Transmit/Receive Modules

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Invited Paper

***Abstract*—This paper begins with a discussion of the microwave functions performed by transmit/receive (T/R) modules for phased-array antenna applications. The paper then addresses performance and cost aspects of semiconductor, packaging, and assembly technologies associated with T/R modules.**

***Index Terms*—Attenuator, circulator, limiter, MMIC cost, phase shifter, phased array, transmit/receive module.**

I. Background

SYSTEMS realized with a phased-array antenna offer a number of significant advantages over those that utilize a conventional parabolic-dish antenna. These advantages include the ability to generate multiple independently steered antenna beams from a common aperture, the ability to make antennas conformal with their mounting structure, and the ability to produce directive beams that can rapidly be electronically repositioned. Solid-state technology has allowed phased arrays to overcome the low reliability inherent with tube-type transmitters and their associated high-voltage power supplies and also improves system efficiency.

The transmit/receive (T/R) module provides the final stage of amplification for transmitted signals and the first stage of amplification for received signals. Aside from amplification, it controls the phase and amplitudes of these signals to electronically steer the antenna beam. Low module cost is desirable due to the large number of modules required in a typical phased-array application. For these reasons, T/R modules are a critical element for phased-array antennas, and the T/R module cost-performance trade greatly affects the entire phased-array antenna architecture.

T/R module development for phased arrays began in 1964 with the application of silicon technology to the Molecular Electronics for Radar Applications (MERA) Program [1]. Since this time, the maturation of higher performance, highly producible gallium–arsenide devices, automated hybrid assembly, and packaging technologies has allowed active phased-array antennas to be developed for the majority of new RADARs. Phased arrays are also under consideration for many commercial and military communication systems.

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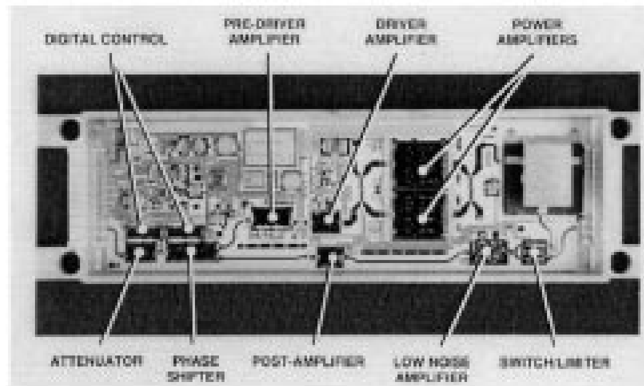


Fig. 1. Typical RADAR T/R module.

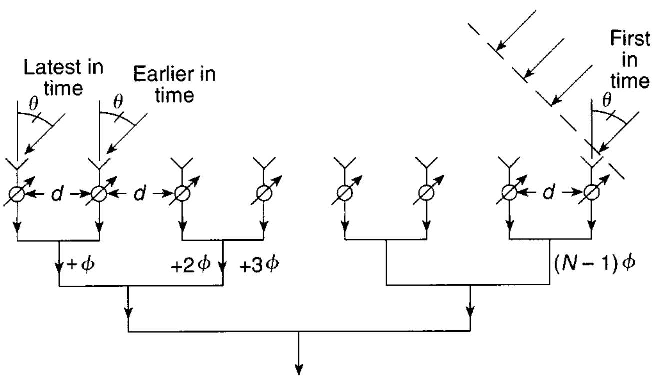


Fig. 2. Coherent combining off-broadside with phase shift.

Fig. 1 shows a T/R module listing the functions typically required for a RADAR application. The first portion of this paper will discuss the need for each of the RF functions from a phased array perspective. This will be followed by a discussion of T/R module technologies and their related issues.

II. T/R Module Microwave Functions

A. Phase Shifters and Attenuators

Phase shifters and attenuators are needed for electrical, rather than mechanical, repositioning of the antenna beam. Their use can be understood by considering a planar wave of electromagnetic energy incident on a planar array of radiating elements, as shown in Fig. 2. If an incident planar wave of electromagnetic energy is not parallel to the array face, each antenna element will receive a sinusoid with a different phase. By applying an appropriate phase shift within a T/R module at each antenna element, the energy can be coherently combined. If the spacing between antenna elements is constant, the difference in phase shift between adjacent elements is constant. Energy can be received from N directions in space simultaneously if N phase shifters with appropriate settings are used in each T/R module with N beamformers.

