A Low-Cost RF Multichip Module Packaging Family

Lewis R. Dove

Martin L. Guth

Dean B. Nicholson

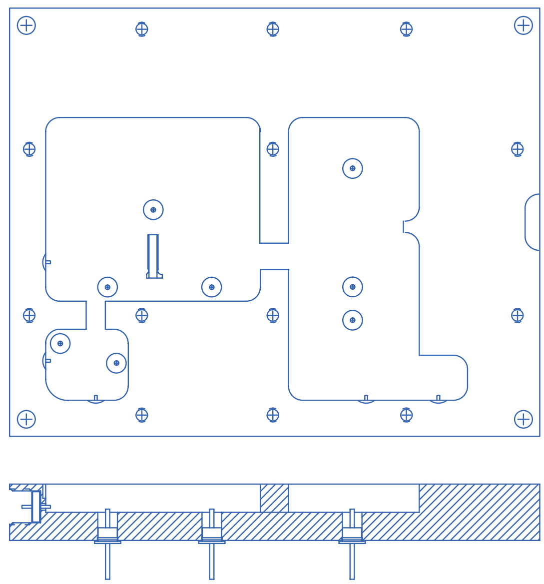
These packages provide much lower cost than traditional high-frequency packaging, shielding, and interconnects, while still providing low-reflection transitions and high electrical isolation.

Packaging of RF and microwave microcircuits has traditionally been very expensive. The packaging requirements are extremely demanding: very high electrical isolation and excellent signal integrity to frequencies of 10 GHz and above, as well as the ability to accommodate GaAs ICs dissipating significant amounts of heat. The traditional approach has been to start with a machined metal package and solder in dc feedthroughs and RF glass-to-metal seals (**Figure 1**). Thin-film circuits on ceramic or sapphire are then attached to the floor of the package using electrically conductive epoxy. The channels machined into the package form waveguides beyond cutoff, which provide isolation from one circuit section to another. Next, GaAs or Si ICs are attached to the floor of the package in gaps between the thin-film circuits. After wire bonding is done to interconnect the ICs and the thinfilm circuits to each other and to the package, the RF connectors are screwed on over the RF glass-to-metal seals to form the finished assembly (**Figure 2**).

Traditionally, both the placement of the thin-film circuits in the microcircuit package and the bonding to connect them have been done manually. The microcircuit typically plugs into a small bias printed circuit board that is connected to the rest of the instrument through a dc cable, while RF connections to the instrument are made by semirigid coaxial microwave cables, which screw onto the RF connectors on the microcircuit. This solution is capable of providing excellent electrical performance and quick turnaround times from design to implementation. However, traditional microcircuits do have the substantial drawbacks of being very expensive, bulky, and heavy.

Figure 1

Traditional microcircuit package with dc and RF glass-to-metal seals. (a) Top view. (b) Cross section.



Until the end of the cold war, much of Hewlett-Packard's test and measurement equipment was bought for defense-related applications, for which performance was often of paramount importance. Today, the demand for RF and microwave test and measurement instrumentation is driven primarily by consumer applications, such as the satellite, wireless, or fiber-optic communications markets. In these extremely competitive markets, keeping costs down and getting good value are crucial. To lower the cost of RF and microwave instruments, the cost of their microcircuits must be reduced, since this is often a significant portion of the manufacturing cost of the instrument. It is important when reducing costs, however, that the predictable performance and quick turnaround time of the traditional microcircuit be preserved.

