Transmit/Receive Module Packaging: Electrical Design Issues

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Radar systems realized with a phased array antenna offer several advantages over systems using a conventional parabolic dish or mechanically steered antenna. These advantages include the production of directive beams that can be rapidly repositioned electronically, the generation of multiple independently steered antenna beams from a common aperture, the ability to make antennas conformal with their mounting structure, and the minimization of single-point failures. The recurring cost and design issues of transmit/receive modules and their associated packaging are challenges to fielding phased array antennas for future surface Navy radar needs. This article will provide an overview of the electrical performance trade-offs and techniques for transmit/receive module packaging.
(Keywords: Microelectronics packaging, MMIC, Phased array, T/R module.)

PHASED ARRAYS

Need for Phased Arrays

A phased array is an antenna comprising several radiators, or elements, coherently combined to form a directive antenna beam. By combining numerous elements, an antenna with very directive characteristics (high gain) can be realized. For radar applications, which usually require very high gain antennas, a typical phased array may have several thousand radiating elements. By applying a linear phase progression between elements, the direction of the antenna beam can be changed electronically within a few microseconds. Rapid electronic beam steering has made the phased array extremely advantageous for modern radar applications in which many functions have to be performed quickly. In contrast, a conventional mechanically scanned reflector antenna has a slower mechanical rotation rate and lower search rate for radar applications.

Phased Array Antenna Basics

If an incident plane wave is parallel to a planar array of antenna elements, all of the energy will add in phase and amplitude as shown in Fig. 1. If the planar wavefront is not parallel to the array face, the energy will reach the elements that are progressively farther away at later times. Appropriate time delays can be added to each element to ensure that the energy from each radiator will still be in phase at the collumination

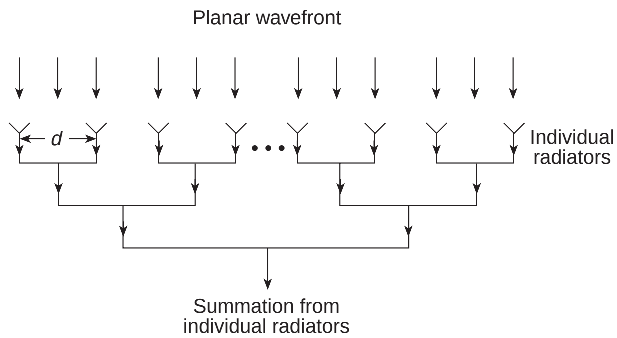


Figure 1. Planar wave incident to a linear array of radiators. All of the energy will add in phase and amplitude as shown (d = spacing between radiators).

point, but time delay units are not typically used because of their high cost and/or large size. Alternatively, phase shift can be added to each element so that the energy from each radiator is in phase at a single frequency as shown in Fig. 2. The direction of maximum antenna gain can then be steered to a desired angle through the appropriate application of phase shifts.

For radar applications, it is usually desirable to design the array to have low sidelobes in order to suppress jamming, clutter, or other interference sources located outside of the desired beam direction (the mainlobe region). The beamwidth and sidelobe level of an array can be tailored by applying amplitude weighting to the element excitations. This weighting comes at the expense, however, of increased beamwidth and reduced gain. In practice, several methods for implementing amplitude weighting functions are possible, including using attenuators located at each element, or by design of the beamforming network. Although arrays can be designed in theory to have arbitrarily low sidelobe levels, error effects due to component variations and manufacturing tolerances provide a practical limit on achievable sidelobe levels.

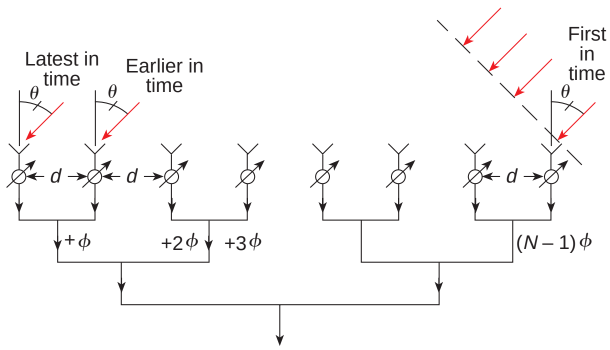


Figure 2. Linear array of elements with phase shift added to compensate for the incident energy angle (ϕ = phase increment applied at each individual radiator, d = spacing between individual radiators, θ = angle of incident energy, and N = number of individual radiators).

The element spacing in an array determines the total number of elements required to populate a given-size aperture and determines the area behind each element available for the electronics. In general, the radiating elements in an array must be spaced closely enough to prevent the phase of the sinusoidal wavefront from changing by 360° before it reaches the next antenna element. If the phase difference between adjacent elements is greater than 360° at the frequency of interest, there will be two or more locations in space where the antenna will have maximum gain. These additional maxima are referred to as grating lobes. Because of conservation of energy principles, the grating lobes will reduce the power in the main beam and thus reduce the antenna gain. They also provide additional high-gain paths for undesired energy sources, such as jammers and clutter. Grating lobes can be entirely avoided over a ±90° scan range if the element spacing is less than half of a wavelength.