The incremental amount of phase shift between elements ϕ in Fig. 1 is given in (1) [2]. Since the sinusoid function has a period of 360°, the maximum amount of phase shift within a T/R module is 360°. The incremental phase shift ϕ depends on both the frequency of the electromagnetic wave, the angle of the incident wave with respect to the array face, and the spacing between elements. Unlike time-delay techniques, the amount of compensation applied for beam steering is proportional to frequency. For this reason, the phase shifters must be reset even if the beam position is not changed each time the frequency of operation is varied. This limitation is offset by the availability of low-cost high-performance integrated-circuit phase shifters. Phase shifters can be realized with circuitry that provides either an analog or digital phase shift value. The value of phase shift provided by an analog phase shifter is directly affected by the noise on the control line and, for this reason, digital phase shifters are typically used in phased arrays [3]

$$\phi = 2\pi \left(\frac{d}{\lambda}\right) \sin(\theta). \tag{1}$$

The periodic nature of the sinusoid can create multiple distinct angular locations where coherent signal addition will occur. This occurs if the distance between elements is large enough to allow the sinusoidal wave to traverse over 360° during the time interval between adjacent elements. These additional maxima are referred to as grating lobes and are undesirable due to conservation of energy principles. The formation of grating lobes can be prevented by appropriately limiting the element spacing d for a maximum incident angle θ, as shown in (2) [4]. This requires that the element spacing d be set to less than $\lambda/2$ at the highest frequency of operation to prevent grating lobe formation over a $\pm 90°$ scan volume for a rectangular element lattice. The spacing required to prevent grating lobes can be larger for smaller scan volumes. The size of the T/R module packaging is constrained by the grating lobe suppression requirements and can create a significant T/R module packaging challenge for very high-frequency operation

$$\frac{d}{\lambda} \leq \frac{1}{1+\sin(\theta)}. \tag{2}$$

The preceding phase-shift values for beam steering assumed that each path of the array, exclusive of the phase shifters, imparts the identical phase on each signal until it reaches the common port. There will be a distribution of phase shifts through the beamformer, however, dependent on the manufacturing and design techniques used. These phase differences will decrease the amount of energy at the desired beam location and will increase the energy at other angles, referred to as sidelobes. Antenna elements and other T/R module components used at each element, such as amplifiers, will also create element-to element phase shift differences. The phase settings from (1) can be adjusted to account for these differences in a process referred to as array calibration.

Similarly, it was assumed that the gain through each path of the array was identical. The gain will vary, however, due to manufacturing variations and design techniques. An attenuator at each element can be used to correct these amplitude errors. The attenuator can only provide a reduction in gain. Therefore, unlike the phase shift, the gain at each element should be set to the lowest level of the gain distribution acceptable, not the mean value. The range of attenuation required for gain correction is equal to the maximum gain value minus the minimum gain value. Additional attenuator range is sometimes used to create an amplitude taper across the antenna elements to tailor the radiation pattern.

To minimize the complexity of array calibration, the phase shifter's gain will ideally remain constant as the phase settings are varied, while the attenuator's insertion phase can vary as a function of the phase setting. In this situation, the calibration process only has to be done at the broadside beam location. The first step of this calibration process is the variation of the attenuators to achieve uniform gain at each element. The phase shifters are then set to compensate for insertion phase differences from the nominal insertion phase through each element. The beam can now be steered to any desired position by appropriately varying the phase shifters. This calibration process may be done at numerous frequencies or temperatures depending on the system requirements and component performance variations over frequency and temperature.

If the phase shifter's gain varies more than desired as the phase is varied, the calibration process is significantly more complicated. Each time the phase shifters are varied, the attenuators need to be varied to account for the phase shifter's amplitude error. The phase shifters then need to be varied again to account for the attenuator's phase variations. This process continues until the desired errors are achieved or the improvement of the errors is minimal. Since phase shifters and attenuators are the only components required to reposition the antenna beam, they are referred to as control components.

B. Centralized Versus Distributed Amplification

A distributed amplification approach uses T/R modules at each antenna element, while centralized amplification uses one single transmitter, as shown in Fig. 3. Centralized amplification has several disadvantages for phased-array applications. The main centralized disadvantage is that the insertion loss of the beamformer and phase shifters occurs after the transmit amplifier or before the receiving amplifier. These losses directly degrade the phased array's output power and noise figure. If attenuators are used to taper the gain, they may also degrade a centralized system's output power and noise figure. The power-handling requirement for centralized phase shifters and attenuators is significantly higher than a distributed system.

A centralized amplifier will also impart the same phase noise to each antenna element. T/R module phase noise is created by the power supplies interaction with the T/R modules in addition to the inherent amplifier noise [3]. Each centralized element's phase noise contribution is correlated, unlike the distributed amplifier whose noise may be uncorrelated at each antenna element. When compared to a centralized architecture, a distributed

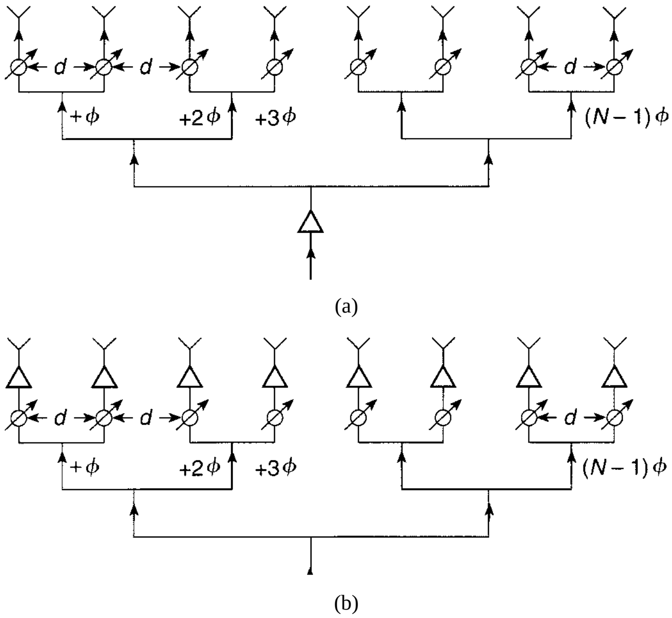


Fig. 3. (a) Centralized versus (b) distributed transmit amplification.

amplifier has the potential to reduce the phase-noise contribution of the T/R modules by the number of T/R modules.

