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Microwave Integrated Circuits: New Achievements from a “Mature” Technology

OVERVIEW

For more than 60 years, microwave technology has been synonymous with Microwave Integrated Circuits (MICs). The first MICs appeared in the 1940s, just over a decade after the first microwave circuits were introduced in waveguide form. Now, even though monolithic MICs (MMICs) have revolutionized (and made possible) most of today’s wireless-enabled devices, products based on MIC fabrication techniques remain the bulk of the output of the microwave industry. Such a comment may seem odd considering the massive amounts of attention devoted to MMIC design in the last quarter century, but the fact remains that in many cases, the MIC presents the best – or only - practical way to implement a high-performance, multifunction subassembly.

Still, with increased focus on MMICs and other “wafer-scale” approaches to miniaturization, there are those who view the MIC as a played-out technique from which every bit of performance and innovation have been extracted. However, a closer examination of Narda’s innovations in its Ultimate MIC and Advanced MIC technologies shows that MICs continue to deliver significantly greater performance than critics believe are possible. Considerable room exists for further advancement through attention to fabrication techniques, materials and component selection, digital implementation of traditionally analog functions, and ironically enough, through incorporation of MMICs within the MIC itself.

IN THE BEGINNING…

The first microwave circuits appeared in the early 1930s, fabricated using waveguide. Development soon accelerated, fueled by the demand for radar systems during World War II. This feverish development led to the emergence of a variety of fabrication techniques, enabled in part by the work of an RCA Engineer by the name of Phillip H. Smith, creator of the well known Smith Chart. Since the Smith Chart can represent impedances and admittances, reflection coefficients, scattering parameters, noise figure circles, constant gain contours, and regions for unconditional stability, it is universally recognized as a dramatic improvement over tabular data. Its ubiquity today is testament to the importance of Smith’s creation. The name “Smith” is still a registered trademark of Analog Instruments Company.

The MIC appeared on the scene after development of planar structures such as stripline, microstrip, coplanar waveguide, and suspended-substrate, semiconductors that could operate at microwave frequencies, and the ability to deposit thin-film layers on substrates through photolithography. These and other advancements made it possible to create comparatively compact microwave modules housed in aluminum enclosures “hogged out” by milling machines. Variously called “thin-film hybrids” and “chip and wire” (for the way chips are attached to the substrate), the MIC rapidly grew in both capability and performance.