In practice, spacings somewhat larger than half of a wavelength are typical, since most arrays do not scan a full ±90°. For planar arrays, use of a triangular grid arrangement of elements is also typical, since this arrangement permits a larger element spacing for a given scan volume than a rectangular grid arrangement. In general, for the same amount of grating-lobe suppression, a triangular grid requires approximately 15% fewer elements to populate a given-size aperture than a rectangular grid requires.

Centralized versus Distributed Transmitters

The transmitter for a phased array can be realized with one centralized source or consist of a transmit amplifier at every element as shown in Fig. 3. One advantage of the distributed transmitter is that the antenna will still maintain functionality after the failure of an individual amplifier. The distributed transmitter noise can also be decorrelated, unlike the centralized transmitter, which provides the same noise to each antenna element. This decorrelation allows the distributed system's transmitted noise to be lower than the centralized system's approach by as much as the antenna's gain.

A centralized transmitter also requires a high-power RF power distribution network, unlike the lower power level required for a distributed network. The resistive losses of the centralized distribution network also come after the last stage of power amplification, whereas the distributed transmitter losses occur before the power amplifiers. In addition, more transmitter power is necessary for the centralized transmitter to overcome phase shifter losses (along with higher power-handling phase shifter requirements). These issues make the distributed transmitter more efficient with associated prime power, cooling, and weight advantages. For

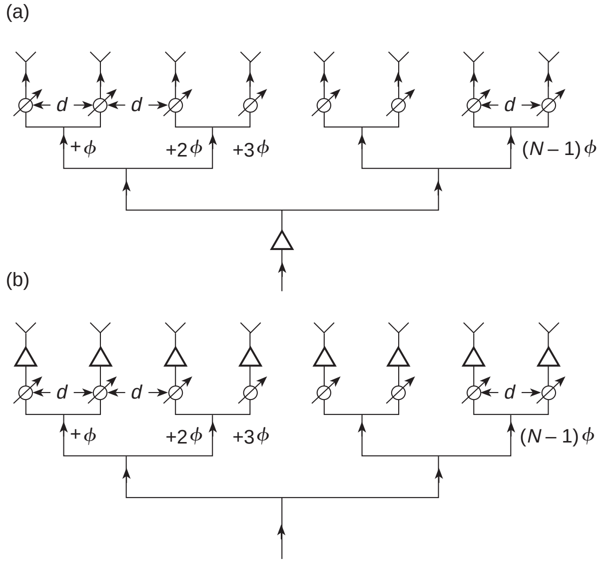


Figure 3. (a) Centralized and (b) distributed phased array transmitters (ϕ = phase increment applied at each individual radiator, d = spacing between individual radiators, and N = number of individual radiators).

these reasons, distributed transmitters are generally used.

Transmit/Receive Module Functions with a Distributed Transmitter

This section will develop the basic functional block diagram of a transmit/receive (T/R) module with a distributed transmitter. Amplification, phase shifters, and attenuators are required at each antenna element to electronically steer the beam and shape the antenna pattern. Additionally, each element must be protected from electromagnetic damage, which can be caused by other systems or reflected energy. The transmitter and receiver must also be connected to a common radiating element.

The first amplifier in the receive chain needs to amplify small signals and generate a minimum amount of noise to provide maximum sensitivity. The last amplifier in the transmit chain needs to efficiently generate a high power level. These conflicting requirements, along with the unidirectional performance of amplifiers, often lead to the use of separate amplifiers for the transmitter and receiver. The phase shifter and attenuator are bidirectional and can satisfy both transmit and receive functions.

The basic electronic requirements at each element of the phased array can be achieved using the layout shown in Fig. 4. This setup constitutes the basic functionality commonly referred to as a T/R module. This block diagram assumes that the receive and transmit functions are not simultaneous (referred to as half-duplex operation).

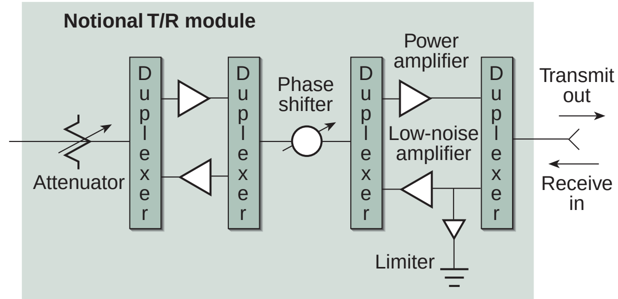


Figure 4. Basic T/R module functionality.

HYBRID VERSUS MMICs

Cost and Performance

The microwave components in a T/R module are realized as monolithic microwave integrated circuits (MMICs) or hybrid circuits incorporating discrete transistors. MMICs allow all of the passive components (inductors, capacitors, resistors, and transmission lines) to be fabricated on the semiconductor wafer along with the active devices (transistors, diodes, etc.). Hybrid assembly techniques use discrete parts for capacitors, inductors, and resistors, which are then integrated with the transistors using microelectronic interconnection and assembly techniques.

