T/R MODULE ARCHITECTURAL CONSIDERATION FOR ACTIVE ELECTRONICALLY STEERABLE ARRAYS.

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Abstract

The increasingly complex threat environment for target detection radars has driven the system architects to the use of electrically steerable active aperture antenna arrays. Transmit and receive modules are key elements in any active aperture system. T/R module architecture is unique for each system application and must be designed carefully to assure performance goals as well as platform limitations are met. This paper will discuss T/R module architectural considerations and show specific examples of wideband and narrow band modules which have been implemented into functional arrays.

T/R Module Architecture

System parameters such as prime power consumption, system cooling capacity, effective radiated power (ERP), scan limits, antenna beam sidelobe levels, antenna radar cross section (RCS), radiated and received polarization, system noise figure, system input third order intercept (3rd OIP), operating bandwidth, pulse width, duty cycle, and operating mode requirements all affect the T/R module architecture.

Aperture scan angle limits, radiated and received polarization, radar cross section, and the highest operating frequency required affect the radiating element spacing and element grid spacing for the antenna. There are several grid geometries that can be implemented. If circulator polarization is necessary, a square grid pattern may be used. For scan limits that are different for azimuth and elevation, a rectangular grid may be required. Equilateral triangular girds are often implemented if T/R module count needs to be reduced relative to a square grid configuration. This module count reduction may amount to as high as 15%. Other triangular configurations are possible when unique system constraints must be considered. Radiating element grid pattern determines the cross sectional area allotted per T/R module and tends to drive the mechanical structure required for cooling and module packaging.

Radiated and received polarization types can affect T/R module packaging significantly. Circular polarization requires two radiating elements to be simultaneously driven by RF signals that are 90° out of phase. This can be accomplished by a single transmitter with split output, but is optimally achieved by using two separate transmitters operating at half the total radiated power, each having its own phase shifter. If system modes required transmitting two separate, simultaneous beams, one vertically polarized, the other horizontal, the two independent transmitter T/R module is needed. Likewise, two independent receive channels are needed in order to receive circular polarization. If the system need is to maintain full separation of received orthogonal channels for target ID and cross correlation of data, then the two receiver channels need to feed two independent antenna receive manifolds and two separate receiver down converts all the way to the AD converter.

T/R Module Transmitter Channel Architectures

Parameters that set overall T/R module transmit channel gain are derived from system flowdown requirements. Given the aperture size needed to obtain the beam width and ERP that satisfy system probabilities of target detection for the specified target size, and the T/R module grid spacing that provides the desired scan angle, T/R module peak RF power output is then determined. This peak power requirement at the module level must be consistent with the antenna performance and mechanical constraints. Tradeoffs must be performed to establish the proper balance between electrical mechanical and cost issues. For typical X-band modules, currently power amplifier in the 5-10 W_{pk}, are available. Thus the number of modules in the array can be determined to meet the system requirements.

Operating bandwidth establishes the transmit and receive manifold design either to all stripline for wideband operation or all waveguide for narrower band operation. Manifold RF losses are then known. Manifold insertion loss ranges for 2.0 dB for all waveguide to as high as 6.5 dB for all stripline. Corporate feed manifolds are more lossy than center fed traveling wave feeds and provide greater instantaneous bandwidth. Array drivers, the power amplifiers that feed transmit RF power to T/R modules, typically have power output levels in the 10 watt peak to 50 watt peak range (+40 dBm to +47 dBm). RF power out of the array driver is attenuated by manifold losses and then reduced by the power split ratio determined by the number of modules in the array.

$$L(dB)=10*Log(N)$$

Where N is the number of T/R modules in the array. Power available at the T/R module transmitter input in an array with 3000 modules will range between -1.5 dBm and +10 dBm. Design constraints on either the gain trim or phase shifter MMIC in the transmit chain generally limit the maximum power level that is delivered to these components.

