA. Note that this is a basic T/R module block diagram. Requirements such as polarization diversity, transmit or receive linearity, waveform diversity and/or low phase and amplitude errors will add complexity to both the module design and its solid-state components.

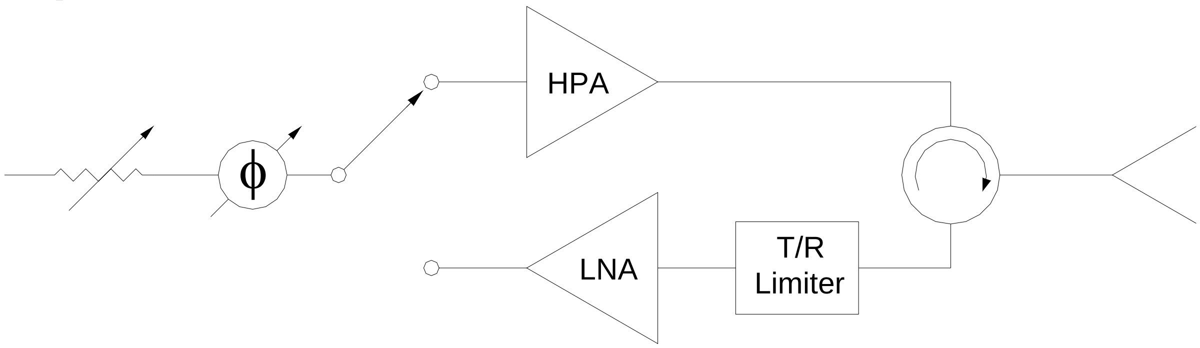


Figure 3-1: Block diagram of a typical solid state T/R module.

3.1.2 T/R Module Design Challenges

The first challenge for the T/R module designer is fitting all the components in a package that will fit in a radiating element spacing that will allow scanning without grating lobes. For example, a scan requirement of ±60° limits the spacing of the radiators to a half wavelength.[2] This limitation is particularly difficult to overcome as the frequency of operation increases. However, even for arrays operating at lower frequencies, the size requirements create problems due to the heat generated by the HPA. The high EIRP requirements of a radar phased array, coupled with the low power added efficiency (PAE) of solid-state HPAs, create a cooling challenge for the antenna designer. This problem is further complicated because the water cooling is located in the same space that is needed to distribute the DC power. Moreover, self heating of the HPA degrades its performance and limits its life.[3] Active phased array designers achieve the desired EIRP by power combining in the module and by increasing the number of T/R modules. Unfortunately, power combining in the module is limited by the degradation of module efficiency as the number of MMICS increases. For example, a single amplifier with PAE of 45% degrades to 30% when it is combined with a

[2] G. W. Stimson, *Introduction to Airborne Radar*. Raleigh: SciTech Publishing, 1998.

[3] S. Nuttinck, E. Gebara, J. Laskar, B. Wagner & M. Harris, “RF Performance and Thermal Analysis of AlGaN/GaN Power HEMTs in Presence of Self-Heating Effects,” in IEEE MTT-S Int. Microwave Symp. Dig., 2002, pp. 921-924

second amplifier.[4] In addition, increasing the number of power amplifier MMICs drives the cost of the module. As a result, typical X-band HPA uses only one or two MMIC amplifiers.[5] Unlike ferrite phase shifters, the digital phase shifter used in a T/R module increases in size and loss as the phase resolution increases. As a result, the module designer uses the lowest possible resolution for the phase shifter. Unfortunately, decreasing the phase shifter resolution degrades the beam pointing accuracy and increases sidelobes. The SPDT switches included in T/R modules degrade output power due to load pulling as the antenna scans and the antenna radiating elements' VSWR degrades. Another disadvantage of distributed T/R modules is the increased cost and complexity of locating EMI filters at each T/R module.[5]