A MMIC will cost more than the value of its active devices because of the increased semiconductor size and the complex integration of the passive components. On the other hand, a hybrid requires assembly labor to integrate the passive components with the transistors. This additional hybrid labor cost must be considered versus the increased MMIC semiconductor cost during component selection.

Semiconductor processes are also capable of achieving smaller dimensions with corresponding smaller variations than microelectronic assembly techniques can provide. This ability leads to smaller and more repeatable physical interconnections between active and passive components. The physical size of an interconnection is directly related to its electrical capacitive and inductive characteristics, referred to as parasitics. MMICs generally are capable of lower and more repeatable parasitic levels. Performance requirements ultimately determine what levels of parasitics and component realization are acceptable.

Semiconductors

Gallium arsenide (GaAs) is typically used for MMICs because semi-insulating substrates can be made. The term “semi-insulating” refers to the fact that the semiconductor wafer can be used as a dielectric with low microwave transmission losses to produce low-loss passive structures. Silicon (Si) substrates are currently not amenable to MMIC fabrication because substrate losses are high.

Si transistors can be used in hybrid amplifiers, but GaAs also has superior frequency performance. Field-effect transistors (FETs), pseudomorphic high-electron-mobility transistors (PHEMTs), and heterojunction bipolar transistors (HBTs) are the three most commonly used GaAs transistors.

GaAs can be more expensive than Si because of its increased processing complexity, smaller wafer diameters, and smaller industry infrastructure. Yet, GaAs performance and MMIC advantages make GaAs the dominant semiconductor material for higher frequency applications. At lower frequencies, however, the cost versus performance trade-offs of Si should be considered.

Many other semiconductor technologies such as indium phosphide, silicon carbide, and gallium nitride offer performance advantages over GaAs. These technologies are relatively immature from a manufacturing standpoint in comparison with GaAs, however, and have different manufacturing limitations. Because of the large number of T/R modules required for a typical system, cost rather than performance is the main impediment to fielding phased arrays. Mature manufacturing processes and low overhead will be necessary for these technologies to achieve widespread use in Navy radars.

Amplifiers

Performance capability differences influence the choice between MMICs and hybrids for amplifier applications. Although tighter tolerance and associated parasitic control provide a MMIC with an advantage in frequency performance, a hybrid assembly allows the use of non-GaAs passive components, referred to as off-chip matching. Off-chip matching provides a circuit designer with options for dielectric material (for GaAs: $\epsilon = 12.9$, typical thickness = 0.004 in.).

The width of a trace to achieve a specific transmission line impedance is a function of substrate thickness and dielectric constant (see the boxed insert). Non-GaAs materials (lower dielectric constant and/or thicker substrate) enable the use of wider lines for equivalent transmission line functionality. Off-chip impedance matching can exploit non-GaAs materials for lower insertion loss interconnections than are possible on thinned GaAs wafers. Non-GaAs materials can then be used to lower the insertion loss of input impedance matching networks for low-noise-receiving amplifiers. This reduction in loss corresponds to a reduction in system noise figure.

Conversely, off-chip matching can also be used to realize lower impedance transmission lines with narrower lines than are possible with GaAs (higher dielectric constant and/or thinner). A transistor's impedance level goes down as its output power level is increased. This effect creates the need for very low impedance transmission lines to enable impedance matching to standard 50 Ω levels. It is difficult to integrate low impedance structures with GaAs power transistors because of physical size mismatches. Also, line widths should be kept electrically small to prevent additional modes from propagating. Higher dielectric constants and thinner dielectrics can be used to minimize the line width and to alleviate these issues.

Phase and Amplitude Control Devices

A phase or attenuation change can be realized by using two switches that alternate between two different passive networks as shown in Fig. 5. These circuits can then be placed in series to achieve the required range and resolution. Since this type of circuit switches between two discrete states, it is referred to as a digital control function.

Typically, four to seven digital circuits, referred to as bits, are placed in series to satisfy either the phase or amplitude control needs. This design requires many passive and active components, which makes MMIC assembly labor and part-reduction advantages attractive. Additionally, phase performance is particularly sensitive to parasitics and repeatability. These factors make MMICs well suited for phase shifter applications at higher frequencies.

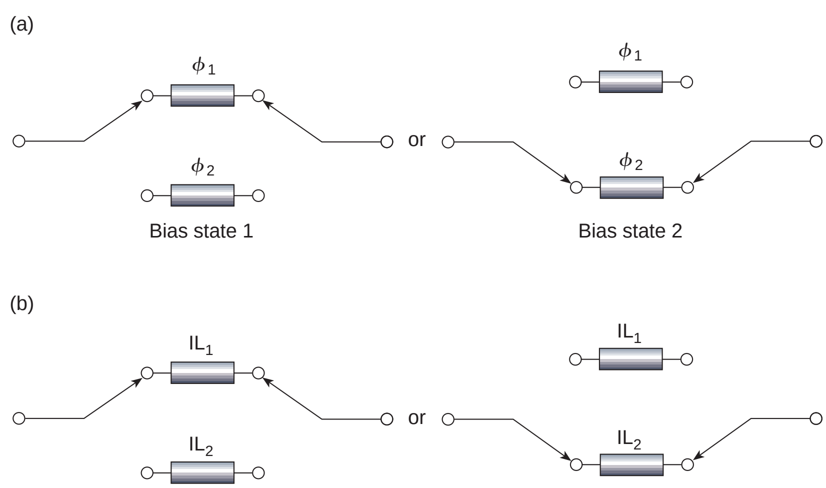


Figure 5. Digital (a) phase and (b) amplitude control circuits (ϕ = insertion phase, and IL = insertion loss).