Transmit channel gain is then the gain needed to develop the required peak output power, given the input power available to each T/R module. Gain that has to be developed by transmitter MMIC amplifiers is the difference between required transmit channel gain and the losses attributed to phase shifters, gain trims, hybrid power splitters and combiners, impedance transformers and impedance matching networks in the module. Total MMIC amplifier gain required in typical T/R module transmit channels is 40 dB to 50 dB for module peak power output in the 5 watt to 10 watt range. Total MMIC gain in excess of 50 dB is difficult to implement without instabilities due to proximity coupling of output to input, which is aggravated by waveguide propagation modes that occur in most package designs.

Transmit channel architecture is also affected by system desires to radiate a transmitted beam that has sidelobe structure different than received beam sidelobes. This often necessitates separate transmit and receive manifolds in order to preserve receive channel gain and noise figure. Phase shifters and gain trims are not shared in these module architectures. It's often cost effective to fabricate separate transmit and receive modules in designs of these type. Figure 1 illustrates different T/R module architectures.

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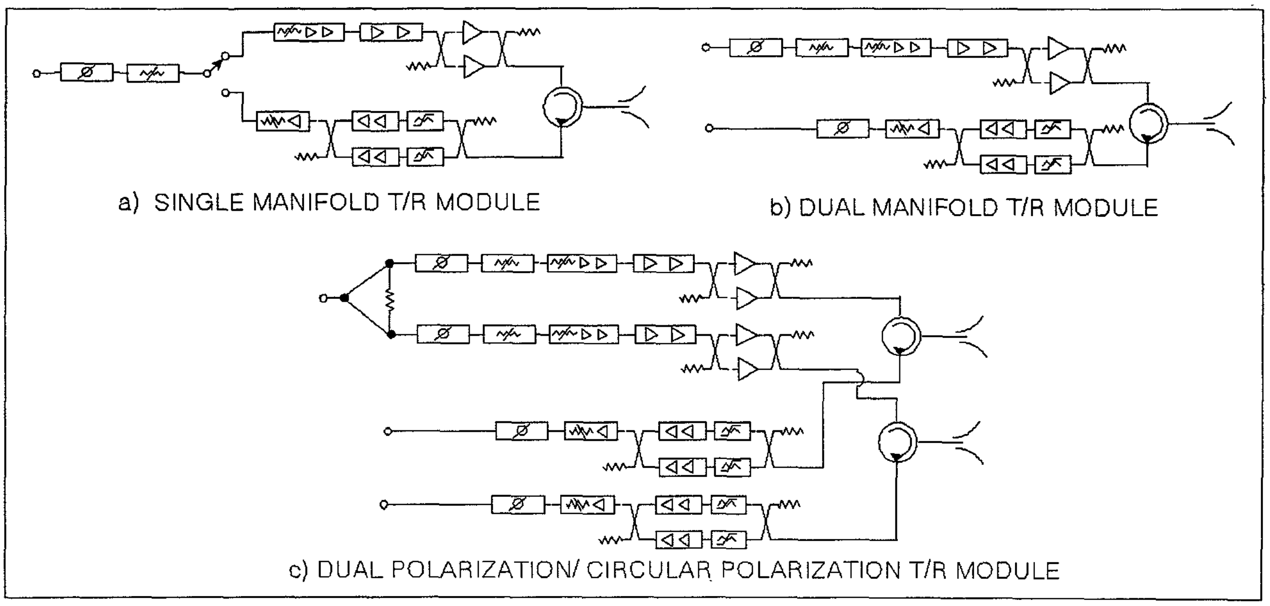

Figure 1. T/R Module Architectures

T/R Module Receive Channel Architectures

System requirements for receiver noise figure, receiver input third order intercept, aperture power consumption, instantaneous bandwidth, minimum detectable signal and operating modes all drive T/R module receive channel architecture. High performance airborne radars use velocity search or pulse doppler detection modes to separate small signals for large levels of ground clutter received when looking down at terrain for the target. The greater the transmitted ERP, the greater the system dynamic range has to be from the T/R module through the A/D converter to handle the ground clutter return and the small target signal, particularly when the target radar cross section is small. Receive channel architectures need to consider the entire receiver as a whole. Gain cannot be arbitrarily set for any part of the receiver system.

