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RADIO-FREQUENCY CONNECTOR AND INTERCONNECT RELIABILITY IN SPACEBORNE APPLICATIONS

Radio-frequency systems employed in spacecraft and satellites require highly reliable interconnects and electronic components. Engineers must therefore address and resolve issues such as improperly designed or manufactured connectors and interconnects. We have developed guidelines for the design of a space-qualifiable connector system, based on our experience with defective hybrid couplers and power dividers and an understanding of the material properties of the connector dielectric.

INTRODUCTION

Reliability concerns about a spaceborne radio-frequency (RF) system, such as an S-band communications antenna aboard a satellite, usually focus on components with complex circuits. Equally important—and most often overlooked—are the interconnections among devices. Failures in defective hybrid couplers and power dividers can often be attributed to unstable interconnections.

Connector reliability is especially important for applications in space environments, which are subject to temperature excursions as large as ±100°C, because the electrical stability of connections is directly related to their thermomechanical stability. In addition, as system performance and testability goals become more stringent, connectors, like all components of modern high-performance systems, must meet increasing demands for tighter tolerances and specifications.

Our investigations indicate that connector problems are primarily rooted in the design and the manufacturing processes. To correct them, we must be able to detect and compensate for related component parameter changes. We have analyzed the pros and cons of different types of RF connectors, focusing on their design, manufacture, material properties, and testing. In this article, we present our results and recommendations for the optimal design of RF connection systems.

CHARACTERISTICS OF TRANSMISSION LINES FOR RF CIRCUITS

For purposes of design and construction, complex electronic systems are usually treated as a number of physically discrete building blocks, often referred to as packages or boxes. This modular concept is attractive because the individual boxes can be designed, built, and tested independently as long as they conform to proper interface specifications and controls. The boxes can also be separated physically in the system, if necessary, and linked by some means for transporting signals and power and a convenient connect/disconnect system. Electrical cables are the most common means of interconnecting the boxes, although fiber-optic cables are gaining increasing popularity for signal-transfer applications. Electrical connectors perform the connect/disconnect function. To maintain electrical continuity between wires on the two sides of the connector, two bare conductors are mechanically forced into contact, in much the same way as an AC power cord is plugged into a wall outlet.

For electronic circuits operating at radio frequencies, interconnecting boxes is more involved than simply establishing electrical continuity. At low frequencies, the wavelengths emitted are considerably longer than the dimensions of most microwave components. Hence, the magnitude and phase of the electric and magnetic field intensities E and H are practically constant along the dimensions of the devices, and circuit behaviors can be adequately predicted without modeling a cable as a separate element.

In contrast, since wavelengths at RF and microwave frequencies on a cable are approximately the same order of magnitude as the device dimensions, the cable itself becomes a significant circuit element. This element is generally known as a transmission line, and its electrical behavior can vary markedly depending on the geometry of its conductors and insulators, their electrical properties, and, especially, frequency.

Figure 1 is a schematic of a two-conductor transmission line circuit, one of the types of transmission lines commonly used for high frequencies (discussed in the next section). It is characterized by its resistance to current flow R, inductance L (the voltage induced by the current), conductance G (the readiness of the circuit to conduct current, $= 1/R$), and capacitance C (the energy storage capacity of the circuit). As frequency increases, so do the mutual and self-inductances of the conductors (series impedance), the capacitor-modified coupling between the conductors (parallel admittance), and the interactions among the cables. These factors must be considered in the design of high-frequency transmission lines.

High-Frequency Transmission Lines

The two types of transmission lines commonly used for high frequencies are the waveguide and the two-conductor line. A waveguide is a single hollow conductor with

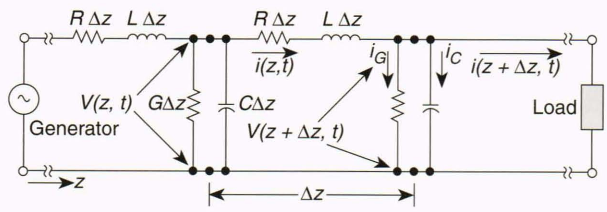


Figure 1. An elementary portion of a uniformly distributed two-conductor RF and microwave transmission line. Inductances (L) and capacitances (C) are distributed along the transmission line and their effects combine at each point on the line. R = distributed conductor resistance in Ω/m, L = distributed conductor inductance in H/m, G = distributed conductance between the two conductors in S/m, C = distributed capacitance between the two conductors in pF/m, and Δz is an incremental section of the transmission line in m. Note that the voltages (V) and currents (i) along the transmission line are functions of both time (t) and distance (z). (Reprinted, with permission, from Ref. 1, p. 63. © 1990 Prentice-Hall, Englewood Cliffs, N.J.)

carefully controlled internal dimensions. This technology became well established during World War II with the development of radar. A waveguide offers several benefits: it is well shielded, it has low loss, and connectors for it are usually simple flanges that can be securely bolted together. Signals, however, cannot propagate in it below a certain size-dependent frequency. It can, therefore, become bulky at the commonly used microwave frequencies with limited usable bandwidth (e.g., a standard WR-75 rectangular-aperture waveguide with an aperture dimensional ratio of 2:1 has a usable bandwidth of 10–15 GHz).

The second type of high-frequency transmission line is essentially an extension of low-frequency technology and consists of two conductors with equal and opposite currents flowing in each. The geometry along the length of the line is held constant so that the voltage-to-current ratio of a single wave on the line (the characteristic impedance) assumes a specified value. Two-conductor transmission lines have no lower frequency limit and can be made much smaller than hollow-tube waveguide, although they generally suffer higher losses. Two parallel wires can form a twin-lead transmission line, but this simple geometry has poor shielding and radiation characteristics. Better performance is obtained from specially selected geometries comprising two conductors separated by an insulating medium called a dielectric. Three common types are coaxial cable, microstrip, and stripline (Fig. 2).[2]

A coaxial transmission line (Fig. 2A) comprises a center conductor surrounded by a concentric outer conductor. It is typically used to connect modules and subassemblies because it is flexible, can bridge gaps, and can span relatively long distances. Microstrip (Fig. 2B) and stripline (Fig. 2C), which are primarily used inside subassemblies and modules, are fabricated using printed circuit technology and consist of planar conductors in proximity to parallel ground plane(s).