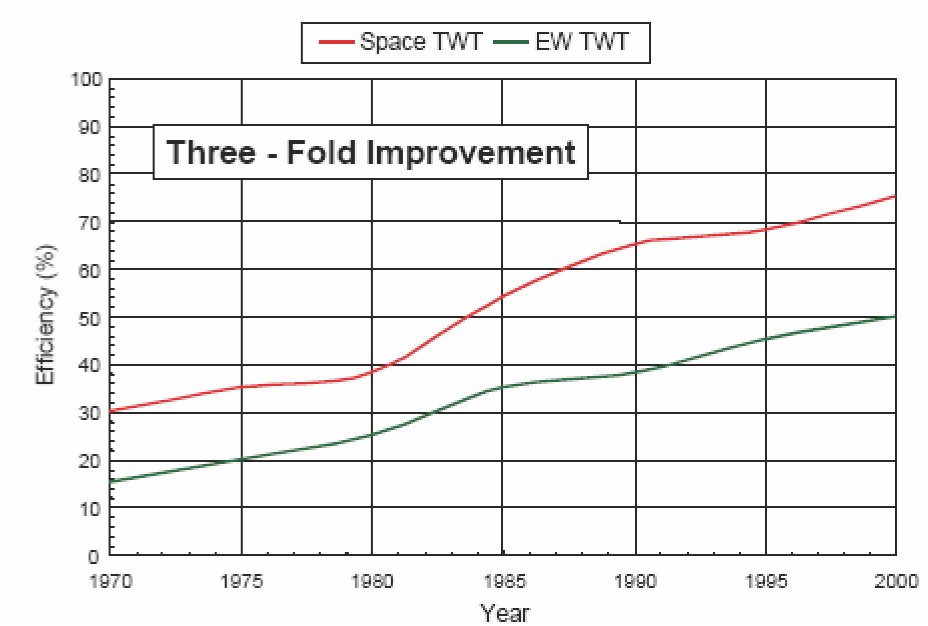
4 Passive Phased Arrays

4.1 *High Power Tubes*

The use of high power tubes in radar antennas began in the early years of World War II with the development of the magnetron. The magnetron is prized for its "low cost, small size, light weight, high efficiency and rugged simplicity." In fact, it is still used today in radars such as the U.S. Navy's AN/SPN-43 air traffic control S-band radar system, which can be found on all aircraft carriers and amphibious assault ships. In addition, the magnetron is used in the ubiquitous microwave oven. Passive phased arrays typically use high power tubes such as magnetrons, Traveling Wave Tubes (TWT), Klystrons and Gyrotrons for the transmitter. The tubes are used because of their ability to generate extremely high power with high efficiency. For example, the magnetron used in the AN/SPN-43 produces 850 kW peak. High powers are not limited to magnetrons. State of the art coupled cavity TWTs generate up to 170 kW of peak power at S-band, 200 kW of peak power at C-band, and 120 kW of peak power at X-band. Klystrons have long been used to generate high power for particle accelerators. For example, CPI Klystrons generate up to 6 MW of peak power at S-band, 1 MW peak at C-band, and 120 kW peak at X-band. The microwave tube industry has made dramatic improvements in tube efficiency over the years as shown in Figure 4-1. In addition to the improvements in efficiency, the reliability of tubes has also improved over the decades. This is illustrated in Figure 4-2.