A typical system receiver chain may consist of elements as shown in Figure 2. In order to calculate gain distribution for the chain, several system parameters must be specified.

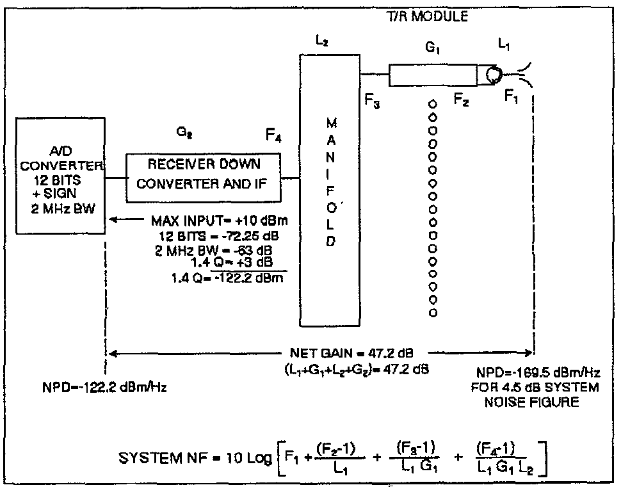

Figure 2. Receiver Noise Power Density Levels and Gain.

For example, if a system noise figure of 5 dB is required with A/D converter parameters of 12 bits plus sign dynamic range, 2 MHz bandwidth and +10 dBm maximum input signal level, then the chain parameters can be analyzed. A system noise figure of 5 dB establishes a noise power density at the input to the receiver, at the antenna element attached to the T/R module, at a level of -169.0 dBm/Hz.

The A/D converter has to have a noise input great enough to toggle the least significant bit on and off in order to process any small signal. The largest signal it handles is +10 dBm, and with 12 bit range the smallest signal that will toggle the least significant bit is

$$LSB = 10 - 20 * lOG(2^N)$$

$$LSB = 10 - 72.25$$

$$LSB = -62.25 \text{ dBm}$$

Common practice is to adjust gain in the receiver to cause noise into the A/D converter to be 3 dB greater than the minimum needed to toggle the LSB, so the total integrated noise at the A/D converter is established at -59.25 dBm in a 2 Mhz bandwidth. Noise power density is equal to

$$NPD_{A/D} = -59.25 - 10 * Log(2 * 10^6)$$

$$NPD_{A/D} = -122.26 \text{ dBm/Hz}$$

Total Receiver gain is established by the noise power density that needs to be maintained at the T/R module receive element and the noise power density needed at the A/D converter input to toggle 1.4 quanta. In the example illustrated in Figure 2 that is only 47.74 dB of gain.

System noise figure, input third order intercept, and aperture power consumption trades center around the gain and loss distributions assigned to T/R module receive channel MMICs. In general, the optimum configuration is one where receive manifold loss is minimized allowing T/R module receive gain to be in the range of 13 dB with low insertion loss in the receive channel phase shifter, gain trim, and receiver protector MMICs. The receive manifold introduces loss depending on the manifold construction which is driven by operating bandwidth, and hybrid stripline-waveguide configurations designed to satisfy volume and weight constraints.

The portion of the receiver chain behind the array manifold which processes the combined power out of all of the T/R modules needs to have a high dynamic range. Its noise figure impacts overall system noise figure a small amount because system architecture trades of input third order intercept, noise figure, and aperture power consumption won't allow an arbitrarily high gain in the T/R module to swamp poor noise figure at that point.