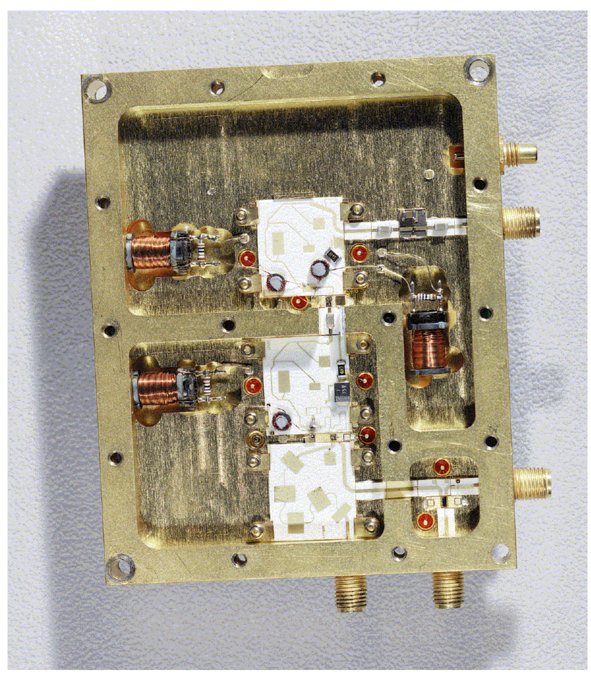
MIPPS Modules

We have developed a family of high-performance microcircuit packages to be used for RF and microwave applications. Within HP, the new family is called MIPPS, which stands for *multichip integral-substrate PGA (pin grid array) package solution*.

The MIPPS modules meet the requirements discussed above by providing high RF and microwave performance at a lower cost per function than previously available through a new design that replaces many expensive, traditional microwave packaging components with simpler, less-expensive alternatives. The MIPPS modules have been designed to work well up to 10 GHz, which addresses most of the present consumer-driven applications where cost is critical. To be inexpensive, the MIPPS modules were designed from the outset for manufacturability and to use high-yielding assembly processes. High-frequency electrical modeling using HP's High-Frequency Structure Simulator (HFSS) 3D modeling tool was used to synthesize the RF transition into the MIPPS module, resulting in an electrical design that worked the first time it was prototyped. Leveraging the MIPPS design and manufacturing processes for new MIPPS microcircuits continues to shorten the time needed to introduce each succeeding MIPPS design.

Figure 2

Finished traditional microcircuit assembly.

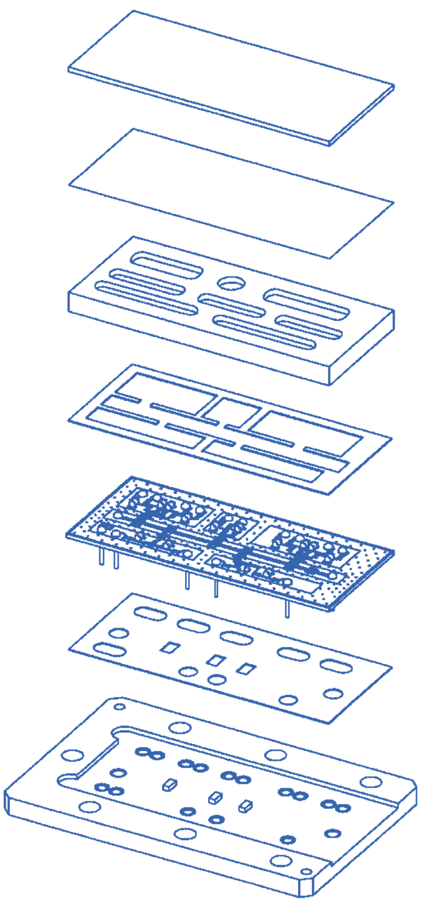


Reducing Cost

Figure 3 shows an exploded view of the basic MIPPS concept. The expensive portions of the traditional microcircuit have been changed to produce a lower-cost assembly. The first example of cost reduction is the way the module is electrically connected to the rest of the instrument. All connections from the instrument to the MIPPS module are made by way of 0.020-inch-diameter pin grid array (PGA) pins that cost pennies each, and are connected to the thick-film metallization on top of the ceramic by a hemisphere of solder. This PGA connection is inexpensive compared to the filtered dc feedthroughs and RF glass-to-metal seals used in a traditional microcircuit.

Figure 3

Exploded view of the MIPPS (multichip integral-substrate PGA package solution) assembly.