Microstrip consists of a flat metal conductor strip attached to one side of a flat dielectric substrate and a single ground-plane conductor covering the other side of the

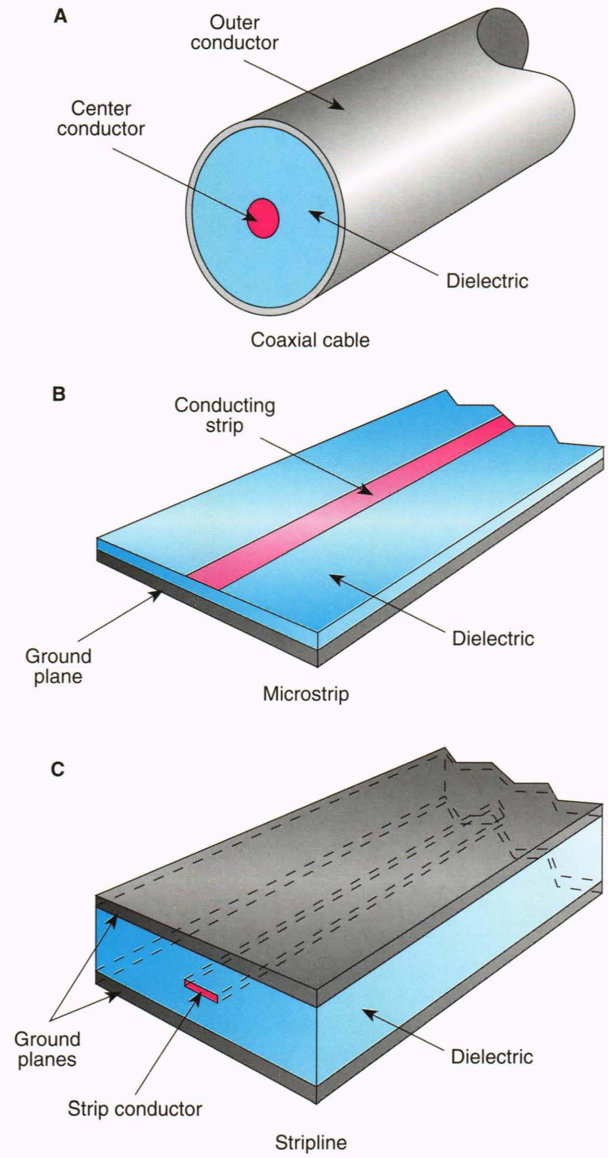


Figure 2. Three common types of RF transmission line configurations. **A.** Coaxial lines are primarily used to interconnect modules or subsystems. **B** and **C.** Microstrip and stripline are used inside most RF and microwave circuits. All three consist of a dielectric insulating medium separating a center conductor from one or more ground planes.

dielectric. Stripline (Fig. 2C) is a flat metal conductor strip sandwiched between two dielectric substrates whose outer surfaces are covered with ground-plane conductors. Microstrip is easier to use than stripline for interconnecting discrete active and passive elements because the conducting strip is on top of the substrate rather than between two substrates. On the other hand, stripline's sandwich configuration confines the electromagnetic fields within the substrate, resulting in lower propagation losses than with microstrip. Although active elements cannot be easily interconnected via stripline, discrete passive elements can be replaced by metal traces configured in specific patterns and lengths, known as distributed elements.

Dielectrics for RF Transmission Lines

Several types of material are used as the dielectric in microwave connectors and transmission lines: polytetrafluoroethylene (PTFE), air, and polyethylene. By far, the dielectric and substrate materials most used in microwave transmission lines are Du Pont's PTFE resins, sold under the trade name of Teflon. Air dielectric is most commonly used in the precision measuring connectors on the test cables of an automated microwave spectrum or network analyzer. Polyethylene is less expensive than PTFE and has similar physical and material characteristics, but its usable temperature range is only −65 to 85°C compared with ±250°C for PTFE.[3]

Polytetrafluoroethylene (Teflon)

Polytetrafluoroethylene resins have numerous industrial, commercial, and military applications because of their unique combination of mechanical, electrical, chemical, physical, and thermal properties. A mechanical property of PTFE resins that is especially significant for RF connectors is their deformation, or creep, with temperature and loading. Creep is the total deformation per unit time, including the instantaneous deformation upon loading, due to an externally imposed stress. Unlike metals, plastics usually exhibit creep at or below room temperature, hence the descriptor "cold flow."[4] Cold flow is important to connector reliability because it affects PTFE gaskets under compression in flanged, bolted joints. Cold flow causes the gaskets to creep and deform between the flanges, which, in turn, decreases the compression pressure, allowing the joints to loosen and leak. Tightening the joint once ensures a good connection, since any subsequent deformation will be insignificant.[4]

Polytetrafluoroethylene resins also have a positive near-linear coefficient of linear expansion from −284 to 25°C. At higher temperatures, the rate of linear expansion progressively increases. For example, PTFE resins undergo a volume increase of about 1.7% from 15 to 35°C. This relatively large change may have been responsible for the abrupt shift in the insertion phase of the hybrid couplers that we tested, as described later. Outside this temperature range, the cubical coefficient of expansion is at most $1 \times 10^{-3} cm^3/cm^3 \cdot °C$, as noted in Reference 4.

Despite their cold-flow tendency at low temperatures, PTFE resins have high strength, toughness, and self-lubrication down to −268°C. At higher temperatures, they are usable up to 260°C, their decomposition temperature. (Decomposition occurs at all temperatures but is significant only beyond the decomposition temperature.[4])

Reinforcing fillers may be added to PTFE resins to improve such characteristics as resistance to creep, stiffness, hardness, thermal conductivity, and thermal dimensional stability. A higher resistance to creep, along with proper connector and transition designs, generally increases the mechanical and electrical reliability of PTFE RF and microwave connectors. Dielectrics used in stripline and microstrip are laminates consisting of PTFE-based materials reinforced with fillers. The laminates retain all the properties of pure PTFE resins and have better mechanical, thermal, and handling characteristics. Their dielectric constants—one of the two most important characteristics of microwave materials—are nearly constant over the military temperature range of interest and across a broad range of frequencies. Another critical property, dielectric thickness, typically changes by only 2% over the same temperature range. If the tolerance of the dielectric thickness is tightly controlled, and the linear thermal expansion or contraction of the laminates is small but known, the change in the characteristic impedance of the stripline or microstrip with temperature can be predicted and properly compensated to prevent signal loss.