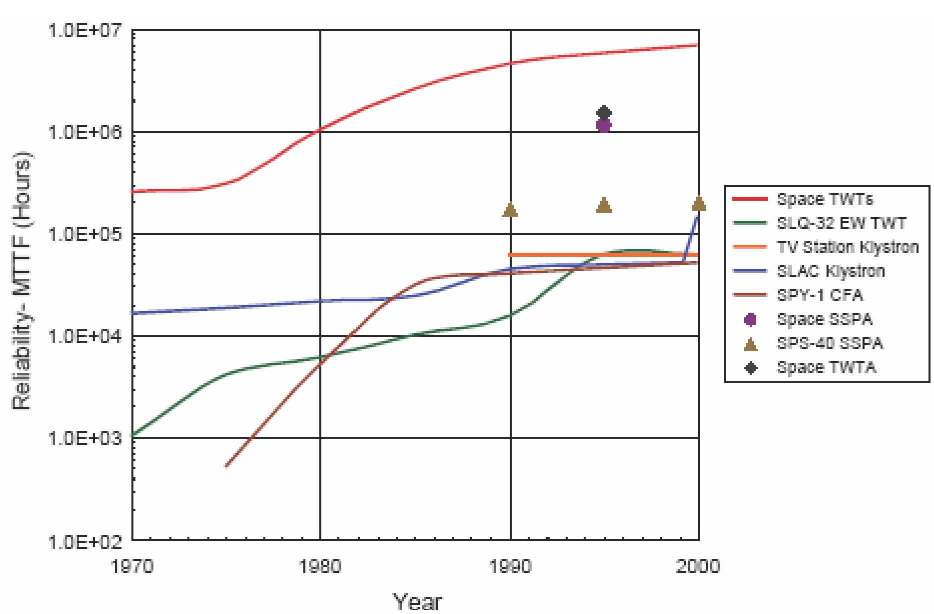
[4] A. P. Zhang, L.B. Rowland, E. B. Kaminsky, J. W. Kretchmer, V. Tilak, A. F. Allen, B. J. Edward, "Performance of AlGaN/GaN HEMTs for 2.8 and 10 GHz Power Amplifier Applications," in IEEE MTT-S Int. Microwave Symp. Dig., 2003, pp. 251-254

[5] B. A. Kopp, M. Borkowski, & G. Jerinic, "Transmit/Receive Modules," IEEE Trans. Microwave Theory and Tech., vol. 50, pp.827-834, 2002.



Source: Report of Department of Defense Advisory Group on Electron Devices
Special Technology Area Review on Vacuum Electronics Technology for RF Applications

Figure 4-1: Traveling Wave Tube (TWT) Efficiency over Time



Source: Report of Department of Defense Advisory Group on Electron Devices
Special Technology Area Review on Vacuum Electronics Technology for RF Applications

Figure 4-2: Microwave Tube Reliability Improvements

High power tubes are used in the final amplifiers for the radars found in the U.S. Air Force F-14, F-16 and F-18 fighter aircraft. In addition, they are used in the Air Force's AWACS aircraft and the Swedish fighters Grippen and Viggen. Coupled Cavity TWTs are used in the

U.S. Army's TPQ-36 and MPQ-64 Battlefield Surveillance Radars. Microwave tubes are used for some of the most powerful deep space radars in the world, such as those operated by MIT Lincoln Laboratory at Millstone Hill. They also supply power for many of the air traffic control stations in the United States and abroad. Microwave tubes are used on the Navy's Aegis system for fleet defense both in the CWI radar for the standard missile and the Phalanx close in weapons system. Helix TWTs are used in Electronic Warfare systems like the ALQ-184 Electronic Attack Pod on the F-16 and the AN/SLQ-32 on U.S. Navy ships. Gyrotrons are even more impressive in their output power at high frequencies. Tests in March of 2005 at the Max Planck Institute for Plasma Physics in Greifswald, Germany of a CPI manufactured gyrotron, the VGT-8141, produced nearly 900 kW of output power, at a frequency of 140 GHz, for 30-minute pulses.

4.2 *Ferrite Phase Shifters*

EMS Technologies has over 30 years experience in the design of passive feed networks and ferrite components. Our custom designs give the best combination of size, loss, and power handling. Table 1 shows typical RF performance for phase shifters in frequency ranges of interest for communications and radar applications. Switching times are typically in the range of 2-5 µs and the phase shifters can be switched at rates in the tens of thousands of switching events per second. As discussed below, phase shifter setting resolution and accuracy is the main determinant of beam pointing accuracy. EMS phase shifters and drivers can achieve phase resolution up to 10 bits (0.35°) and phase accuracy up to 3° RMS depending on driver selection.