For dc connections, the unwanted RF energy on the bias lines in the MIPPS module can be stripped off with low-cost surface mount components to an adequate degree in place of the coaxial capacitor used for the traditional microcircuit feed. The PGA pins used as dc feeds can either be attached to the printed circuit board by inexpensive single-contact sockets, or by soldering the pins directly to the backside of the printed circuit board. Experience has shown that plugging the MIPPS module into single-contact sockets is desirable because it allows much faster assembly or replacement of the MIPPS assembly.

RF connections are made using the same 0.020-inch-diameter PGA pins used for the dc feeds. Good RF performance is obtained by choosing the diameter of the hole in the baseplate that the PGA pin goes through. The proper hole diameter compensates for the capacitive discontinuity of the metal pad on the top surface of the alumina to which the PGA pin is soldered. The RF transitions can be made either directly to the printed circuit board if a low-RF-loss printed circuit board is being used, or to an SMA connector (either barrel or flange mount) if the RF signal is to be sent or received through a coaxial cable.

The next cost savings come from replacing the multiple small thin-film circuits used in traditional microcircuits with a single, large, thick-film-on-ceramic circuit. A thick-film circuit that has both conductors and resistors printed on it generally costs only 10% to 25% as much as a similar thin-film circuit on ceramic, and additional savings are accrued in assembly. Assembly of the substrate to the metal baseplate needs to provide mechanical rigidity as well as electrical shielding. Two things must be done to make this attachment reliable (no attachment failures over temperature excursions). The first is to minimize the TCE (temperature coefficient of expansion) mismatch between the ceramic and the baseplate. Type 416 stainless steel was chosen as the best compromise of raw material cost, ease of machinability to minimize cost, and TCE matching with the ceramic, which is 96% purity alumina. The next step to minimize the stress on the conductive epoxy joint is to choose a material that forms a somewhat flexible bond between the substrate and the baseplate. This helps absorb TCE mismatch induced stress. MIPPS modules with 0.800-by-1.700-inch circuits have been temperature cycled ten times over the −55°C to +150°C temperature range with no failures.

Using a single large ceramic substrate instead of multiple smaller substrates as in traditional microcircuits also provides substantial savings during assembly. Instead of having to manually place and line up multiple circuits in a package, a single substrate is assembled to a baseplate that has the epoxy preform already tacked onto it. The alignment between the thick-film circuit and the baseplate is accomplished by using tooling, instead of "eyeballing it" as in traditional microcircuits. The problem of conductive epoxy wicking up between circuits and shorting out the conductive traces to ground, a perennial issue with traditional microcircuits, is completely avoided in the MIPPS module design.

Another technique for reducing costs in the MIPPS module was to design it to take advantage of automated assembly techniques. With a planar ceramic circuit that has all the circuitry accurately aligned to the other circuitry to within the tolerance of the thick-film printing process, automated die attach and automated wire bonding are very straightforward. This is contrasted with a traditional microcircuit containing small thin-film circuits placed down inside deep channels, requiring careful manual wire bonding. Autobonding is significantly faster and more repeatable than the manual bonding process typically used in RF microcircuits.

Maintaining Traditional Microcircuit Performance

Traditional microcircuits have good RF transitions into and out of the package, low loss and low reflections along transmission lines in the package and when transitioning between transmission lines and ICs, and high isolation between circuit functions in the package. All of these elements need to be preserved in any proposed alternative packaging scheme. The first performance challenge to be tackled was the RF transition into and out of the MIPPS module. Our target for MIPPS modules was to have good RF performance up to 10 GHz. The starting point was choosing the diameter of the PGA pin as 0.020 inch. The 0.020-inch-diameter pin is standard for connecting to an SMA connector. Thus, this choice allows us to make RF transitions to the MIPPS module either from printed circuit board or semirigid coaxial cable. The thickness of the baseplate was set by structural rigidity concerns at 0.090 inch. The diameter of the thick-film solder pad used for pin attach was chosen as a best compromise between mechanical strength and parasitic capacitance.