Another disadvantage for centralized amplification is that, if the amplifier is comprised of a single device, its failure will lead to failure of the phased array. If a single distributed amplifier fails, it will have little effect on the performance of a phased array containing N elements where N is $\gg$1. A centralized amplifier can be made by power combining several lower power amplifiers (PAs) to minimize the impact of a single amplifier's failure. This may be done if the centralized transmitter is comprised of solid-state devices, where each device typically provides a relatively low power level. However, output power and efficiency degradation created by the insertion loss of the output power combiner is a significant drawback for solid-state centralized amplifiers. Conversely, a distributed solid-state amplifier is spatially combined by the array without degradation due to power combiner ohmic losses.

The main disadvantage of distributed T/R modules is the increased cost and complexity associated with filtering. Filters may be required to reduce electromagnetic interference (EMI) to or from other systems. In a centralized system, only one EMI filter is required, and is not subject to size restrictions created by grating lobe considerations. Distributed amplification requires a filter for every T/R module location. Distributed filtering will typically have higher insertion loss than centralized filtering due to grating lobe packaging size restrictions. The filter's loss may degrade system noise figure and output power depending on its location in the phased array.

C. T/R Module Protection: Circulators and Limiters

A duplexer is used to direct the output power generated by the PA to the antenna element. It also must direct any energy received by the antenna into the low-noise amplifier (LNA). A system is referred to as full duplex if receive and transmit operation can be performed simultaneously. If they are done sequentially, the system is referred to as half-duplex. Radars are typically half-duplex, while many communication systems are full duplex.

The duplexer plays a critical role in preventing damage to the power or LNA [5]. A simple single-pole double-throw (SPDT) switch can be used as a duplexer for half-duplex applications. A SPDT switch provides no protection for the PA, however, since any energy into the antenna during transmission will be directed into the transmitter. Energy into the antenna during transmission can be created by another system or from the own system's reflected transmission. An SPDT switch can also lead to output power degradation due to load pulling due to the variations in the individual antenna element impedance during scanning. In particular, a phased array's individual antenna element's voltage standing-wave ratio (VSWR) is often very poor $(>2.5{:}1)$ at very large scan angles $(>\pm 60^\circ)$.

A circulator can be used for either half-duplex or full-duplex systems to aid in protecting the transmitter from damage or load pulling. With a circulator-based duplexer, energy into the antenna flows into the LNA, preventing it from directly damaging the transmitter. A circulator will allow some energy to leak into the undesired channel, but it is typically attenuated by 15–20 dB.

The circulator directs received energy into the receiver. To prevent receiver damage, a limiter can be placed before the receiver's LNA. The energy reflected by the limiter will then be directed into the transmitter. An additional circulator or a balanced limiter can be used to prevent this reflected energy from damaging the transmitter. The balanced limiter is typically preferred due its smaller size, lower cost, and higher performance when compared to the use of dual circulators. The LNA can also be placed within the balanced limiter to increase its third-order intercept point by 3 dB.

In some full duplex systems, in particular, many communication systems, it is critical to provide a high level of isolation between the transmitter and receiver. In these applications, separate transmit and receive phased arrays may be used to enhance isolation through physical separation of the receiver and transmitter. Alternatively, a diplexing filter may be used if the transmitter and receiver operate at distinct frequencies. The preferred approach is a tradeoff of the additional components required for separate arrays versus the impact of the additional filtering.

III. T/R MODULE TECHNOLOGY

Fig. 4 is an example of an RF block diagram for a typical RADAR T/R module. Differences among array applications may require differences in module functionality and performance, such as polarization diversity, transmit or receive linearity, waveform diversity, and/or low phase and amplitude errors required for low antenna sidelobes. All of these can add new dimensions of complexity to the design of the module and the solid-state components that comprise the module.