TRANSMISSION LINES

Equal component impedances (typically 50 Ω) are required for maximum power transfer between components within a T/R module. The physical dimensions of the conductors, thickness of the dielectric, and the dielectric constant are design variables that control a transmission line's impedance. The same impedance can be achieved for two different sets of conductor dimensions by changing the dielectric constant and/or thickness. Dielectric constant and/or substrate thickness selection can be exploited to improve performance and/or producibility for a specified impedance level. The following paragraphs describe packaging considerations for the four transmission line configurations shown in the figure with varying applicability to T/R modules.

COAXIAL LINE

A benefit of coaxial line is that the ground sheath isolates the inner conductor from external components. A drawback of this configuration is that the center conductor cannot be accessed without removal of the ground sheath. The structure is also nonplanar, which creates hybrid assembly challenges. These issues limit the use of coaxial line in T/R modules. Its main application is in bringing RF signals through the housing walls.

STRIPLINE

A planar variant of the coaxial transmission line is stripline. The stripline ground planes minimize radiation, although coupling through the dielectric between components located within the ground planes is now possible. Although stripline is planar in structure, the center conductor is still inaccessible because of the ground planes. Consequently, connections to this transmission line require the use of other configurations (typically microstrip).

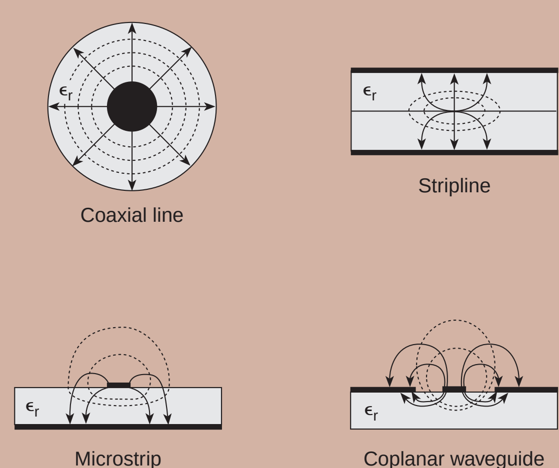
MICROSTRIP

Microstrip is amenable to hybrid assembly techniques because of its exposed conductor and planar structure. The unshielded conductor leads to higher radiation and coupling than the shielded coaxial and stripline configurations. The exposed planar conductor simplifies the manufacture of this configuration, however, which often outweighs radiation limitations.

COPLANAR WAVEGUIDE

Another variation of the coaxial transmission line is coplanar waveguide (CPW). CPW is planar and has an exposed center conductor, so it is also amenable to hybrid assembly techniques. CPW has an advantage over microstrip in that connections to ground do not require passage through the substrate. The minimum ground plane separation is then determined by photolithography rather than by substrate strength. Ground connections can then be made shorter with a lower parasitic level and subsequent higher frequency performance. This approach also allows a designer to limit radiation more effectively by using small ground plane separations that cannot be manufactured in microstrip.

A disadvantage of CPW is the additional substrate area required for the ground plane. In addition, maintaining ground planes at a constant potential can be difficult as the frequency increases. Also, models for coupled–lined CPW are not as widely available as microstrip configurations. For these reasons, microstrip is much more commonly used than CPW.



Transmission line configurations (ϵ_r = relative dielectric constant).

GaAs FETs can be used to make high-performance microwave switches, which are also attractive because they have low DC power requirements in comparison with diode switches. GaAs FET switches also use the same planar processes as GaAs FET amplifiers, unlike vertically processed GaAs PIN (p-type, intrinsic, n-type semiconductor) diode switches. This situation allows functional integration of GaAs amplifiers and control functions. Diodes also require bias circuitry, referred to as chokes, to isolate the switching DC power supply from the RF circuitry. FETs are switched through their gate terminal, which eliminates the need for RF chokes. These advantages make GaAs FET-based MMICs well suited for phase and amplitude control functions.

Analog switches that alternate between a range of states rather than two states can also be used for control functions. In particular, varactor diodes have a capacitance that varies with applied voltage, and this variation can be exploited to modify phase or amplitude. The voltage resolution required to control the capacitance is very small, however, and can place stringent noise requirements on the analog control supply.