CONNECTORS AND INTERCONNECTS

One unique problem facing an RF systems engineer is how to connect transmission lines located in separate parts of a system and still maintain a 50-Ω matched impedance. Impedance must be continuously well matched along an RF transmission line, or the signal it carries will be significantly degraded. How an RF element is situated in a circuit or how obstacles such as box walls are physically connected may also contribute to impedance mismatch, undesirable coupling, signal losses, and degradation.

These connection problems become more complex when two portions of a circuit use different transmission line types. For instance, a coaxial-to-microstrip transition is more difficult than a coaxial-to-stripline or coaxial-to-coaxial transition. The most important factor in this case is the propagation mode of the microwave energy. Microwaves travel in a true transverse electromagnetic (TEM) mode in coaxial cable—that is, the magnetic field intensity lines are concentric to the center conductor and are completely confined within the dielectric material (usually Teflon). The propagation modes in the stripline transmission line are also true TEM since the magnetic lines are confined by the planar substrates. On the other hand, signals propagate along the microstrip transmission line in a quasi-TEM mode because the electric and magnetic field lines pass partly through the substrate and partly through the air. Radiative power losses will therefore be higher for the coaxial-to-microstrip connection than for two lines with similar TEM modes.

Coaxial-to-Stripline Transition

Configuration differences are the main problem in the transition from coaxial cable to stripline, which is commonly used in such components as RF couplers. As we discussed earlier, the cable is circular with a ground conductor surrounding the center signal conductor, whereas the stripline is flat with the signal connector attached to one side of the substrate and the ground conductors lying in planes underneath and above the substrate. Moreover, the wall of the coupler, which makes up a part of the coupler housing, stands between the two transmission lines (Fig. 3).

A typical approach to solving these problems is to continue one of the transmission lines through the wall of the coupler and to provide a launch at the juncture from the center conductor of the coaxial line to the flat signal conductor of the stripline. The coaxial cable is attached

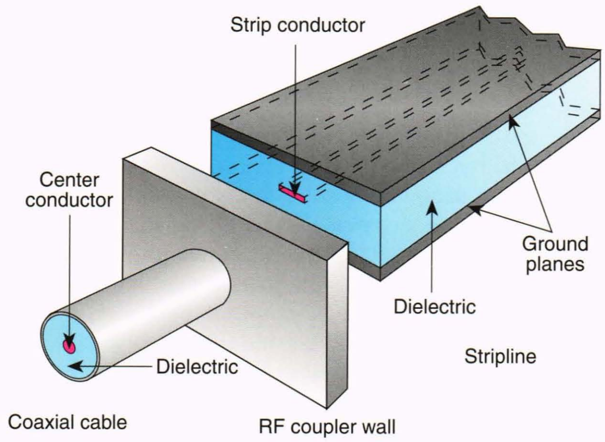


Figure 3. Transferring microwave energy from a coaxial cable to a stripline transmission line and vice versa. The geometry differences between the two lines and the wall of the coupler housing are the main impediments to coupling.

to the coupler wall via RF connectors, such as subminiature (SMA) female connectors. The SMA connector is inserted through the wall, and a male connector on the cable is plugged into it, allowing for easy connect/disconnect of the cable from the coupler.

The most difficult problems in this situation are to determine the size and shape of the launch and how to connect it to the stripline circuit. We examined three methods: (1) an SMA connector with a built-in launch in the shape of a flat tab either soldered or press fit to the stripline metal trace, (2) an SMA connector with a female contact on both ends and a separate launch pin soldered to the stripline circuit, and (3) a connector with a built-in launch attached to the stripline circuit with a looping gold wire bond.

In Method 1, a common flanged RF connector with a launch protruding from its back end is inserted in the coupler wall. The launch is $0.10 \times 0.05 \times 0.005$ in. thick and is designed specifically for attachment to a stripline circuit. Figure 4 shows the orientation of the connector and its launch with respect to the stripline circuit. The tab can be either soldered to the stripline metal or press fit to it. In press fitting, the lid of the RF coupler is screwed onto the coupler housing, compressing the top and bottom Duroid* insulating layers toward the center. The inward pressure forces the tab against the stripline trace and maintains the contact.

Neither the solder nor press-fit contact is ideal because the flat-tab launch is such a delicate interface. It is machined from a round pin, a process that induces stress-related microcracks at the transition point from round to flat (Fig. 5). The press-fit design allows the tab to slide on top of the stripline as the materials expand and contract with temperature, thus relieving strain on the delicate launch. Since the tab is not permanently soldered to the stripline, however, the contact can easily be displaced as the Teflon (the main component of the Duroid insulating layers and the dielectric inside the connector) undergoes cold flow and thermal expansion and contraction. The loss of mechanical pressure by the Duroid boards at each transition junction of the circuit can cause loss of contact or even an open circuit between the tab launch and the stripline metal. The effect would be especially pronounced because of the large temperature variation experienced by a connector in a space-based application.

Soldering the tab launch to the stripline metal also has its disadvantages, since a solder connection provides no strain relief for the launch. Over extremes of temperature, the different coefficients of expansion of the materials for the circuit board, conductor strips, and housing can create enough force to break the delicate launch pin.

Method 2 for a coaxial-to-stripline connection is intended to provide good electrical contact over a large temperature range and still provide strain relief for the launch. This design calls for an SMA connector with a female contact on both ends and a separate flat-tab launch pin, as shown in Figure 6A. In use, one end of the launch pin is soldered to the stripline circuit while the other end is allowed to slide in and out of the female contact within the SMA connector to alleviate strain due to temperature variations. Figure 6B is a cross-sectional view of the sliding pin within the connector.