Module Evolution

Over the past ten years, Westinghouse Electric Corporation has been involved in multiple active array T/R module programs. These modules span electronic warfare wideband (4-18 GHz) to 10-40% bandwidth X-band varieties. Over a 6 month period (1988 - 1989) a large number of modules (~ 2000) were fabricated as part of the Demonstration/Validatgion (DEM/VAL) phase of the ATF program (figure 3) to populate a flying testbed array to demonstrate the feasibility of AESA technology. Westinghouse and Texas Instruments are joint venture parters of the ATF program and each partner built 50% of the modules. In addition to exceeding performance goals, over 20,000 MMICs were utilized and module cost goals set back in 1985 were achieved. These modules were configured as shown in figures 4 and 5.

The RF transmit chain utilized a high efficiency power amplifier. In addition, the energy storage, controller, and regulator/modulator circuitry was included within the module. As shown in the figures, the T/R module plus associated circuitry was contained within a single kovar housing.

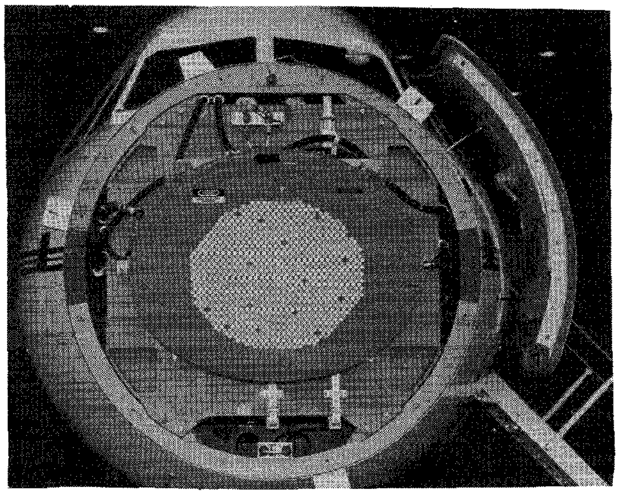

Figure 3. DEM/VAL Test Array.

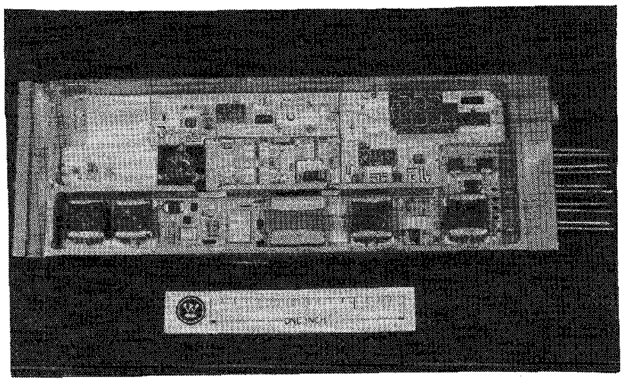

Figure 4. RF and Power Conditioning Side of T/R Module.

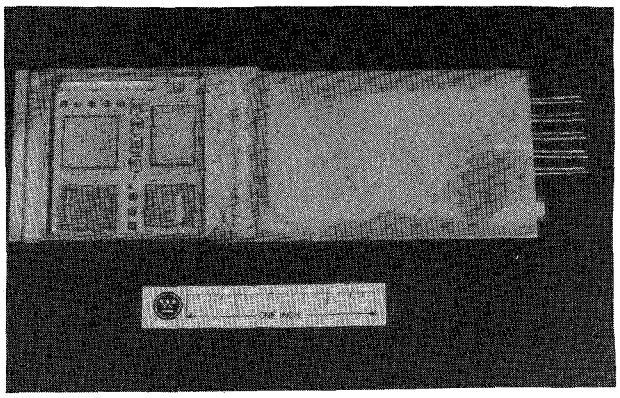

Figure 5. Controller Side of the T/R Module.

In 1989 and 1990, under internal IR&D, an advanced module configuration was developed which resulted in a smaller, lighter, more producible module than the DEM/VAL design. Nine GaAs and three custom Si Regulators and Controllers were successfully used in each module pair. Separate Transmit and Receive modules were designed facilitating easier testing, higher yield, less troubleshooting time per module and better spectral purity performance. A 3 to 1 reduction in process steps was realized and a 4 to 1 reduction in wirebond interconnects was obtained over the DEM/VAL design. Each module was assembled using automated part placement epoxy dispensing and wirebonding equipment. Sixty each transmit and receive modules shown in figure 6 were produced.