Electromagnetic Protection: Limiters

The electromagnetic protection function is commonly referred to as a limiter. The nonlinear resistance of a diode is typically exploited to realize a limiter. If the incident RF energy is larger than the diode's threshold voltage, the diode resistance is significantly lowered. At lower RF levels, the diode resistance is high. A protection device can then be created by connecting a diode between the input conductor and the ground plane. Signals larger than the diode's threshold voltage will then be rectified to the threshold voltage. Some incident energy will still leak through after rectification, and subsequent lower threshold diodes can be used to reduce this leakage to a desired level.

Limiters require few parts, and their performance is fairly insensitive to parasitic variations. Conventional limiter diodes use processes that are incompatible with GaAs MMIC FET and PHEMT amplifier processes, however (vertical versus planar processing). This incompatibility mitigates many of the advantages of GaAs MMIC realizations. Si is also a superior thermal conductor in comparison with GaAs, and thus Si-diode-based hybrid limiters are commonly used in T/R modules.

Radiating Element Connection: Circulators

A circulator is commonly used to connect the radiating element to the transmitter and receiver functions. A circulator exploits the magnetic properties of ferrite to connect and isolate the receiver, transmitter, and antenna element.[1] A circulator is a three-port device that essentially acts as a revolving door for energy. Energy incident on the transmitter port will be sent to the antenna element, not the receiver. Likewise, energy incident on the antenna port will be sent to the receiver, not the transmitter. A signal flow diagram of a circulator is shown in Fig. 6.

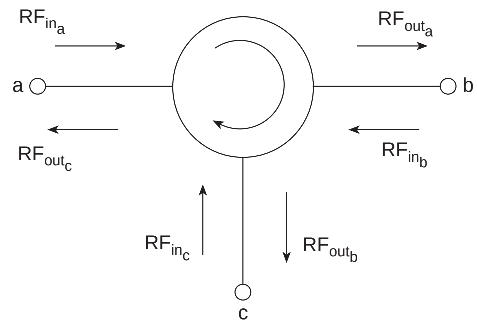


Figure 6. Signal flow diagram of a circulator.

Passive circulators comprise discrete ferrite, magnetic, and ceramic materials and do not require semiconductors. These devices are built with different processes than MMICs or hybrids and typically require separate production facilities. A circulator typically involves a high level of assembly labor. Active MMIC circulators have been investigated to reduce the labor cost but are not suitable for phased arrays because of inferior noise figure and/or output power performance.

Circulators are often the thickest T/R module component, and thinner circulators are desirable to prevent grating lobe formation for very high frequency applications. Ferrite tape systems and magnetless circulators are being pursued to reduce both thickness and the amount of assembly labor required.

A semiconductor switch can also be used to connect the receiver or transmitter to the antenna element. Unlike a circulator, a switch does not isolate the transmitter from energy input into the antenna element. This incident energy can damage the transmitter and/or increase the amount of incident energy reflected out of the antenna (creating a higher radar cross section).

A switch also does not isolate the transmitter from the antenna element's impedance, which varies as the phased array is scanned. This impedance variation can cause the power amplifier's performance to change as the antenna is steered. For these reasons, switches are unsuitable as circulators for most phased array applications.

SURFACE OR CAVITY MOUNTING OF MMICs

Transmission lines on substrates are used to integrate all of the microwave and digital functions together. The MMICs are thus combined into a hybrid assembly. MMICs can either be mounted on the surface of the substrate or placed next to the substrate as shown in Fig. 7. Surface mounting can be done with either conventional or flip-chip processes.

Interconnection length and associated electrical parasitics differ for conventionally surface-mounted

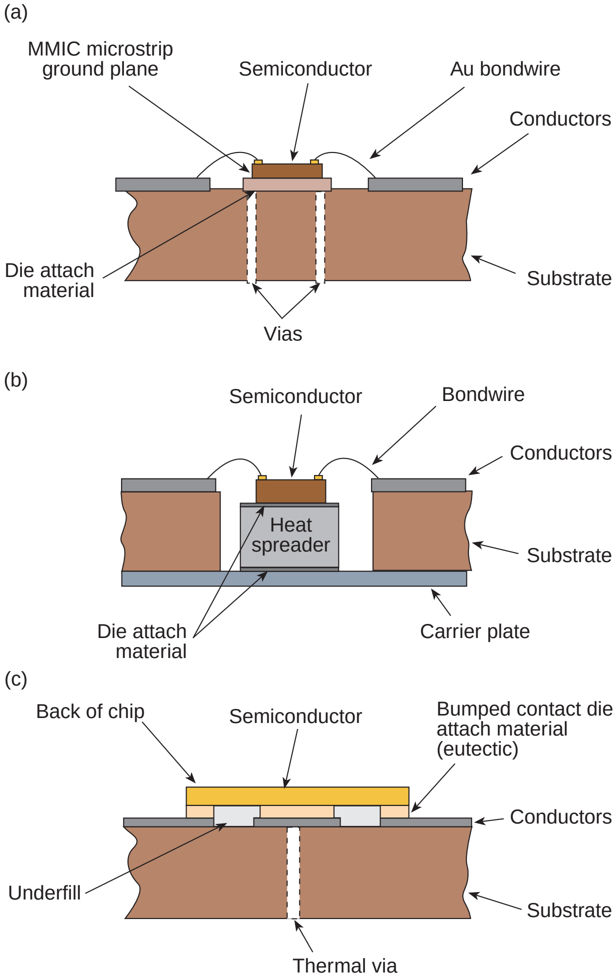


Figure 7. (a) Conventional surface mounting, (b) cavity mounting, and (c) flip-chip mounting techniques for MMICs.