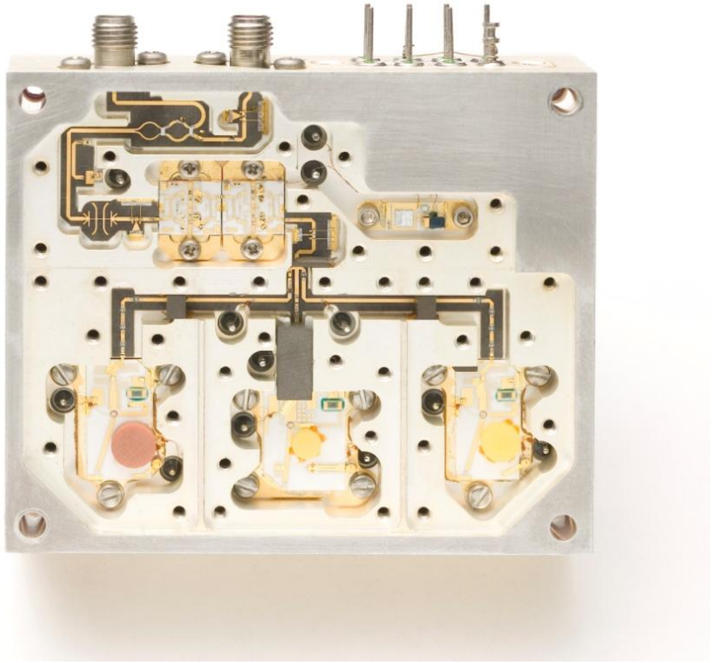

Figure 1 - A classic MIC that employs traditional techniques for fabrication

A typical MIC (Figure 1) is characterized by a substrate made of ceramic material (typically alumina) onto which a metal coating is applied. Through masking techniques, a circuit pattern emerges. Various types of passive and active components are attached to the substrate and interconnected with bond wires. Early MICs were generally limited to a single function because the integration of multiple functions required attachment of multiple chips and was thus difficult to fabricate. There are thousands of examples of single-function MICs on the market today, from Narda and dozens of other manufacturers. The MIC module technique, in which various single-function blocks are grouped together within cutouts in a housing, accommodates a variety of different sets of specifications by combining proven single-function blocks from a “library” of designs.

MICs require use of a metal carrier that must be thermally matched to that of the substrate as well as a sealed enclosure whose characteristics must be accommodated during the design process. Aerospace and defense systems often require a hermetic seal, adding even more cost to the product.

ROOM FOR IMPROVEMENT

Though the MIC remains the predominant technique for fabrication of the most mundane passive components to the most high-performance microwave assemblies, the MMIC gets the lion’s share of attention, and the MIC is considered by those peripherally involved with microwave design as archaic. Superficially speaking, there is some justification for this, since MIC development at many manufacturers has not progressed much over the years. “Classic” MIC devices are indeed large, heavy, and encumbered by mechanical attachment methods needed to locate and secure carriers and circuit boards within the housing. Carriers are typically screw-mounted into the housing, which increases size and weight, introduces mechanical challenges that complicate fabrication, and creates discontinuities that reduce performance and require significant effort to reduce or eliminate.

So it may be reasonable to ask why the MIC is the reigning champion of complex microwave design and why hasn’t it been replaced by some more “modern” technique. For one thing, MICs have inherent characteristics that enable considerable functional integration and high performance, especially at millimeter-wave frequencies, that is unattainable by any other means. It is safe to say that this will remain the case in the fabrication of the most complex millimeter-wave systems for many years to come. A more detailed answer requires a comparison of what MICs can achieve versus their MMIC (and printed circuit board) counterparts.

MIC vs. MMIC

MMICs are obviously orders of magnitude smaller than MICs and can be fabricated in huge numbers, since they can be created en masse on a single wafer. The most sophisticated of today’s devices can combine several functions such as switching and filtering along with a core function, or even a complete receiver. However, the main benefit of wafer-scale fabrication (high-volume production and low cost) is also its most significant limitation. Once fabricated, performance or characteristics of the device cannot be changed. Instead, it must be re-designed and re-fabricated at significant cost. This limits the MMIC’s viability in specialized low-volume applications.

Even though MMICs can integrate multiple functions, their ability to achieve higher levels of integration is currently hindered by cost and complexity. Microwave subsystems, especially those for aerospace and defense applications, require considerable specialization, and combine the need for rapid deployment with limited production volume and low non-recurring engineering costs. It is here where the MMIC fares poorly in comparison with the more flexible MIC. As a result, microwave subsystems frequently employ a combination of generic MMIC-based functional blocks integrated into a within a larger, more complicated MIC.

NARDA'S NOVEL APPROACH

Most microwave assemblies designed and manufactured by Narda are employed in aerospace and defense applications. Although not subject to the same cost pressures that exist in the commercial market, today's aerospace and defense programs nevertheless face a demand for higher levels of performance at lower cost. To satisfy performance, cost, and other requirements of modern defense systems, Narda has spent considerable effort to re-invent its approach to the design and fabrication of MICs, which it has been manufacturing for more than 40 years. The results of this work are multifunction microwave assemblies that are smaller, lighter, less expensive, more reliable, and better performing than "traditional" MICs. They also lend themselves far better to customization, which significantly reduces development time and cost.

Narda has developed a number of innovations to surmount the inherent problems of conventional MIC design. High-frequency PTFE based multilayer circuit boards with via interconnects, use of FPGAs for digital signal processing, control, and temperature compensation, and leveraging of previously-exploited techniques within the MIC domain have delivered unprecedented levels of analog, digital, and microwave integration.