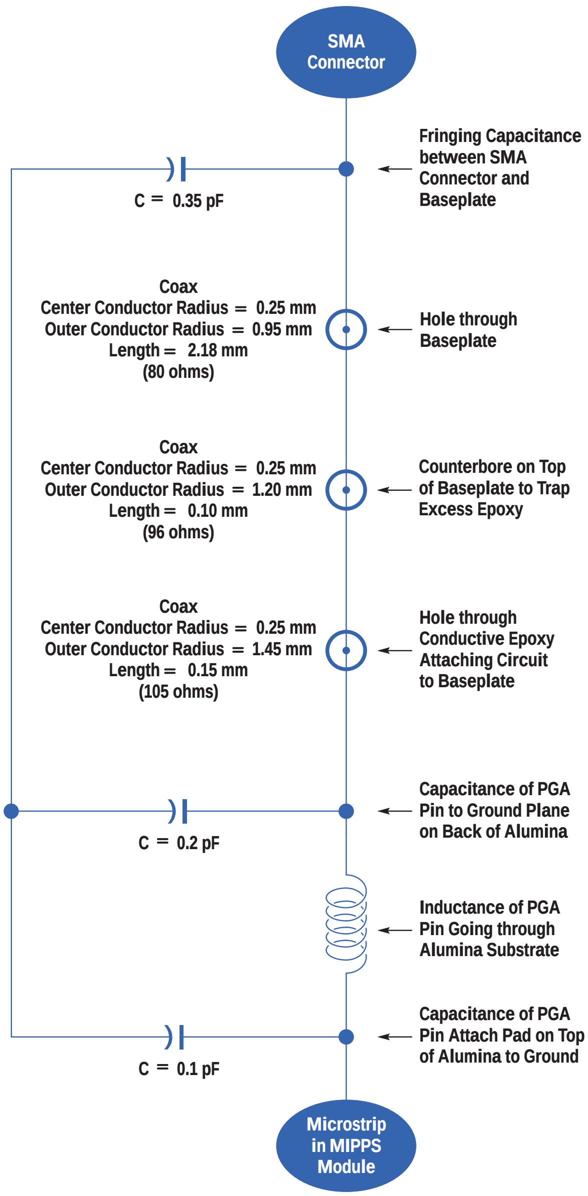
HP's High-Frequency Structure Simulator (HFSS) was used to determine the hole diameter through the baseplate and backside groundplane relief on the alumina circuit that would give the best RF transition to 10 GHz. These simulations eventually led to a design that correctly electrically compensates the launch and gives better than 40-dB return loss up to 3 GHz and better than 15-dB return loss to 10 GHz for a transition from an SMA connector to a 50-ohm line in the MIPPS module. HFSS was also used to design the RF transition to the MIPPS module from an inner-layer printed circuit board stripline. The HP Microwave Design System (MDS) was then used to create a physically based model of the transition, shown in **Figure 4**. New users of the MIPPS module family can use this MDS model in circuit simulations to determine how well the package will work for their application.

After the RF signal enters into the MIPPS module, it needs to be able to propagate down the transmission line with low loss and minimal reflections. The 0.025-inch-thick 96% alumina substrate used for the MIPPS modules allows the use of gold conductor traces 0.024-inch wide for 50-ohm signal lines. This is a wide enough line to have low resistive losses for RF signals ($<$0.6 dB/inch at 10 GHz), yet the substrate is thin enough that the impedance of the transmission line stays fairly constant from dc to 10 GHz. The next-higher-order microstrip mode that could cause unwanted impedance discontinuities is well above 10 GHz. Finally, to have low loss and low reflections as an RF signal propagates down a transmission line, the edges of the line must be smooth. The HP thick-film process used provides the necessary edge smoothness for good performance to 10 GHz.