parts, cavity-mounted parts, and flip-chip surface-mounted parts. Conventional surface mounting requires the interconnection to traverse the height of the MMIC and solder or epoxy attachment. Substrate transmission line conductors must be spaced sufficiently far away from the MMIC's mounting area to prevent epoxy or solder from shorting the conductor to the backside of the MMIC. This gap is also necessary to minimize parasitic capacitance between the transmission line and MMIC mounting area. Larger gaps increase the interconnection length and associated parasitics.

The bottom of a MMIC can be used as the ground plane for microstrip transmission lines on the GaAs and/or as a ground plane for transistor connections. The T/R module housing is typically connected to the system ground. The connection between the ground plane of the surface-mounted MMIC and the housing is typically accomplished with a plated hole through the substrate, referred to as a via. The length and diameter of the via determine its parasitic inductance and can limit higher-frequency performance. Several vias in parallel or larger-diameter vias can be used to minimize inductive effects.

Cavity-mounted parts can be used to minimize inductive parasitics to ground. MMICs placed on pedestals within holes cut into the substrate can also reduce the interconnection distance between the MMIC and substrate transmission line. This reduced distance lowers the parasitic inductances associated with bondwire length. Cavity mounting also provides a lower-resistance thermal path and subsequently improves reliability by lowering device junction temperatures.

Cavity mounting can significantly increase costs, however, because of the increase in parts and assembly requirements associated with substrate machining, pedestal fabrication, and tolerances necessary to minimize parasitics. Typically, the space between the cavity and MMIC edges required for low-cost assembly can make bondwire lengths comparable to or longer than surface-mounted parts. This situation eliminates the interconnection parasitic reduction benefit if high-volume assembly procedures are desired.

The parasitics created by conventionally mounted and cavity-mounted parts can generally be taken into account during the design process at X-band frequencies and below. Parasitics can seriously limit performance at higher frequencies, however. Also, lower impedance devices are more sensitive to parasitic levels and repeatability. This sensitivity makes off-chip matching of low-impedance devices difficult to achieve in high volumes with conventional or cavity-mounted MMICs. Low and consistent parasitic levels are necessary to enable high-power, low-cost amplifier off-chip matching.

Flip-chip MMICs can be used to minimize interconnection inductance associated with bondwires. Flip-chip GaAs MMICs and assembly processes are not widely available, however. Flip-chip transmission line structures also differ from microstrip lines typically used on MMICs. This situation creates a need for custom passive circuit models not available in commercial linear circuit simulators. Heat removal from flip-chip also requires a large interconnection area for heat spreading, although the semiconductor is removed from the thermal path, providing a lower junction temperature than a conventionally mounted part.

SUBSTRATE ELECTRICAL CONSIDERATIONS

Single versus Multilayer Substrates

Microstrip transmission lines require a conductor pattern on one side of a substrate and a ground plane on the other. The electromagnetic fields for a microstrip line are not fully confined between the topside trace and the ground plane because of the dielectric and ground plane asymmetry, which causes fields to radiate into the air and surrounding substrate.

Radiation can cause undesirable component interactions, coupling, and/or oscillations. Physical spacing between microstrip lines and other components can be used to minimize coupling. Substrate properties and coupling distance variations require a case-by-case evaluation of the separation required. Thinner substrates and higher dielectric constants can also be used to minimize radiation.

Coupling between lines can cause serious performance degradation when a microstrip or digital control line has to cross over a microstrip line. This problem is especially prevalent in the vicinity of the phase and amplitude control MMICs, which require a large number of digital control lines.

Multilayer substrates can be used to overcome this problem. With a multilayer substrate, a microstrip ground plane can be placed within the substrate. The digital lines can then be routed under the ground plane, thereby isolating the microwave and digital lines. The digital lines can be connected to topside traces through vias in the RF ground plane and substrate.

Multilayer substrates can also be used to route RF transmission lines beneath each other to limit coupling. When the RF line is buried, an alternative to microstrip transmission line is required. A center conductor with ground planes both above and below, such as stripline, is typically used for buried RF lines. Striplines can also be used in place of microstrip to minimize radiation.

The labor and material requirements and subsequently the cost of a multilayer substrate increase with the number of layers, vias, and other complexity drivers. The control section of a T/R module will typically require a few layers to enable the digital lines of the control section to be routed effectively. The low-noise and power amplifier sections of the module have much lower digital line density and may permit the use of less expensive single-layer substrates.

Stripline transmission lines can require many layers of substrate to achieve the thickness for a desired impedance level because of dielectric constant and photolithographic limitations. Digital isolation from RF transmission lines with a ground plane requires only a three-layer substrate. Stripline transmission lines can then increase the number of layers required for a particular application. Although striplines can effectively minimize RF radiation, more cost-effective solutions such as alternate transmission line structures, physical spacing, and dielectric material selection should be used if possible.