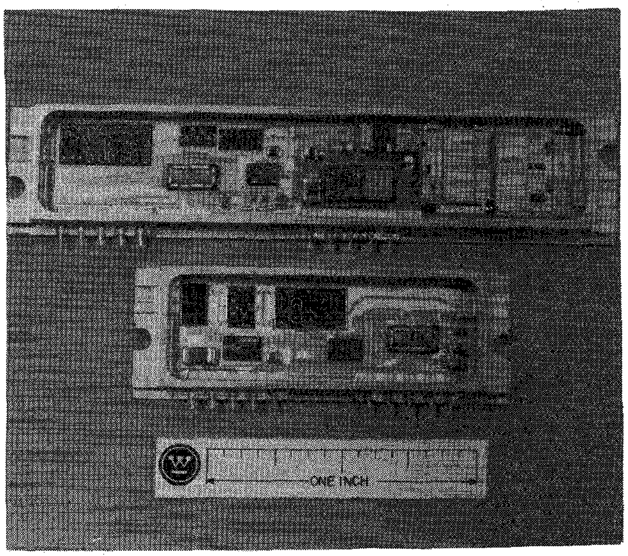

Figure 6. Advanced Transmit and Receive Modules.

Figure 7 shows a wideband (4-18 GHz) T/R module configuration utilizing four modules in a single housing (tray). This configuration was chosen to meet element to element spacing requirements at the high end of the band. Each module consisted of three phase shifters, ten pre-driver amplifier stages, and three power amplifiers, all GaAs MMICs. In addition to the power chain, each module contained a four MMIC low noise amplifier. The phase shifters were configured in the common chain for transmit and receive. A single controller sub-assembly in each tray performed the logic function for all four modules.

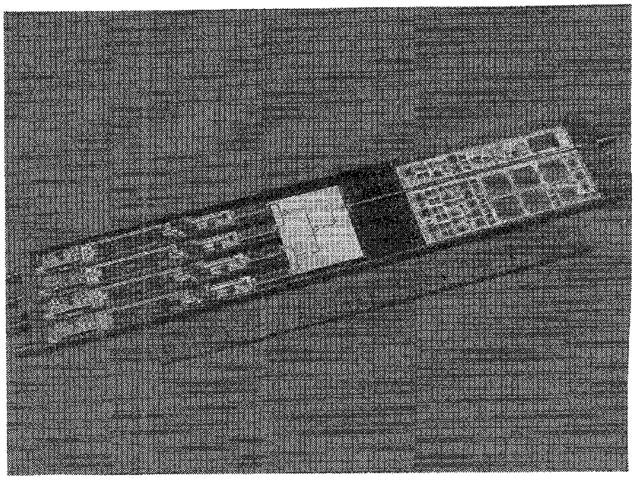

Figure 7. Wideband T/R Module.

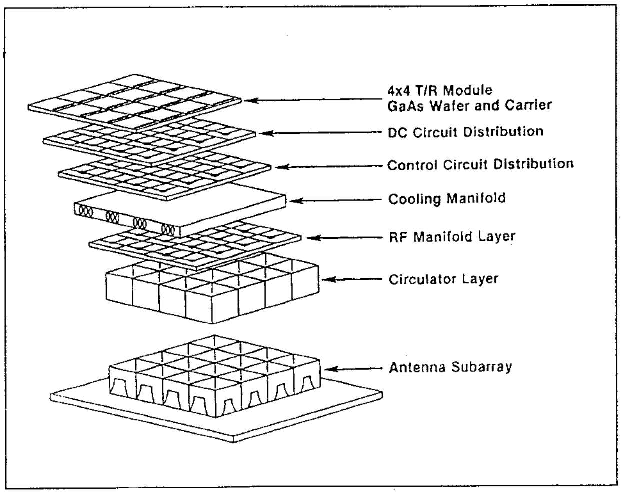

Figure 9. Subarray Coplaner Packaging Concept.