The latter procedure seems to provide both good contact and strain relief, but there are always trade-offs in the world of engineering. A problem arises with this approach because the SMA connector with the female contacts on both sides is a screw-style connector as opposed to the flanged style of the first option. As these connectors are screwed in place, the tab launch is subjected to a torsional force that is usually sufficient to tear it apart at its weakest point—that is, where it steps down from a cylindrical shape to a flat-tab shape. Sometimes, even if the launch is not damaged, the torque imposed breaks the

*A PTFE material with reinforcement fillers manufactured by Rogers, Inc., Tucson, Ariz.

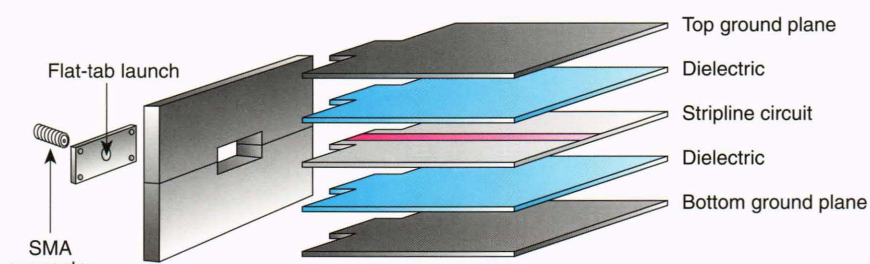


Figure 4. Using a flat-tab launch and subminiature (SMA) connector to connect coaxial cable to a stripline. The launch can be either soldered or press fit to the stripline.

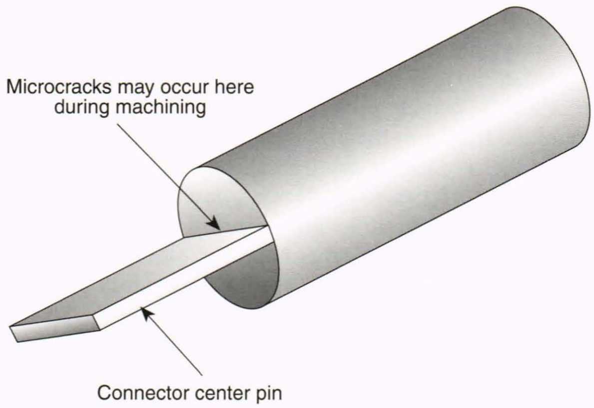


Figure 5. The connector center pin of a flat-tab launch is susceptible to machining-induced microcracks where the diameter changes.

solder joint at the stripline metal. Success with this method depends on using a launch with a different shape, the right SMA connector, and meticulous assembly procedures.

We have evaluated various launch shapes as alternatives to the flat tab. For example, a straight 0.036-in.-dia. pin with no machined flat portion would fit into a standard SMA female contact and would be much stronger than the machined flat tab. Such a pin would be too large to be soldered to the stripline metal trace, however, and would introduce a large amount of undesirable stray capacitance that would affect the characteristic impedance of the transmission line and therefore the performance of the circuit.

Figure 7A shows another launch design, a chamfered pin tapered in diameter from 0.036 to 0.015 in. In theory, the machining operation for this launch will not induce microcracks, and the more gradual change in the shape of the pin will minimize potential fracture points, but

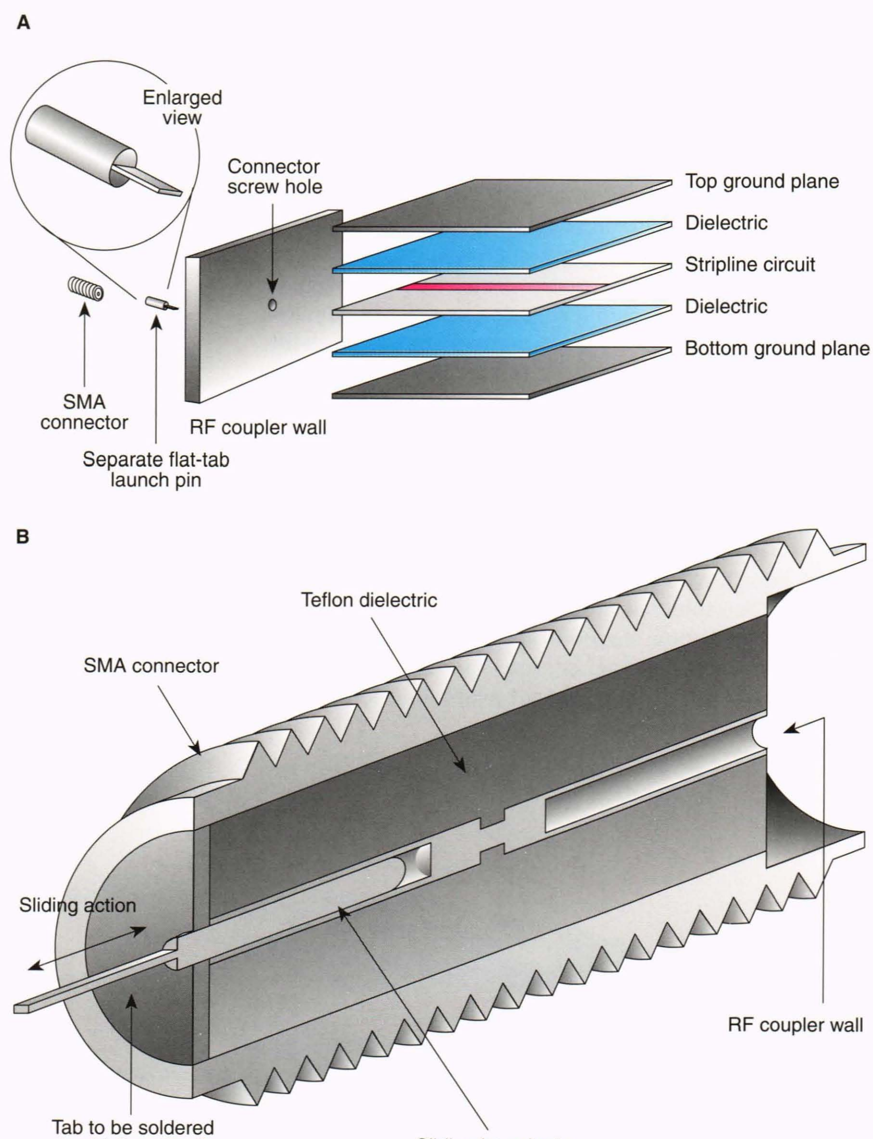


Figure 6. Another method of coaxial-to-stripline transition. **A.** One end of a separate flat-tab launch pin is soldered to the stripline circuit while the other end is free to slide into and out of the center connector female-to-female contact. This method offers good mechanical and electrical contact in addition to strain relief for the delicate flat-tab launch. **B.** Cutaway view of sliding launch pin in the connector.