Substrate RF Properties

As with the multilayer substrate, the control MMIC section and power/low-noise amplifier section of the module have different RF performance requirements. Transmission line losses in the control section of the module are generally not critical, and several decibels of loss can be accounted for in the design stage with little cost or performance impact. Transmission line losses before the low-noise amplifier or after the power amplifier will degrade noise figure and output power, respectively, and directly reduce system capability.

In general, a low-loss single-layer substrate is appropriate for the low-noise and power amplifier portion of the T/R module, and a multilayer higher-loss substrate can be used for the control section of the module. Thus, designers can select dielectric constants and substrate thicknesses independently for these two sections to manage the different requirements in a cost-effective manner. Dielectric constant and substrate thickness can then be exploited as previously mentioned to tailor transmission line dimensions, radiation, and undesired moding.

Substrate Power Combining

Power combiners on the substrate are required if the power amplifier is not realized with a single MMIC. Single-layer substrates can be used to realize Wilkinson power dividers, which can be realized with microstrip transmission lines and resistors.[2] This type of power divider splits the input signal into equal amplitude output signals with equivalent phase. Resistors are ideally fabricated as part of the substrate but can also be applied as hybrid components for higher-power applications.

A 3-dB hybrid coupler can also be used for power division. This device splits the input signal into two equal amplitude output signals with a 90° phase difference. The phase difference can be exploited to minimize reflections between components due to unequal impedances. Reflections are reduced by placing components in what is referred to as a balanced configuration, as shown in Fig. 8.

If the two components (typically amplifiers) in Fig. 8 are identical, their reflections will be 180° out-of-phase and cancel at port four. The in-phase reflected energy is terminated in the resistive load. A balanced configuration provides the power combining capability of a Wilkinson power divider with the added benefit of reflection reduction. Balancing is also often used to terminate the energy from a reflective limiter. The input power division also reduces the limiter's power handling requirements by a factor of 2.

A 3-dB 90° hybrid coupler requires tight coupling between two transmission lines. Single-layer substrates

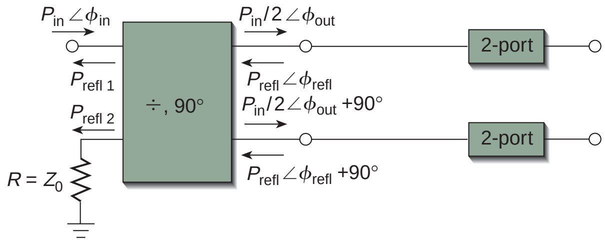


Figure 8. Balanced configuration used to reduce reflections (P = power, ϕ = phase angle, R = resistive load, Z_0 = system characteristic impedance, and refl = reflected).

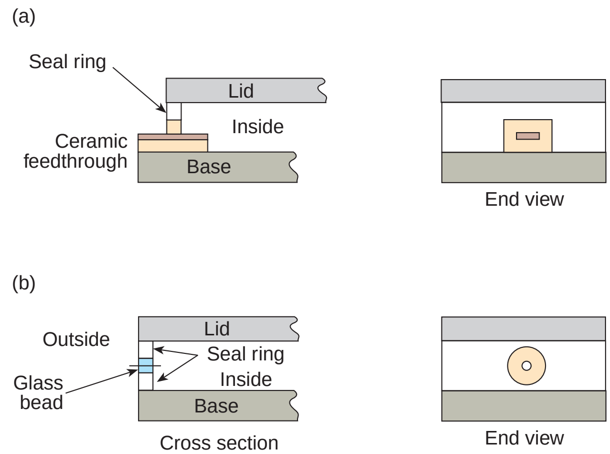


Figure 9. Package cross section with (a) stripline and (b) coaxial connectors.

use coupled transmission lines in the same plane, which is referred to as edge coupling. The tight spacing and tolerance requirements typically require thin-film processing, however, which can significantly increase single-layer substrate costs.

Coupling can also be achieved through the layers of a multilayer substrate, which is referred to as broadside coupling. Broadside coupling mitigates the tight spacing requirements because of the increase in coupling area. Either technique can satisfy coupler functionality, and a cost analysis is necessary to select the appropriate technique.

RF CONNECTORS

Planar versus Coaxial Connectors

Connectors are required to join the RF source distribution network, antenna element, DC power supply distribution network, and array-level digital control distribution network to the module. The RF connections are typically achieved with either stripline or coaxial transmission lines through the housing wall as shown in Fig. 9.

For stripline connections, often referred to as planar feeds, the upper dielectric and ground plane are removed on both the substrate and RF distribution network sides of the wall to permit connections. Microstrip transmission lines are used in these areas. The width of the conductor can be varied to maintain a constant impedance for both the microstrip and stripline areas.