The "ULTIMATE" MIC

An excellent example of how dramatically different the design and fabrication of these assemblies can be is demonstrated by the Model 10512 (Figure 2), a programmable signal source that provides VCO linearization along with arbitrary FM waveform generation. The module employs both custom and standard components, novel printed circuit board fabrication techniques, and digital implementation of functions traditionally performed by discrete analog devices.

The Model 10512 is extremely compact, measuring only in a 4 x 4 x 0.6 in. in its hermetically-sealed enclosure, weighs less than 14 oz., and consumes less than 11 W of DC power. While the standard model operates at 3 GHz, its inherently broadband design can be adapted to other frequency ranges by choosing appropriate VCOs. Its output can be translated to higher microwave or millimeter-wave frequencies with converters as well. This makes it well suited for use in digital RF modems and fast-switching synthesizers in which its linear, spectrally-pure arbitrary noise waveforms can be used for fast-hopping signals, as well as to produce controlled noise, and for calibration and test signals in secure communications, radar, electronic warfare, and electronic countermeasure systems (Figure 3).

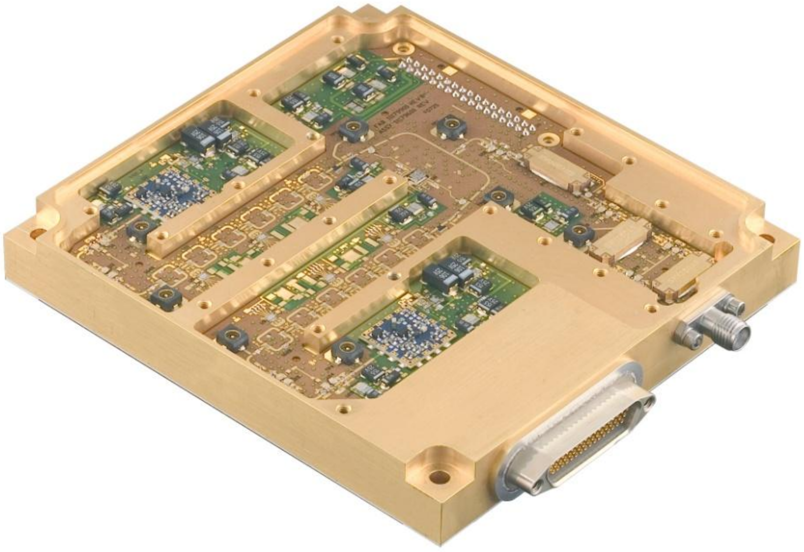

Figure 2 - The Model 10512 combines VCO linearization with the ability to generate arbitrary noise and FM waveforms and switch frequencies at high speed for use in a diverse array of commercial and defense applications