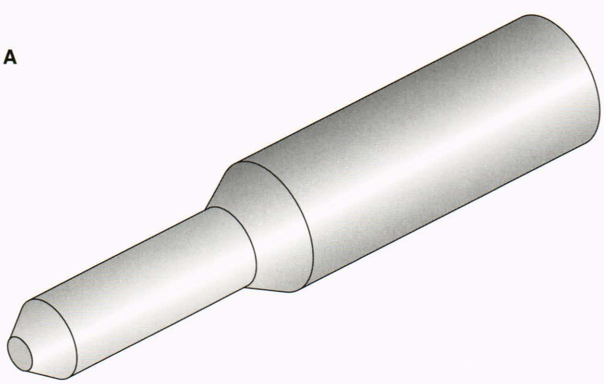
temperature cycling tests on sixteen hybrid couplers with this pin design showed that the pins were not appreciably more reliable than the flat tab. Four out of the sixteen couplers experienced an abrupt insertion phase shift (i.e., an open connection), a failure rate of 25%, compared with 40% for couplers with a flat-tab pin design. These launches may have failed because they were still weak enough at the tapered point to tear when the connector was screwed into place. Even when the launch did not tear, the applied torque often sheared the solder connection to the stripline. Figures 7A and B are scanning electron microscope photomicrographs of a fractured diameter-change point on a tapered launch pin.

We developed one launch design that eliminates many of these disadvantages—a straight 0.020-in.-dia. pin that requires no machining. The connector used with this launch pin provides a female contact on one side that accepts the straight pin and a standard 0.036-in.-dia. female SMA pin on the opposite side (facing outward from the coupler), as required for mating with standard SMA cable assemblies. To accommodate thermal changes in the PTFE insulator, the conductor is surrounded by a 0.001-in. air gap and is offset 0.005 in. from the edge of the connector (Fig. 8), design features that reduce excessive pulling forces on the launch pin as the PTFE material expands and contracts with temperature. Without such expansion relief, the PTFE material would expand radially toward the center, pulling the female contact and its captured launch pin outward in the axial direction and, eventually, breaking the pin-to-stripline solder connection. The air gap and offset do not affect the performance of the connection because the gap is small and the dielectric constant of air (near unity) is close to that of the PTFE (2.21).

In the third method for a coaxial-to-stripline connection, a connector with a built-in launch (as in the first method) is attached with a looping gold wire bond to a stripline constructed in Green Tape[†]. A looping wire bond is not possible with the stripline methods previously discussed because the lid and floor of the housing are used to compress separate Duroid boards to form the stripline circuit in those methods, leaving no space for a looping bond wire. A stripline circuit constructed in Green Tape, however, is in the compact form of a monolithic block, with the top and bottom ground planes, the metal traces, and four bond pads all within the block. The block is dropped into a Kovar package and attached to the bottom of the coupler housing with conductive epoxy, as shown in Figure 9, creating a cavity for a bond wire attachment to the connector.

[†]Du Pont's trademark for low-temperature cofired ceramic.

A



B

C

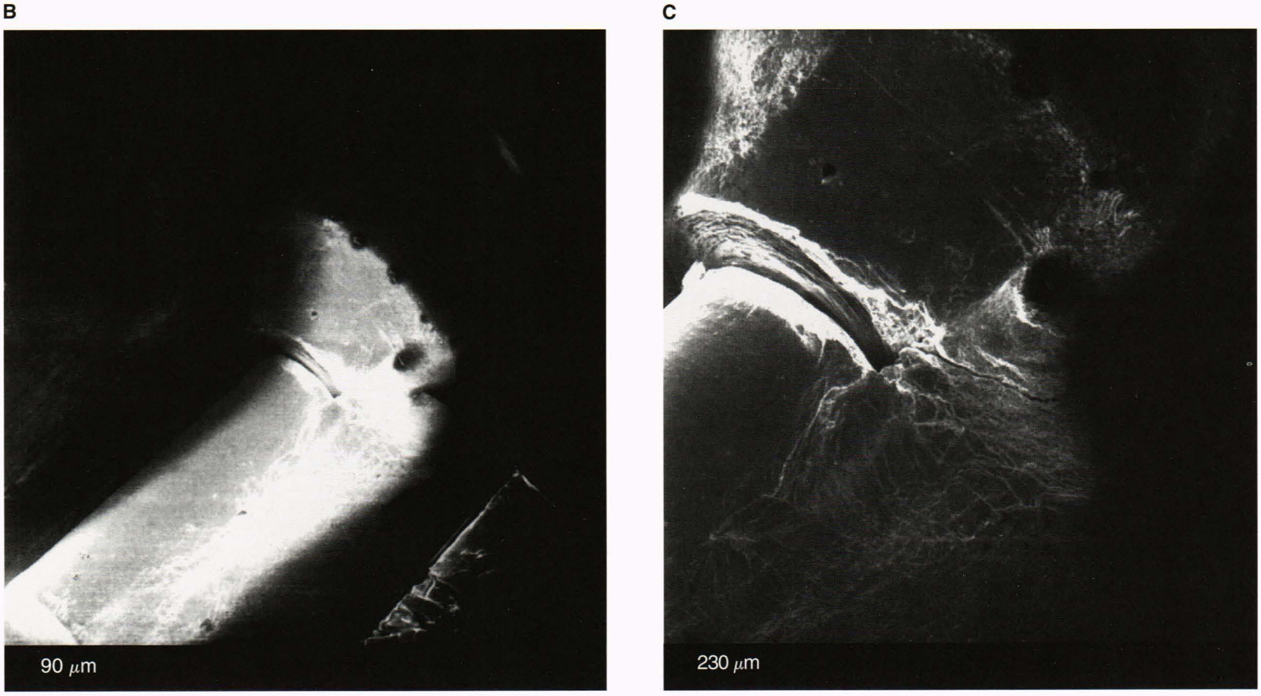


Figure 7. **A.** Diagram of a tapered launch pin designed to avoid the disadvantages of the flat-tab launch pin. The design improved connector performance only marginally. **B.** Scanning electron microscope photograph of a fractured pin, taken using a 20-kV electron beam at a 30° tilt. **C.** Enlarged view of the rift shown in B, taken at the same electron beam settings.