Figure 8 shows the hardware for a 24 element test array. This array was configured as a 3x8 array with horizontal and vertical polarization.

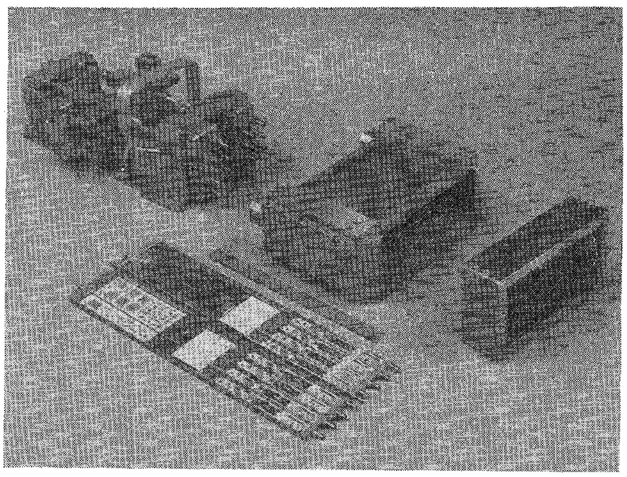

Figure 8. Wideband Module Test Array.

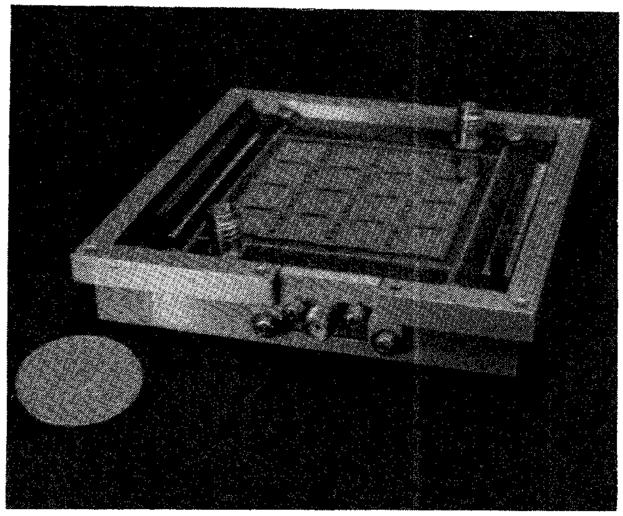

Figure 10. Wafer Scale Active Aperture.

Future Active Array Technologies

Active aperture applications in future aircraft will provide full 4π steradian coverage for situation awareness and missile guidance as the aircraft turns away from the target. To accomplish this, the apertures will have to be designed into the aircraft's wing and fuselage surfaces. Westinghouse has been addressing that design challenge with work performed on several recent programs. Our GaAs Wafer Scale Program has demonstrated the feasibility of fabricating monolithic T/R module circuits on 3 inch GaAs wafers (1), the planar assembly including distribution and cooling can easily be adapted to a minimal depth, conformal aperture. The mechanics of designing the wafer scale idea into a surface mounted array has been studied under USAF/ASD contract F33615-89-C-1038, "Advanced Airborne Avionics Packaging Technology-Phase 1". An active aperture has been assembled with funding under internal IR&D and a DARPA sponsored effort "RF Wafer Scale Integration". Figure 9 shows the subarray coplaner packaging concept. The photo in figure 10 shows the assembled wafer scale active aperture.

Reference

(1) L.R. Whicker, J.J. Zingaro, M.C. Driver, and R.C. Clark, "A New Approach to Active Phased Arrays Through RF-Wafer Scale Integration" 1990 IEEE MTT-S International Microwave Symposium Digest, Volume III, pp. 1223-1226.

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