Many measurements need much greater than 100 dB of dynamic range, so high isolation is an extremely important criterion for microwave instrumentation packaging. In the traditional microcircuit package, high isolation between circuit functions is maintained by keeping the circuitry in narrow channels, which act as waveguides beyond cutoff for the RF signals, being too narrow to pass radiated emissions. The same function is performed in a MIPPS module by having hundreds of conductor-filled vias that connect the bottom ground plane of the circuit with the metallization on the top. When the lid with its machined channels and cavities is conductively epoxied to the topside metallization, the lid is very effectively

Figure 4

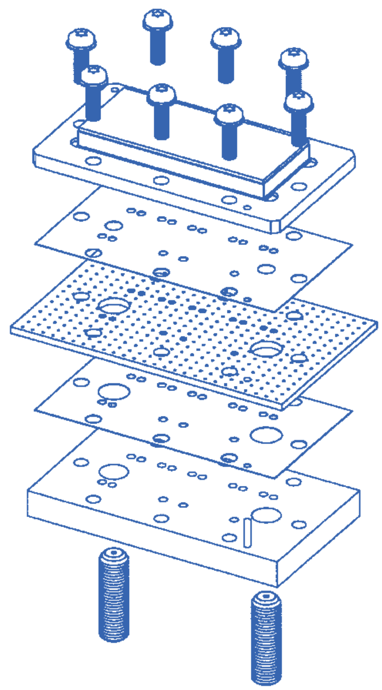
Electrical model for an SMA-connector-to-MIPPS microstrip transition.



grounded, and the waveguide beyond cutoff channels in the lid then provide the needed isolation. To isolate the dc feedthroughs and RF transitions to the printed circuit board from stray RF signals, a metal waffle gasket is placed between the MIPPS module and the printed circuit board as shown in **Figure 5**. A similar waffle gasket is

Figure 5

MIPPS connection to a printed circuit board and SMA connectors.



placed between the printed circuit board and a backing plate to shield the backside of the printed circuit board.

Test Strategy

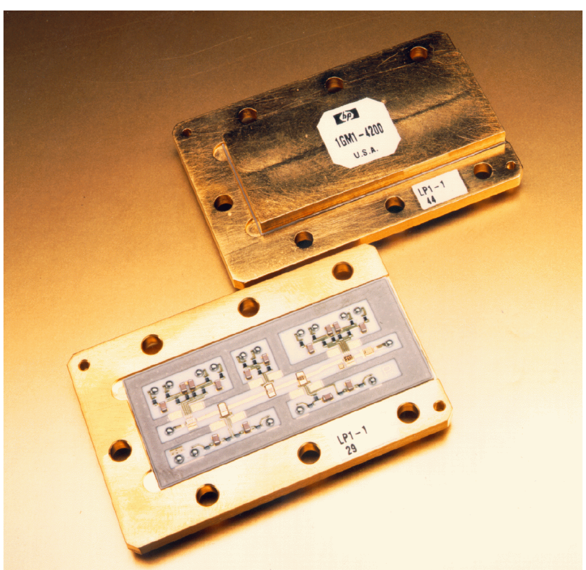
Early in the project a decision was made to have all of the PGA pins on 0.100-inch centers for compatibility with low-frequency PGA packages. This allows MIPPS modules to be easily tested at frequencies up to 20 MHz using industry-standard zero-insertion-force sockets. The first MIPPS product is a 130-dB electronic step attenuator used in RF signal generators at up to 4 GHz. Once the RF performance was initially characterized, a low-speed ac test was implemented, taking approximately 30 seconds to complete. A full RF test is done after the part is installed on the instrument printed circuit board, with better than 97% yield resulting. By providing a quick, low-speed screening at the module level, duplication of a lengthy instrument-level test on the module itself is avoided. In addition, the MIPPS assembly is tested before sealing the lid, allowing easy replacement of defective ICs. For more complex module designs, if a high yield at final RF test cannot be achieved with a simple low-frequency module-level test, more extensive RF testing can be implemented before lid seal to get the desired yield at final RF test.