Table 1: Typical performance of EMS ferrite phase shifters in various frequency bands

Frequency (GHz)	Insertion Loss (dB)	Return Loss (dB)	Power Handling (W)
3-3.5	1.0	20	1000
7-11	0.70	21	650
11-18	0.70	21	500
20	0.70	21	400
30	0.90	21	250
44	1.20	21	150
60	2.0	20	100
94	3.0	18	60

Figure 4-3 shows the cross section of a dual toroid ferrite phase shifter. It consists of two rectangular tubes or toroids of ferrite material placed on either side of a high dielectric constant center slab. This combination is placed inside a metal enclosure. The result is a slab-loaded waveguide that supports, to a good approximation, Longitudinal Slab Magnetic (LSM) and Longitudinal Slab Electric (LSE) modes.

A typical RF field distribution for the dominant LSE_{10} mode is shown in the figure. With this geometry, the plane of circularly polarized magnetic field (maximum interaction with the ferrite) moves farther into the high field region of the waveguide as frequency increases. At the same time, since the phase shifter operates at a frequency higher than that of magnetic resonance, the magnetic activity of the ferrite falls off with increasing frequency. By careful adjustment of material parameters and cross sectional geometry, it is possible to make these two effects counteract each other, yielding a device that has differential phase shift which is very flat across frequency. The phase shift is approximately proportional to the remanent magnetization level of the ferrite material. This remanent magnetization level is set by sending current pulses through the magnetizing latch wires. Since the toroids form closed magnetic circuits, they can hold a remanent field without a holding current in the magnetizing wires. So phase shifters of this type only consume power while they are being set; between setting operations they can be powered down and act as passive microwave devices.

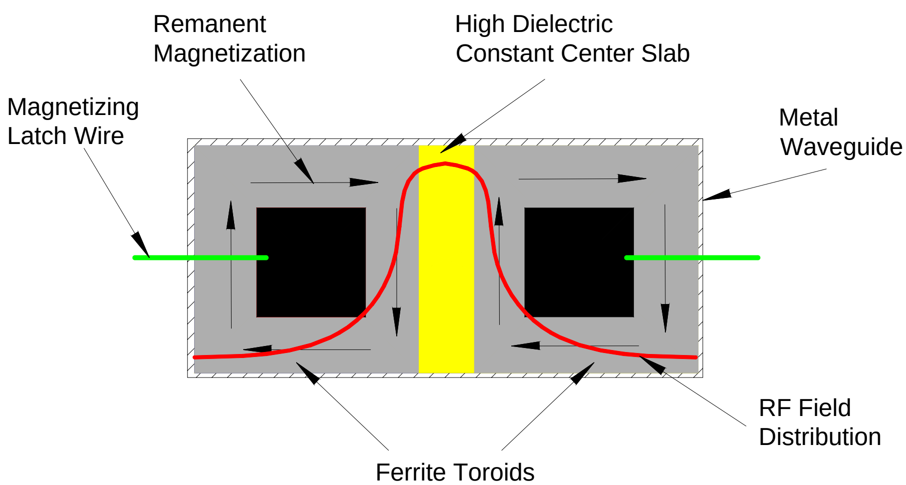


Figure 4-3: Cross section of a dual toroid ferrite phase shifter magnetized in the electrically longest state

5 Summary

The active phased array is an order of magnitude more complex than the passive phased array. For active arrays, the T/R module cost-performance trade greatly affects the entire phased-array antenna architecture, and cost considerations drive every aspect of the T/R module design and performance specifications. As a result, performance is often sacrificed to reduce costs. In contrast, the ferrite-based passive phased array provides a cost-effective, well-proven approach to achieving a high performance radar antenna. The high power handling capability and low loss of ferrite phase shifters allow power amplifiers, low noise amplifiers and phase shifters to be chosen to achieve optimum performance, with relatively little impact to cost.