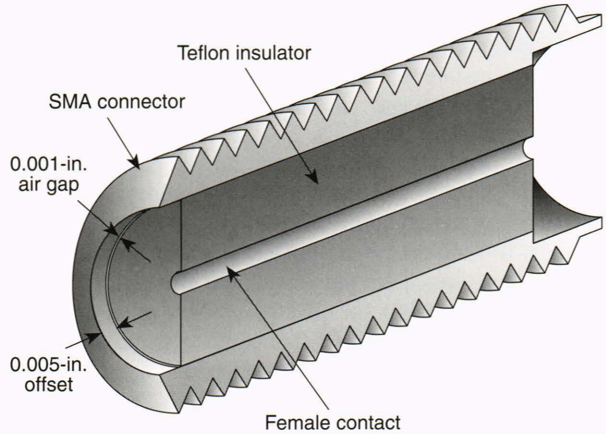


Figure 8. A subminiature (SMA) connector that compensates for the effects of temperature cycling on Teflon. To allow room for Teflon expansion, the Teflon insulator is separated from the metal case by a 0.001-in. air gap and is offset 0.005 in. from the edge of the connector.

This type of connection provides strain relief and maintains good electrical contact over large temperature variations. Also, the assembly process presents fewer risks compared with the other methods described. Since the bond wire attachment is made after the stripline block and the connectors are secured, the assembly process does not impose any stress on the delicate coaxial-to-stripline interface. Even this method has a few disadvantages: the loop in the bond wire can add stray inductance to the circuit, increasing both the insertion loss (i.e., power loss) and the voltage standing wave ratio somewhat. In addition, the Green Tape technology is not yet fully mature in the RF area and is expensive. However, if the performance and cost penalties of this method are acceptable for critical applications, it is a very reliable approach.

TESTING AND ANALYSIS OF COUPLERS

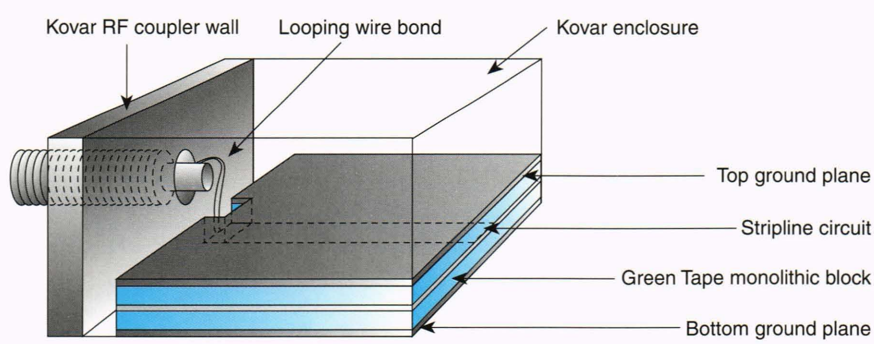
Detecting and diagnosing interconnect faults correctly, effectively, and efficiently are of paramount importance for ensuring connector reliability, especially in high-performance applications such as spacecraft and satellites. Even RF devices with properly designed connectors and interfaces must be tested for possible manufacturing processing defects.

We recently used a 3-dB coupler operating from 2 to 4 GHz to test techniques for analyzing device performance. The coupler was intended for use in a pilot-tone distribution network that requires highly precise phase relationships between the input port and the output ports.[5] Our focus was the weakest part of a passive RF component, the coaxial-to-stripline junction at the connector of each port. During temperature calibration of the insertion phase between the input and the diagonal 3-dB output ports from +30 to −55°C, we observed abrupt changes of as much as 40° at 2.24 GHz in the insertion phase. In addition, the insertion loss increased from 3.5 to 5.2 dB, indicating noncompliance with the specification on the insertion loss (0.25 dB maximum), the amplitude balance (±0.5 dB maximum), or both.

To determine the location of the fault, we tested the coupler using the time domain option of an HP8720 network analyzer with a frequency sweep from 0.13 to 11 GHz and a bandpass transform to mimic a time-domain reflectometer. Figures 10A and 10B show the room-temperature and −55°C analyzer displays, respectively. Marker No. 1 is the input port of the coupler, Marker No. 2 is the 3-dB port directly opposite the input (terminated in 50 Ω for this test), and Marker No. 3 is the diagonal 3-dB port connected to a cable. The large energy reflectance spike at the input port in the −55°C test (Fig. 10B) indicates that this coaxial-to-stripline junction is the source of the anomalous behavior for this coupler. In a similar test, another coupler with a different serial number also showed a problem at the junction of the diagonal 3-dB port.

To learn more about the sudden insertion loss and phase changes, we devised a simple screening test using known good parts and bad parts from the same lot, and a control part (a feedthrough adapter used in place of the coupler). Each coupler was placed separately in a temperature chamber, and its input and diagonal 3-dB ports were connected to test cables. The other two ports were terminated in 50-Ω loads. The temperature of the coupler case and the insertion phase were recorded every minute as the temperature was ramped down to −55°C at the maximum rate of the chamber. At the same time, using an HP8510C vector network analyzer, we continuously measured the insertion phase for each coupler as a function of time (decreasing temperature). Figure 11 shows the results for the two good parts, two bad parts, and the

Figure 9. A coaxial-to-stripline connection with a looping wire bond soldered to the stripline circuit. This design eliminates manufacturing and assembly-induced stresses on the launch, but the looping wire bond may increase insertion loss more than the designs depicted in Figures 4 and 6.