The immediate challenge becomes one of developing the best receive noise figure, the highest transmit power output, and the best efficiency with the lowest cost. It is axiomatic then that the design fully exploits each technology's capability. The module design must unfold in concert with the production capabilities

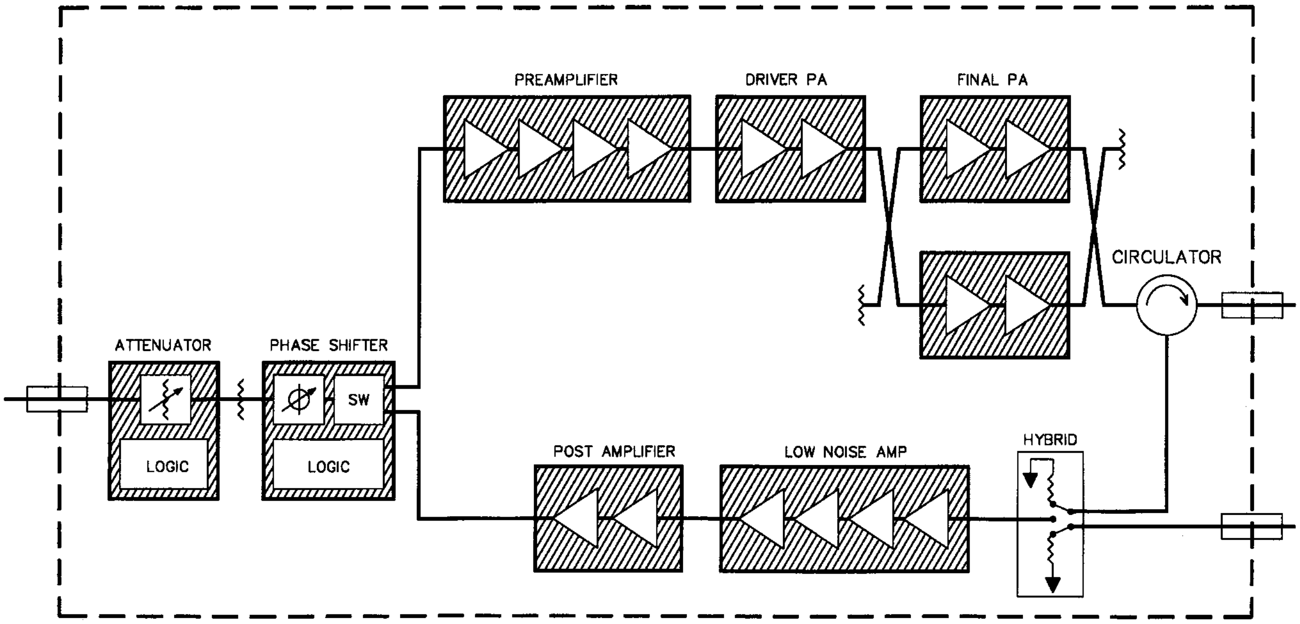


Fig. 4. Typical RADAR T/R module RF block diagram.

TABLE I
TYPICAL MMIC PERFORMANCE

Function	Parameter	X-Band	Ka-Band
Power Amplifier	Power Output	to 7-12 Watts	to 2-4 Watts
	Gain	6-8 dB/stage	5-7 dB/stage
	Efficiency	35-45%	25-35%
Low Noise Amplifer	Gain	8-9 dB/stage	7-8 dB/stage
	Noise Figure	0.8-1.5 dB	2.0-2.5 dB
Phase Shifter	RMS Phase Error	2.0-4.0 deg RMS	2.0-4.0 deg RMS
	Loss	3-7 dB	3-7 dB
Attenuator	Resolution	0.25 to 0.50 dB	0.25 to 0.50 dB
	Range	32-64 dB, Typ	32-64 dB, Typ

of the semiconductor foundry for the chips, the microelectronic factory for the modules, and the electronic assembly factory for the antenna.

A. T/R Module Monolithic Microwave Integrated Circuit (MMIC) Performance

Table I illustrates typical performance for MMICs at X and Ka-bands for some T/R module elements. MMIC devices are commonly used rather than hybrid designs at frequencies between UHF and Ka-band. Passive circuit losses diminish the attractiveness of the MMIC technology below 500 MHz, and technologies above Ka-band are arguably in the stages of demonstration.

Power combining within the module can increase the T/R module power over that available from a single MMIC, but is also limited by the degree of power combining that can be tolerated. Module efficiency can degrade rapidly as the number of PA MMICs combined increases. The manufacturing and packaging complexity and cost will also significantly increase with the number of MMICs. For these reasons, typical high volume X-band T/R modules use only one or two PA MMICs [6].

Wide-bandgap semiconductors have achieved significantly higher power densities than GaAs devices at X-band. X-band GaAs devices typically have power densities of 0.5–1.0 W/mm. Small periphery silicon–carbide (SiC) transistors operating at 60 V with 4.3-W/mm power density, 9-dB gain, and 20% power-added efficiency (PAE) at 10 GHz have been fabricated [7]. 0.125-mm gallium–nitride (GaN) transistors operating at 30 V with 6.9-W/mm power density, 9.0-dB gain, and 51.0% PAE at 10 GHz have also been made [8].

The efficiency of SiC devices will require significant improvement for their use in T/R modules. Also, larger periphery devices will be needed for GaN and SiC. The high operating voltages of wide-bandgap devices minimize bias distribution and impedance matching issues associated with large periphery devices. The main challenges will be process uniformity required to yield large periphery devices and thermal management.