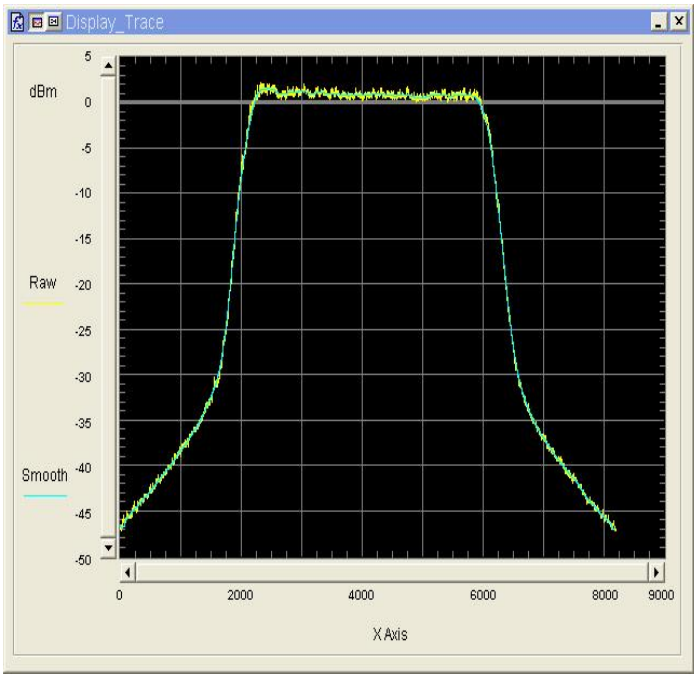

Figure 3 - Noise spot shapes can be tailored to the user's requirements by adjusting modulation video amplitude as well as modulation bandwidth

The fabrication concept of the Model 10512 along with its extensive use of digital signal processing allows it to be reprogrammed to meet new customer requirements without disassembly or hardware rework. Final alignment is performed digitally on a sealed unit, which would be impossible if the unit exclusively employed analog techniques. After assembly, the only manual alignment required is to trim two Digitally-Controlled Attenuators (DCAs) to meet accuracy requirements. All remaining alignment is accomplished by running the unit through an automated test routine that performs characterization on each unit and loads digital calibration data into nonvolatile memory.

The Model 10512 employs two VCOs and a high-speed, PIN-diode-based SP2T switch to optimize its ability to change from one frequency to another (Figure 4). One of the two VCOs can operate at a specific frequency in the band while the other is tuned to operate at the next frequency in the sequence. By “ping-ponging” rapidly between the two VCOs and always updating the un-selected VCO, the unit can hop between frequencies much faster than by retuning a single VCO – typically in less than 15 ns.

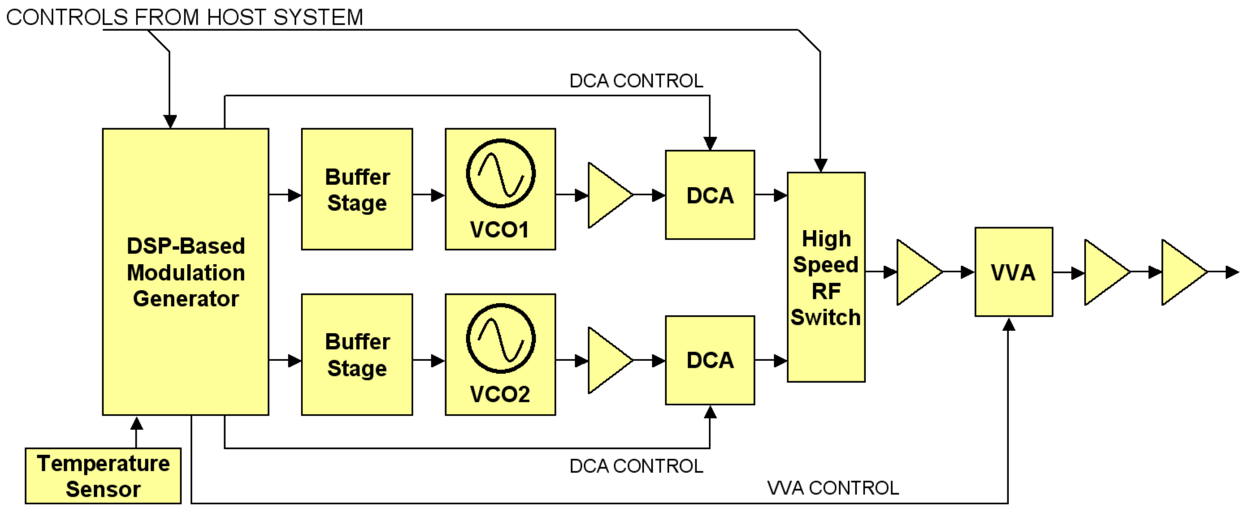

Figure 4 - Dual VCOs and a high-speed switch provide fast frequency hopping capability

The module digitally creates a broad array of complex frequency-modulated waveforms (ramp, sinusoidal, triangle, square wave, and pseudo-random noise, among others) that can be applied to each carrier. The characteristics of the noise waveforms, including video bandwidth, dispersion bandwidth (up to 400 MHz), power level, and other parameters, are digitally programmed either directly by the user or by a host system. Each carrier’s frequency can be changed by up to 50 MHz in less than 100 ns using the current VCO, and larger frequency excursions are possible with slightly longer settling times. RF output is nominally +16 dBm with a 1-dB gain compression point of +21 dBm. The system exerts real-time control over all signal parameters, maintaining them within tight tolerances over a broad range of operating conditions.