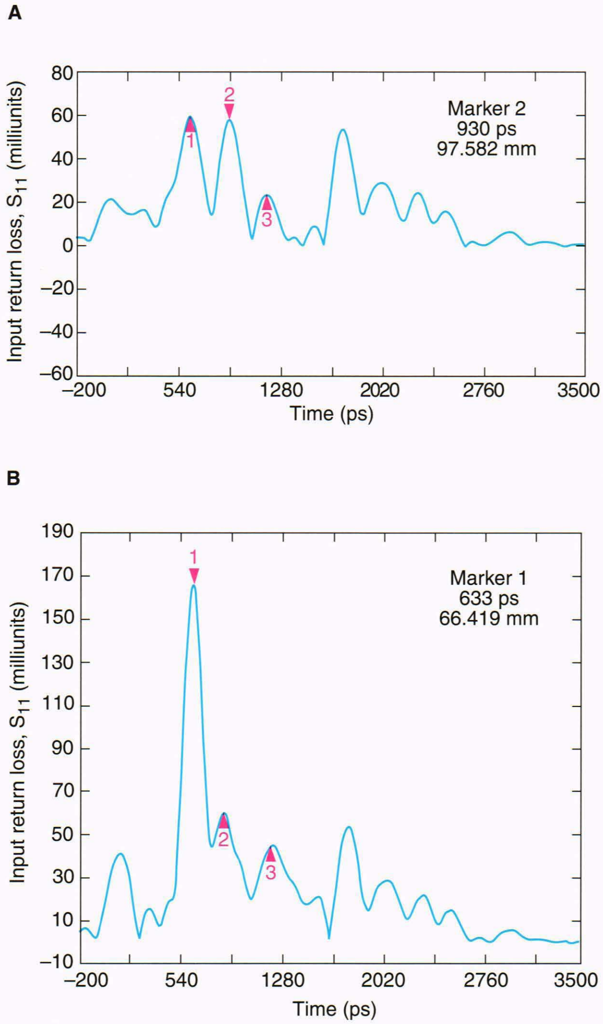


Figure 10. Time-domain displays from an HP8720 network analyzer for a 3-dB hybrid coupler that exhibits a large insertion phase shift. **A.** Room-temperature plot. **B.** Plot at −55°C. The analyzer measures the linear magnitude of the input return loss over time when a transverse electromagnetic (TEM) wave is launched through the coupler (the system arbitrarily sets −200 ps as the start time). Marker No. 1 (arbitrarily chosen) is the input port, Marker No. 2 is the 3-dB output port directly opposite the input port, and Marker No. 3 is the diagonal 3-dB output port. The frequency sweep ranges from 0.13 to 11 GHz. The sharp spike at the input port in B indicates an open connection in the coaxial-to-stripline connection. The network analyzer automatically prints out the time (in ps) and the linear distance (in mm) for the TEM wave to travel to the discontinuity and back to the source, which aids in identifying the location of the discontinuity.

control adapter. The bad parts displayed abrupt insertion phase jumps intermittently at the output ports. The good parts exhibited smooth, monotonic phase changes, and the control test suggested that most of the phase change was due to the test cables.

Perhaps the most frustrating aspect of testing "connectorized" RF devices is the nonreproducibility of test results. Couplers that show large insertion phase changes in one trial might behave like good devices in the next trial, under the same set of test conditions. For example,

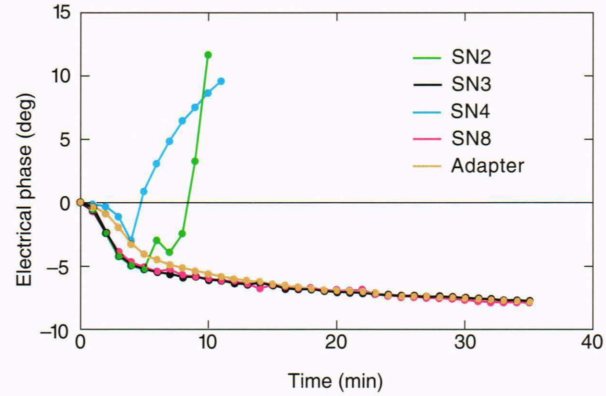


Figure 11. Insertion phase change over time—and therefore temperature—of couplers cooled inside an environmental chamber. Measurements were taken with an HP8510C vector network analyzer. The designations SN2 and SN3 denote good couplers, SN4 and SN8 bad couplers, and "adapter" a control. The "bad" devices show drastically different temperature profiles than either the "good" or control devices, which closely track each other.

we tested one lot of couplers as above, but after a thermal shock treatment consisting of 100 thermal cycles from −55 to 125°C. We then removed the failed devices and again thermally shocked and tested the remaining good couplers. The failure rate among these good devices was 10 to 20%! Then, when we tested the bad parts previously removed from the lot, 50% of them passed! The only conclusion we can draw about these couplers is that they are unsuitable for use in spaceborne systems because of their instability. The intermittent nature of the sudden phase jump phenomenon makes it difficult to determine whether a part is truly defective.

In addition to RF measurements, we made DC short/open measurements on one of the bad couplers. To test DC continuity, we used an ohmmeter for the input-to-diagonal-output path and left the other two ports unconnected. The DC continuity, along with the insertion phase testing, indicated that a resistive (high-resistance) or capacitive (complete) open can cause a greater than 10° shift in insertion phase and as much as a 0.2-dB change in insertion loss. We concluded that the failure mode for this RF coupler was an intermittent open contact in the circuit path; therefore, test measurements would likely be unreproducible.

Our tests led to the following observations:

1. A DC resistance test is useless in qualifying a coupler since a gradual change of 1 Ω can cause a large insertion phase shift.

2. The most sensitive operational parameter for an RF coupler is the insertion phase shift. The pass/fail criterion should be the presence or absence of a large and sudden insertion phase change during the temperature ramp test.

3. Continuous monitoring of RF parameters with rapid temperature change is the most effective method for testing reliability.

4. Random samples from each lot should be qualified (i.e., lot qualification) instead of individual devices because no truly effective method exists to detect defective devices consistently.