While wide-bandgap devices may operate reliably at temperatures higher than GaAs, the output power will still degrade with temperature. It is likely that junction temperatures similar to GaAs devices will be necessary to achieve high performance. Thermal management for large-periphery devices will be a fundamental challenge with this technology [9]. SiC's thermal conductivity of 3.9 W/cm°C (z) and 4.9 W/cm°C (xy) is well suited for high-power-density operation, when compared to GaAs's thermal conductivity of 0.5 W/cm°C.

GaN's thermal conductivity of 1.3 W/cm°C is insufficient, however, to support operation of a large-periphery high-power-density transistor on a GaN substrate with conventional cooling techniques. Large-periphery flip-chips will also have an excessive temperature at high-power densities created by the GaN path between the gate and source heat sink in addition to the thermal resistance of the insulating substrate. An epitaxial layer of GaN on a SiC wafer can support operation of GaN devices at high-power densities.

B. MMIC Cost

Semiconductors, packaging, and labor are the three most significant cost drivers for a T/R module. Semiconductor cost is determined by wafer processing cost, wafer diameter, MMIC area, and yield. The wafer processing cost for GaAs is highly dependent on the volume of wafers produced by a foundry. Foundries typically can produce $>$20 000 wafers per year. The wafer cost at a foundry with less than 20% loading can be $>300\%$ more than that at a foundry with 80% loading due to increased capital amortization and overhead costs [10]. Production volume of $>$10 000 wafers per year is desirable to maintain low overhead costs.

Typical T/R module production rates do not require a sufficient number of wafers to provide high foundry loading. One 4-in wafer has sufficient area to provide the GaAs needed for $>$50 typical X-band RADAR modules. The production of 100 000 of these modules per year would then require $<$2000 4-in wafers per year or $<$1000 6-in wafers per year. Commercial volume using similar personnel and facilities is required to provide the low-overhead structure necessary to support the cost-effective production of X-band T/R modules. Some GaAs producers have successfully achieved this product mix through high-volume sales to support wireless handset products. SiC may achieve low cost through high volumes projected for wireless infrastructure PAs.

Wafer diameter is important to determine the number of devices available from wafer. Most GaAs manufacturers are currently on 4-in wafers. 6-in wafers can provide approximately twice as many parts as a 4-in wafer, but still pose several technical challenges, such as breakage. Converting a 4-in foundry to 6 in also may require a significant capital expenditure. This must be offset by the increased number of die per wafer in order for a 6-in facility to provide lower cost. SiC is currently on 2-in wafers with 3-in wafer production planned in the next few years.

MMIC size also directly relates to the number of devices per wafer. The width of a PA MMIC is primarily determined by the amount of device periphery required in the output stage, and PA MMIC area is then directly proportional to output power. The high power density of wide-bandgap semiconductors will enable a significant reduction in area when compared to a high-power GaAs device at a similar power level.

The size of a MMIC can also been reduced through the use of lumped-element circuit elements, multilayer passive components, and compact layouts. Compact layouts introduce significant stability and related feedback issues, however, and require the extensive use of three-dimensional (3-D) electromagnetic simulation tools. LNAs do not require a significant amount of area and are not typically a significant cost element.

The yield of complex PA and control MMICs is another a significant cost factor. Yield loss associated with device complexity is dependent on the statistical distribution of the yield driver. If the yield factor is randomly distributed across a wafer, yield can be significantly degraded by complexity. Random debris or short- or open-circuited gate electrodes can lead to significant yield loss for complex devices. Complexity factors can include gate periphery, die area, number of vias, and capacitor area. Conversely, if the yield detractors are not uniformly distributed, the yield loss associated with complexity can be minor. The effect of yield on cost is shown in Fig. 5.

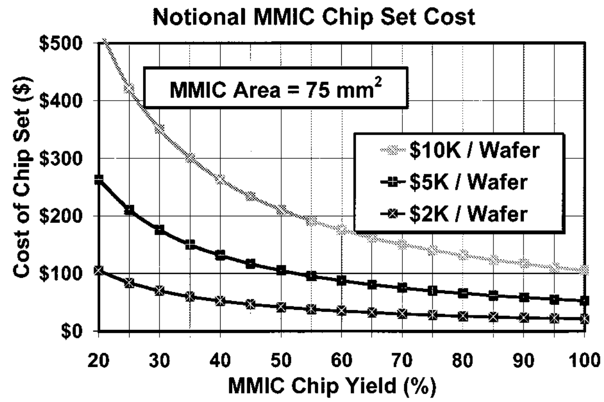


Fig. 5. MMIC cost versus yield.