An optimized combination of analog design techniques and Field Programmable Gate Array (FPGA)-based digital functionality provides temperature compensation without ovenization and VCO linearity that is far superior to that of a “raw” VCO. In addition, Narda’s proprietary circuit board fabrication techniques significantly improve packaging density while increasing the maximum usable frequency.

The assembly requires a VCO with very high linearity and stability over a wide temperature range, a combination that is traditionally achieved through use of oven stabilization. However, an oven in the Model 10512 would consume prohibitive amounts of power. To achieve the required temperature stability and linearity with the least possible power consumption, Narda applies a mix of digital and analog technologies along with an exhaustive evaluation of every component in the design. The standard VCO’s 27-ns settling time along with additional tuning time introduced by the digital circuitry brings frequency settling time to less than 100 ns for a 70 MHz frequency step. Each VCO is powered by its own independent voltage regulator. The analog tune voltage driver stages, which are high-stability, high-speed, low-noise operational amplifiers, do not require any speed-reducing low-pass filtering.

To meet attenuation requirements for adjustable carrier amplitude, Narda’s goal was to provide a range of 0 to 63 dB in 1-dB steps with 100 ns settling time to 90% of final value, while consuming as little power as possible. Fast-settling PIN diode-based, 6-bit DCAs available from several manufacturers – including Narda - typically consume about 3 W. With this level of power consumption, the two DCAs in the unit would alone have consumed more than half of the unit’s total power budget. This led Narda to design its own low-power DCA (described below), which settles between any two states in less than 100 ns. It too employs Narda’s advanced MIC fabrication techniques along with other features that further illustrate what can be achieved in the MIC design environment.

Fabrication

The fabrication technique employed for the Model 10512 to achieve the required performance within a very small enclosure is similar to conventional single-layer, substrate-on-carrier type construction. The RF circuit traces are on the top layer and distribution of control signals and power supply voltages is achieved by connecting the “layer one” traces and “layer three” traces with plated-through via-holes. By removing the substrate material between the first and second layers during fabrication (exposing the second layer's RF ground), pockets are created in the first layer dielectric where devices can be placed.

The depth of each microstrip pocket is approximately equal to the height of the active device being installed. The approach requires several extra processing steps to mask and clean the pocket walls, which eliminates the possibility of discontinuities or short circuits that might otherwise occur from unintentional plating of the edges of the pockets during the PCB via-hole plating process. The ground plane is simply the ground layer of the multilayer board and the RF circuit performs the same as single-layer microstrip. The overall result is an RF transition that has a very high maximum usable frequency.

As briefly noted above, the digital circuits, several of the voltage regulators, and temperature compensation driver circuits are mounted on one side of the assembly while the VCOs, tuning voltage circuits, attenuators, gain stages, high-speed switch, and output attenuator are mounted on the other. The two assemblies are separated by a 0.04-in. housing septum, and interconnects between digital circuits on one side of the board and RF circuits on the other side are achieved using multi-pin PCB headers.

Another example of the benefits of digital implementation of analog functions is in the modulation generator, which employs a Xilinx FPGA whose in-system reprogrammability allows modifications and upgrades to the sealed, programmable signal source without the need for disassembly. It also provides real-time temperature compensation and linearization using a linearization calibration table stored for each of eight temperatures over the unit's operating range and a temperature sensor that is read once per second. The high-speed memory resident in the FPGA stores the linearization and temperature compensation data collected during factory alignment. Calibration data from the tables are combined with a 60 megasample/s digitally-generated modulation waveform and are applied to an output DAC at 60 megasamples/s. The ability to perform digital linearization and temperature compensation saves a significant amount of power by eliminating the need for an oven to temperature-stabilize the VCO.