Microstrip to stripline transitions can create a discontinuity in the ground plane, however. This discontinuity is created because the upper stripline ground plane is not at the same potential as the lower ground plane because of their physical separation. This condition creates parasitics and can excite undesired propagation modes. Plated through-holes on either side of the stripline in conjunction with coplanar waveguide rather than microstrip connections can be used to minimize this problem.

For coaxial connectors, the outer conductor and dielectric are removed to allow connection to the center conductor. The length of the center conductor from the housing wall to the substrate's microstrip is an inductive parasitic that should be minimized. Extraneous modes and parasitics can also be created because of ground plane discontinuities between the coaxial ground sheath and the substrate's microstrip ground plane, but the problem is not as severe as the stripline case.

Planar Connector Attachment to Substrate and Array

Connections from the substrate to the exposed microstrips on planar connectors can easily be made with bondwires. A small ceramic microstrip transmission line is often placed between the substrate and planar feed to prevent connector damage if substrate removal is necessary.

The external portion of the planar feed can be attached to the RF distribution network of the array with either an elastomer or hard attachment (flex circuit with solder). The elastomer is placed under mechanical pressure, which creates a connection between a trace on the elastomer and the microstrip on the planar feed. This setup allows modules to be replaced without the need for microelectronic solder reflow requirements.

Alignment of the elastomer's conductive traces with the planar feeds can require special tooling to achieve consistent RF performance. Also, degradation of the mechanical characteristics of the elastomer after exposure to temperature extremes and corrosive-laden air is of concern for harsh military environments.

Soldered or welded connections can be used to mitigate the alignment and environmental issues associated with elastomers. The advantages of this method need to be considered versus the need for reflow processes to remove a module and limitations on the number of times a module can be removed because of rework damage. In general, elastomers are preferable in development when module design issues remain, and solder connections are advantageous in a high-volume, low-cost environment.

Coaxial Connector Attachment to Substrate and Array

Connections from the substrate to a coaxial connector require the center conductor of the coaxial line to be exposed. Connections to the center conductor can then be made with either solder, ribbon, or bondwire as shown in Fig. 10. Connections to the array are typically made to another coaxial connector.

The exposed center conductor length and interconnection distance should be minimized to limit the associated parasitic inductance and improve the frequency performance. Although the solder connection can provide the lowest parasitic level, tolerance and thermal expansion stress relief issues limit its use. The ribbon loop requires manual assembly to form the loop, which also limits its use in high-volume production. The bondwire approach is the most feasible from a manufacturing standpoint, although it can have the highest parasitic level.

PACKAGING MODE SUPPRESSION

Transmission Lines

Transitions between transmission line configurations (microstrip, stripline, coaxial, etc.) lead to mismatches in the electrical and magnetic field patterns due to differing geometries. These mismatches lead to undesired field patterns and resultant increases in loss as well as to unintended coupling to other circuits within the module. Transitions with bondwires and other interconnections also create field discontinuities.

The field patterns are determined by the transmission line type, the conductor cross-sectional dimensions, the dielectric height, and the dielectric constant. Designers can exploit these parameters to minimize field mismatches.

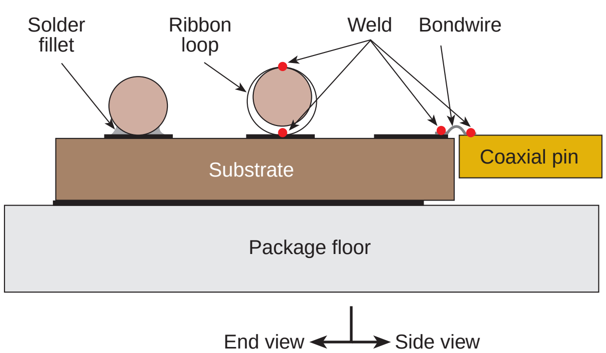


Figure 10. Coaxial connector to substrate interconnections: solder, ribbon loop, and bondwire.

Packaging Modes

Loss of energy and isolation between components can also be created by a metallic package. The packaging cross section creates a waveguide-like transmission line structure. Small amounts of feedback due to the waveguide combined with the high gain typical in modules can lead to unstable amplifier performance. The value of the lowest frequency of waveguide energy propagation is determined by the package's inner dimensions, the substrate's thickness, and the substrate's dielectric constant.

The package width plays a major role in determining the lowest waveguide frequency. The module width should be sufficiently small to increase the resonant frequency beyond frequencies where the module has significant gain. Walls that are electrically attached to the housing base and lid can be used to effectively make narrower waveguides with higher cutoff frequencies. Walls increase assembly and packaging costs, however, and should be avoided.

Another technique to mitigate modes is to place a high magnetic field attenuation material on the inside of the module's lid. These materials can evolve hydrogen, however, which can create reliability problems in MMICs in a hermetic package.[3]

SUMMARY

T/R modules are a performance, reliability, and cost driver for future phased array antenna applications. Semiconductor, packaging, and assembly technologies all play critical roles in determining the performance, reliability, and cost of T/R modules. The packaging design process should consider the effects on both semiconductor and assembly techniques to ensure that the best overall product is achieved. Trade-offs between performance, cost, and reliability must also be carefully considered for successful packaging development.

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