MIPPS Projects

The first MIPPS module designed was a 0-to-130-dB electronic step attenuator operating from dc to 4 GHz, with attenuation adjustable in 5-dB steps. This module is pictured in **Figure 6**, which shows a completely assembled package (top) and a view of the attenuator thick film attached to the baseplate. The module is used in the HP E4400A family of electronic signal generators. It is based on GaAs IC step attenuator chips manufactured by HP. Previous signal generators have used mechanically switched step attenuators, which have exceptionally good electrical performance (very low loss and low levels of reflected energy), but take approximately 50 milliseconds to switch and settle from one attenuation state to the next. Although they are guaranteed to work for greater than five million cycles, they will eventually wear out. With the more complex and higher-speed modulation formats used in new wireless communications protocols, as well as the higher volumes of these products, mechanically switched step attenuators were wearing out in HP's test instrumentation at an unacceptable rate. Electronically switched step attenuators switch much faster and are more reliable, but the challenge was to produce one at a cost similar to a mechanically switched step attenuator. While step attenuator chips in surface mount packages mounted on printed circuit boards would be able to meet the cost goals for the electronically switched step attenuator, the electrical performance at 4 GHz in terms of loss and reflections would be inadequate. For this reason, the bare GaAs chips are epoxied either to the thick-film substrate or onto pedestals machined into the baseplate. With GaAs switches that must have very high isolation in the off state, the inductance between the backside ground of the chip and true ground must be essentially zero. In this case, the grounding vias that go through the 0.025-inch-thick substrate to connect the pad under the IC to ground are too inductive. Therefore, these chips are mounted to a baseplate pedestal that protrudes through a hole in the ceramic substrate. This allows the chip backsides to be connected to an excellent ground.

Figure 6

The first MIPPS module, a 0-to-130-dB electronic step attenuator operating from dc to 4 GHz. (top) A completely assembled package. (bottom) A view of the attenuator thick film attached to the baseplate.



An additional constraint on the electronic step attenuator design was that some of the customers for the HP E4400A signal sources containing this step attenuator were expected to expose it to extremely humid conditions, necessitating that the modules' internal components be completely shielded from moisture. This was accomplished by developing a process to add low-dielectric-constant, low-RF-loss silicone gel to the interior of the MIPPS package, thereby protecting the GaAs ICs and reducing the risk of moisture-induced metal migration from the silver-filled electrically conductive epoxies within the assembly. With the current design, the MIPPS module will function without damage even if liquid water is introduced inside the cavity.

The final MIPPS electronic step attenuator has a somewhat higher insertion loss than a mechanically switched step attenuator. However, the MIPPS electronic step attenuator switches much more quickly and should be able to switch reliably indefinitely, since there are no moving parts to wear out. The finished assembly with the MIPPS module, the switching logic, the RF reverse power protection circuitry, and the additional EMI filtering on the control lines is shown in **Figure 7**.

An interesting addition to the standard MIPPS step attenuator module occurred when the HP instrument division

Figure 7

Finished assembly with MIPPS module, switching logic, RF reverse power protection circuitry, and additional EMI filtering.

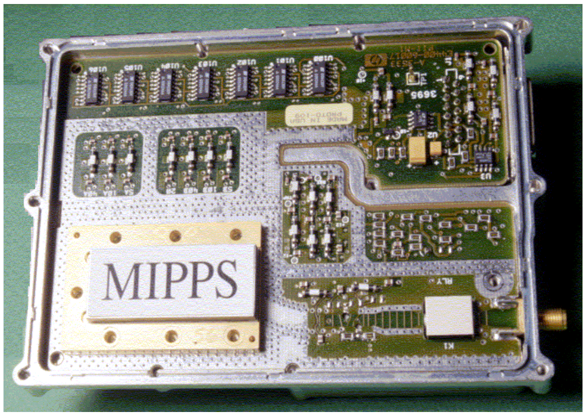
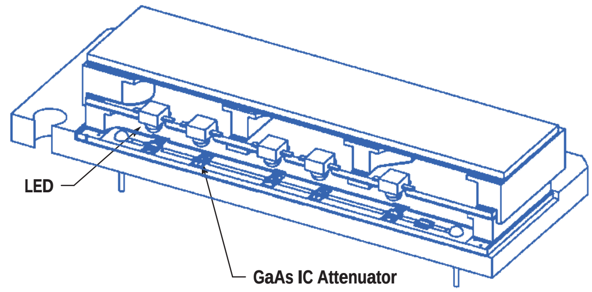