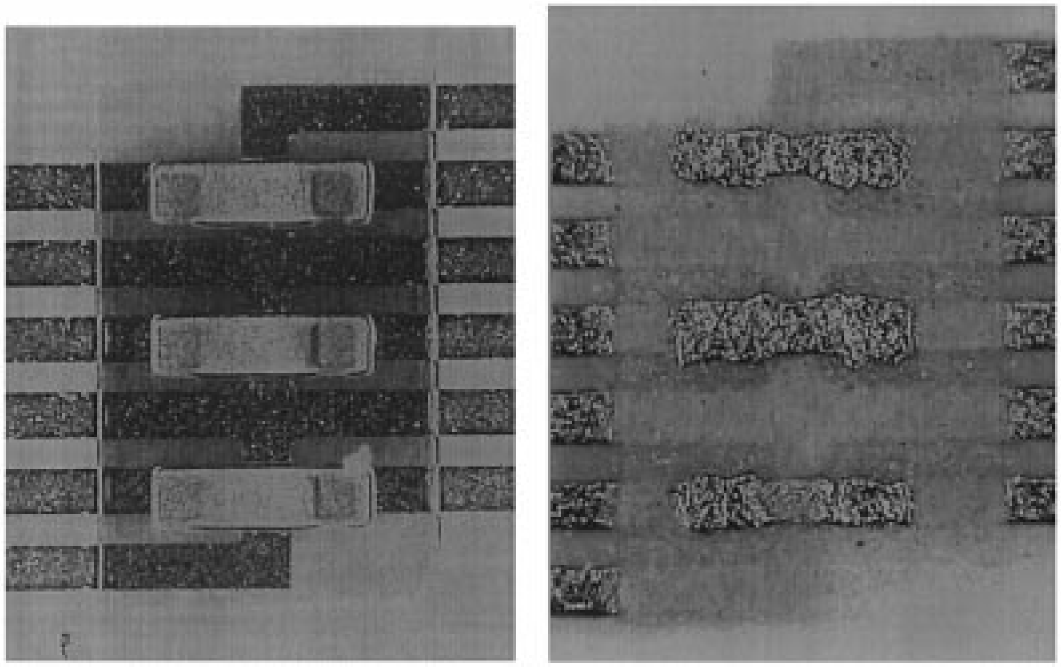
C. Assembly, Packaging, and Test

The connections to MMICs can be made with a variety of technologies and techniques, including wire bonding, flip-chip, and flex circuits. Large corporate investments have been directed toward the formation of automated factories to support the production of large numbers of modules for various applications. High assembly yields have been achieved through the use of programmable highly automated wire bonding and pick-and-place equipment incorporating sophisticated vision recognition capabilities.

Assembly yields are also aided by reducing the number of bond wires and components through the use of appropriate levels of MMIC function integration. The optimum level of integration is a tradeoff between MMIC yield versus packaging and assembly complexity. These improvements have diminished the benefits of flip-chip and other bond-wire elimination techniques for T/R modules. Flip-chip also introduces significant issues associated with dissimilar coefficients of thermal expansion, underfill processing, thermal management, and inspection [11].

The packaging for the control circuitry portion of the T/R module requires a high number of interconnections to control the phase shifter and attenuator, unless digital circuitry is included on the MMICs. Multilayer substrates are attractive for areas with a high density of interconnections to minimize the packaging area needed and coupling between microwave and control signals. Other portions of the module have a lower level of packaging and assembly complexity and single-layer substrates often suffice.

High-temperature co-fired ceramic (HTCC), low-temperature co-fired ceramic (LTCC), or thin-film packaging can be used as a multilayer substrate. HTCC is generally considered the lowest cost of these technologies, but will have more insertion loss than LTCC or thin film. The additional loss will typically have little affect on overall module performance if it is after the LNA or before the PA.



(a) (b)

Fig. 6. (a) Thin-film and (b) thick-film interconnections.

The thick-film conductors used in HTCC provide lower line resolution than thin-film materials. Fig. 6 contrasts the appearance of the fingers of a microwave combining structure using both thick- and thin-film processing techniques. This lower level of line resolution limits the use of fine lithography structures in cost-sensitive T/R module applications.

RF connections are typically made with either coaxial or planar microstrip connector, while ball grid array (BGA)-based connectors are under consideration for size and cost reduction. BGA packaging also allows digital/control signal routing outside of the module and can minimize internal module packaging complexity. BGA poses many of the same assembly issues as flip-chips, however. Immunity to EMI is another challenge related to the use of BGA connectors.

RF parametric testing of modules is performed using high-speed test equipment with probes, similar to the ones used during MMIC wafer testing. These probes provide a coaxial-to-microstrip transmission-line interface. Vision recognition systems allow as many 32 modules at a time to be loaded offline onto common carrier assemblies and to then be presented to a high-speed automated test station and tested in a batch mode with a minimum of operator intervention. Fig. 7 shows an example of probes being used to test T/R modules. Extended operation of modules under normal operating conditions is also typically performed prior to the high-volume production to identify problems such as hydrogen poisoning or power slump [12].