5. The best quality devices will be produced by qualified manufacturers/vendors.

RECOMMENDATIONS FOR SPACE-QUALIFIED CONNECTOR AND INTERCONNECT DESIGNS

Although there are military standards for connector designs, additional requirements are imposed on a connector and interconnect for electronic systems to be deployed in space. For spaceborne applications such as S- and C-band communication systems, the ideal connector must be able to perform to specifications at room temperature and, at a minimum, across the military temperature range. Thus, the weakest links—the connector-to-stripline junctions—must be able to withstand the vigorous thermal cycling of a space environment. We have defined the requirements for coaxial connector and transmission line transition designs in a coupler, using the large body of data gained from our tests on passive devices such as 3-dB hybrid couplers and four-way power dividers. The concepts can be generalized to any RF and microwave passive device.

A well-designed coaxial connector should meet the following general criteria:

1. The connector must conform to the MIL-C-39012 Revision C specification.

2. The connector should be a female part so that it can mate to (male) flexible or semirigid cables, thus allowing external electrical access to the internal coupling circuitry. The female connector case must be threaded for mating to male connectors.

3. The center pin of the connector should be securely captured within the connector to prevent any axial movement induced by temperature change or mechanical handling.

We also developed several specific recommendations on the basis of our connector design work. To accommodate thermal expansion of the PTFE dielectric and the metal case, the connector itself should be configured as shown in Figure 8—that is, with a 0.001-in. gap between the PTFE dielectric and the outer connector case and a 0.005-in. offset from the edge of the connector. In addition, the center pin should be a straight 0.020-in. pin free to slide in a female-to-female contact.

The following requirements address the manufacturing process:

1. Temperature treat the PTFE dielectric of the connector to minimize cold flow.

2. Test the center conductor pin and female contacts for ease of pin rotation, sliding, and insertion.

3. Allow the PTFE dielectric to cold flow during thermal shock screening—that is, do not cap the connectors.

4. To assure good electrical contact with the stripline conductor strip, solder (rather than press fit) the center pin of the connector to the conductor strip with a solder whose thermal expansion coefficient is close to that of the copper conductor strip and Duroid laminates of the stripline.

5. Use Kovar for the outer case of the stripline circuit to match the coefficient of thermal expansion of the PTFE-based and fiberglass-reinforced substrate materials of the stripline circuit (5.04×10^{-6}/°C for Kovar, 9.00×10^{-6}/°C for PTFE materials). A good match limits thermally induced connector damage over the device operational temperature range.

Vendor Qualifications

The best guarantee of high-quality, reliable RF and microwave connectors and devices is a qualified manufacturer/vendor. Based on our experience with RF couplers, we have identified several critical criteria for judging the qualifications of manufacturers. The qualified manufacturer

1. Provides a proven design for the RF device that can withstand the military temperature range.

2. Demonstrates a thorough understanding of the benefits and disadvantages of the design, along with related performance trade-offs, and has closely characterized the inherent failure mechanism(s) of the device to help customers design their systems to compensate.

3. Offers skilled personnel with high levels of training and experience and a precision fabrication procedure that ensures that pins and conductors in the connectors and interconnects will not be damaged during manufacture and assembly.

4. Has in place an effective and efficient test procedure (e.g., an insertion-phase monitoring test with ramping temperature).

CONCLUSION

Proper connector design, construction, and manufacturing processes are critical to RF device quality and reliability. The testability of RF and microwave connectors and transitions remains questionable, however, as was evident from our testing of hybrid couplers. At present, the only effective method for qualifying connectorized RF and microwave passive devices is to qualify the vendor, the design, and the manufacturing processes of the parts. Any RF and microwave parts received from a qualified vendor should be subjected to standard space hardware screening routines, including electrical testing of selected random samples from a lot. Lot qualification is preferable to individual sample qualification because of the intermittent-failure nature of RF connectivity.

REFERENCES

1. Liao, S. Y., *Microwave Devices and Circuits*, 2nd Ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., p. 63 (1985).
2. Wolff, E. A., and Kaul, R., *Microwave Engineering and System Applications*, John Wiley & Sons, Inc., New York, p. 195 (1988).
3. *RF Transmission Line–The Complete Catalog & Handbook*, Times Fiber Communications, Inc., Wallingford, Conn., p. 7 (1983).
4. *Teflon PTFE Fluoropolymer Resins Properties Handbook*, DuPont Polymers, Wilmington, Del., pp. 17, 24–26 (Nov 1992).
5. Nhan, E., *Problem Report on MSX rf and Microwave Parts*, JHU/APL SOR-6-93019 (Mar 1993).

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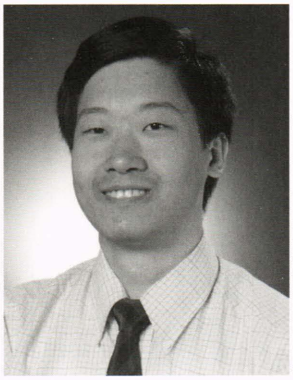

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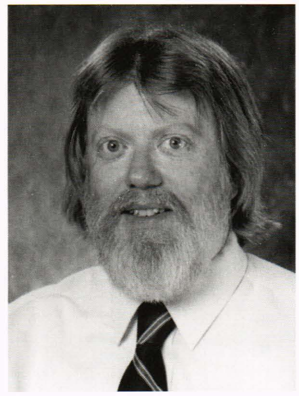

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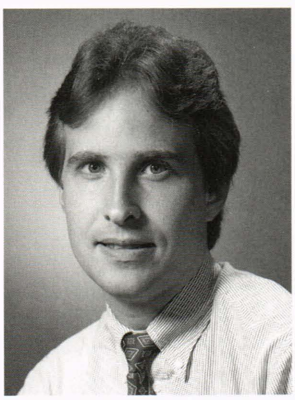

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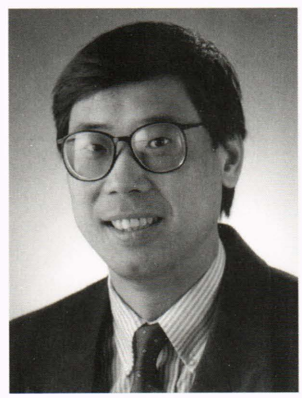

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