Figure 8

Cross section of a MIPPS module with light-emitting diodes.



using the MIPPS module noticed that the output RF level through the module was not completely switched and settled in the 28 microseconds necessary for testing GSM (a European cellular phone standard) equipment. This problem is caused by the GaAs switches in the step attenuator having the *slow tail effect*: the initial switching takes place very quickly, but it can take up to 10 milliseconds to reach the final value. It was discovered that high-intensity light can virtually eliminate the slow tail effect in the GaAs switches, so a printed circuit board containing HP's new miniature high-intensity LEDs (one above each GaAs step attenuator) was incorporated on top of the MIPPS module as shown in **Figure 8**. The low-cost method by which these are integrated into the module also made it possible to do this for a relatively small incremental cost, and shows the flexibility of designing in the MIPPS format.

Another MIPPS module under development is used in the HP 8509X RF electronic calibration module. Previously, most network analyzer calibration has been done using mechanical calibration standards that were screwed onto the end of the network analyzer cables in a procedure that took five minutes or longer. Although electronic calibration modules have previously been offered by HP, they covered a limited frequency range and were relatively expensive. In designing the next-generation RF electronic calibration products, it was important to keep the costs down and provide an operating frequency range of 300 kHz to over 6 GHz. Both of these goals were achieved with the RF electronic calibration MIPPS module, incorporating eight GaAs IC switches to switch open circuits, short circuits, through lines, and 50-ohm loads in and out. It is possible to completely calibrate a network analyzer in about 30 seconds, using only a single set of RF connections.

Acknowledgments

The MIPPS module was a joint development effort between HP's Microwave Technology Center (MWTC) and HP's Colorado Springs Technology Center (CSTC). We'd like to thank the manager of MWTC, Jerry Gladstone, for giving us the time and guidance to start and continue this project. We would also like to thank Roger Graeber from the Microwave Instruments Division (the first customer of the MIPPS technology) for his many helpful suggestions on how to achieve high isolation in small areas, Don Estreich, who managed the project for the last two years at MWTC, for making sure that we had the necessary resources for the job, and Heidi Barnes of MWTC for continuing the MIPPS work on new projects and continuing to refine the concept. From CSTC, we'd like to thank Ron Baker and Vicki Foster for their invaluable help in assembling prototype hybrids and Rosa Clayton, Rosemary Johnson, Brenda Archuleta, and Al Baca for the fine work they have done in manufacturing the thick-film substrates. We would also like to thank Bob Kressin, Jeff Herrle, Chris Eddleman, and Scott Casmer for their continued product engineering support.

Lewis R. Dove

Lew Dove is an engineer-scientist at HP's Colorado Springs Technology Center, where he works on thick-film packages for high-frequency multichip modules. He has BSEE and MSEE degrees from the University of Arizona. He is married and has two sons, and his hobbies include flying, running, and skiing.

Martin L. Guth

Martin Guth is a product design and development engineer at HP's Colorado Springs Technology Center. He worked on the RF attenuator hybrid for the HP E4400A signal generator and the pin driver logic hybrid for the HP F330 Series of test systems. He has a BSEE degree from Florida Atlantic University, and he joined HP in 1979. He was born in Cleveland, Ohio, and his interests include photography, skiing, mountain climbing, electronic music, and scuba diving.

Dean B. Nicholson

Dean Nicholson has spent the last seven years designing mulichip module products using GaAs ICs. He joined the HP Microwave Technology Division in 1980 after graduating from the University of California at Berkeley with a BS degree in electrical engineering and materials science (double major). Born in Orange, California, Dean is married with four children. If he had some free time, he would enjoy soccer, abalone diving, and hiking.

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