The large quantities of elements typically used in an array necessitate the use of a statistical representation of specified and measured parameters. Successful implementations can be demonstrated only if the module design is centered within the limits of acceptable use in the array. The end result is a lower cost module in that the array designer takes receipt of all units that are functionally operative. Fig. 8 illustrates the functionally operative performance distribution for a typical T/R module that

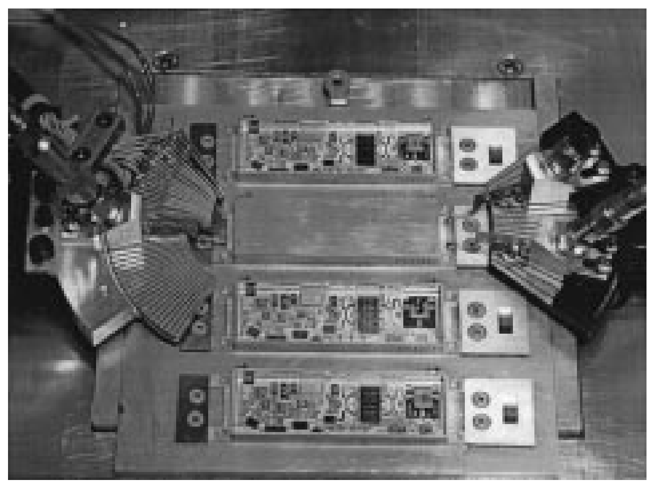


Fig. 7. T/R module test probes.

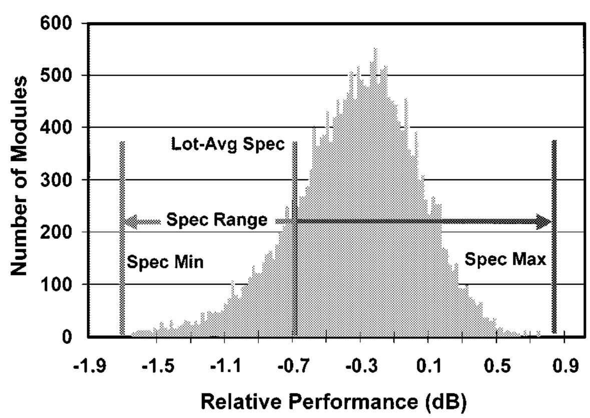


Fig. 8. Gaussian distribution of power output with a heavily saturated module.

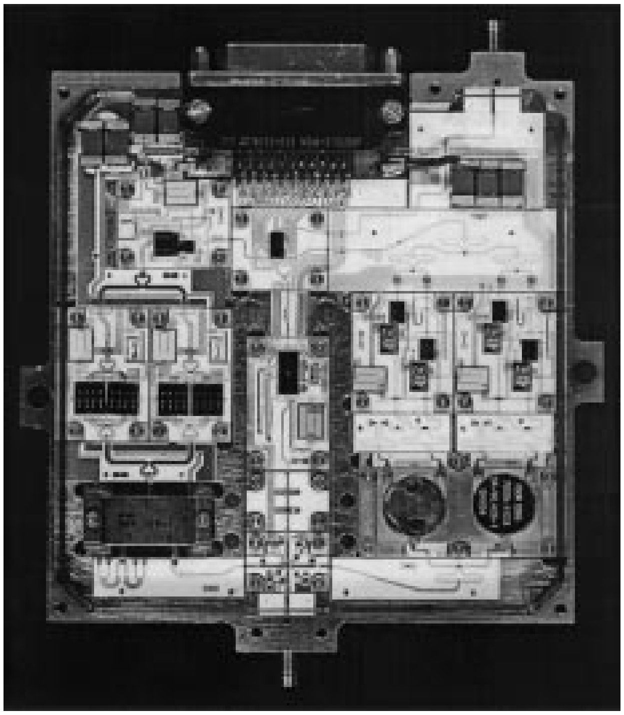


Fig. 9. Early T/R module containing subassemblies.

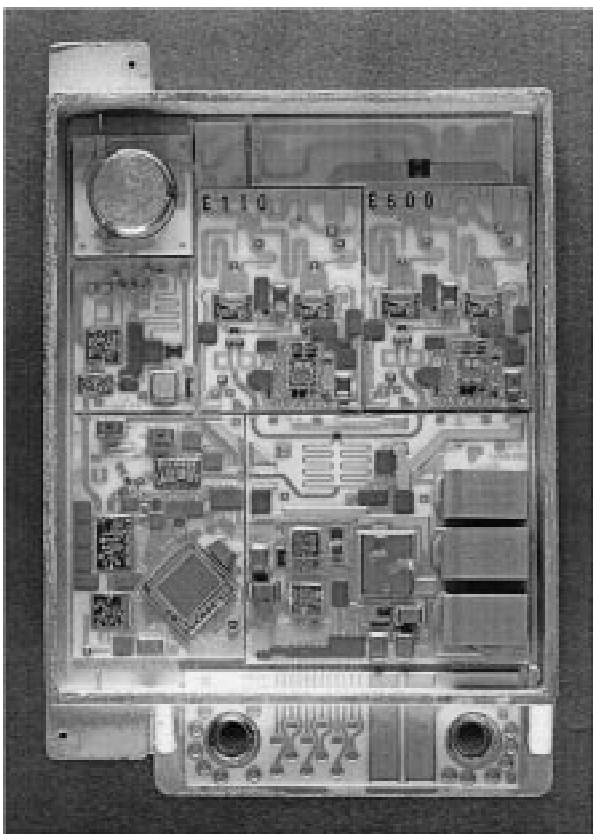


Fig. 10. Contemporary T/R module without subassemblies.

uses a saturating PA. Given this design, an expectation for a standard deviation of power output less than 0.5 dB would severely impact the overall yield of the module and, hence, increase the cost of the delivered product.

IV. Module Examples

Early module designs used manual assembly process whose low yields made high levels of integration prohibitive. This led to the use of individually tested subassemblies requiring a mix of assembly techniques, as shown in Fig. 9. These early modules typically required high levels of rework with associated high assembly labor and test costs.

As the sophistication level of the device and circuit modeling grew throughout the 1980s, the resultant module configurations became more fully integrated and compatible with automated assembly and test techniques that were emerging for microelectronics. An example of such a module is shown in Fig. 10.

This module operates at L-band with a 20-W 1-dB compressed single-tone transmit power output and a 1-dB receive noise figure. The unit measures approximately 2.5-in long to fit within the lattice spacing at L-band. GaAs MMIC devices are used with other silicon devices in a configuration that allows the module to interface with the array controller and other elements of the power system, cooling system, and RF distribution network that forms the radiated beam. Ceramic substrates made of either highly thermally conductive beryllium oxide or the less expensive aluminum oxide also form internal mounting media for the MMIC devices as well as dc and RF interconnection media. The circulator, in conjunction with a switch adjacent to the LNA, acts as a duplexer and protects the PA chips from the damaging effects of high VSWR from the antenna port.

V. Summary

The T/R module plays a critical role in determining the overall cost and performance for a phased-array-based system. The challenges for a designer are extracting the highest performance possible out of technology and carefully considering cost in every aspect of the design trade space. Advances in GaAs MMIC performance and cost, robotic assembly techniques, and packaging have allowed high-performance T/R modules to be produced at high-volume production rates. Future developments will focus on providing current performance levels at a lower cost and implementing higher performance technologies such as wide-bandgap semiconductors.

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From 1986 to 1990, he was with Avantek, Milpitas, CA, where he was a Microwave and RF Component and Subsystem Design Engineer, with an emphasis on passive and control circuit development utilizing printed lumped elements. Since 1990, he has been with the Applied Physics Laboratory, Johns Hopkins University, Laurel, where he currently develops T/R modules and associated packaging and solid-state technologies for phased-array RADAR and communication system applications. He has participated in the development of 30 different T/R modules. He teaches a three-day short course on T/R module cost, performance, and reliability. He has authored or co-authored 17 papers related to T/R modules and related technologies.

Michael Borkowski (M’83) possesses 25 years of experience in the field of solid-state component design and design management. He is currently the Technical Director for multiple gallium–arsenide-based MMIC module designs emanating from the Northeast region of Raytheon Electronic Systems, Andover, MA. Most prominent of these module designs is the T/R module for use in the THAAD solid-state antenna. He was the Department Manager for the Module Design Department, Raytheon Advanced Device Center. He has dedicated his professional career designing solid-state components for use in advanced or emerging radar or communications systems. As Design Team Leader on both the GBR and iridium T/R modules, he was responsible for coordinating the electrical and mechanical design of the T/R module and ensuring the transition-to-production of each design. He has been involved in all areas of T/R module development at Raytheon. His past key activities include Design Department IR&D Coordinator for GaAs MMIC development for T/R module applications (L-band through Ka-band), Lead Engineer on the Multiband (S/X-band) T/R Module Development Program, SPS-49 Solid-State Transmitter Development (L-band), T/R Module Development for Space-Based Radar (L-band), Design Engineer for solid-state PAs (50, 100, and 200 W at L-band, 45 W at S-band) for use in air traffic control and shipboard solid-state transmitters. He has authored or co-authored 25 publications. He holds three patents.

George Jerinic (M’68–SM’84) received the B.S., M.S., and Ph.D. degrees in electrical engineering from University of Wisconsin at Madison, in 1963, 1968, and 1971, respectively.

Since 1968, he has been with the Raytheon Company, Tewksbury, MA, where he has been involved with the design of microwave components and subsystems, solid-state sources, antennas, missile seekers, and T/R modules. The focus of his work has been in the research and development of microwave technology. His contributions have been both as an individual contributor and manager. He has provided leadership as Program Manager for the development of Raytheon’s first solid-state transmitter for active missile seekers (1979), single-chip MMIC T/R module (1986), and X-band solid-state phased array (1989). He has also participated in the management of the Raytheon/Texas Instruments Incorporated Joint Venture MIMIC Program. As the Raytheon Technical Director and JV Engineering Manager, his responsibilities have encompassed the technical direction of Raytheon activities and all JV hardware developments. As a Raytheon Engineering Fellow and the Senior Manager of Engineering Programs, he currently oversees advanced module technology efforts, which include wide-bandgap semiconductor activities. He has authored or co-authored 22 publications and has created, organized, and chaired numerous presentations dealing with T/R module technologies. He holds seven patents relating to solid-state transmitters and power generation.

Dr. Jerinic is a member of Sigma Xi, Tau Beta Pi, and Eta Kappa Nu.