Instead of analog video filters and video attenuators, the Model 10512 creates a modulation signal processing chain with DSP blocks in the FPGA, providing further size and weight reduction. In addition, conventional generation of modulation bandwidths typically requires a video filter whose output is scaled to achieve the desired values. Using a switchable bank of filters, the output of each filter shaped to obtain uniform power spectral density. The Model 10512 uses a digital implementation of this approach. A pseudo-random number generator and linear feedback shift register (LFSR) generate a digital random sequence. As a deterministic sequential state machine, the LFSR cannot generate truly random numbers the way a diode can, but if the pseudo-random sequence is repeated over a long enough period, the result is effectively random. The long LFSR output is passed through a digital low-pass filter bank and shaping is applied to create uniform distribution with a high-speed look-up table. A digital multiplier block provides programmable frequency excursions.

A NOVEL DCA

The DCA Narda developed for the Model 10512 is another example of innovative MIC design and fabrication approaches that in this case reduce or eliminate typical DCA compromises. This success of the design resulted in Narda's decision to make it a commercial product (the DCA Series). In addition to its smaller size and lighter weight, the DCA Series attenuators are easier to manufacture, amenable to customization with minimum effort, and producible in higher volumes. The design allows additional components such as filters and other active and passive components to be integrated with the attenuator to form a multi-function module that occupies less space than designs fabricated with conventional MIC techniques.

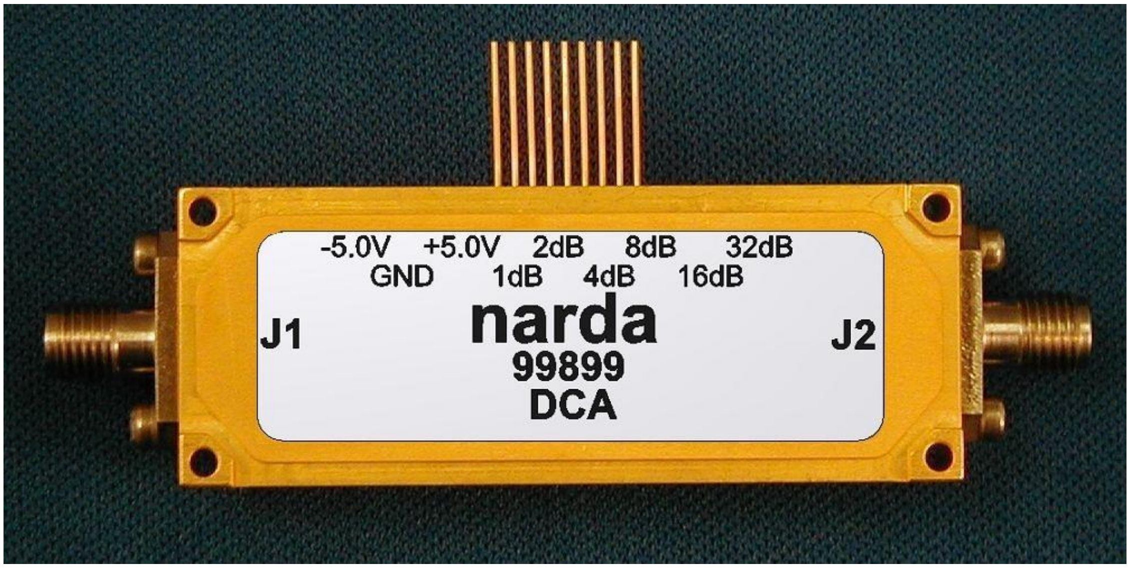

Figure 5 - The DCA Series digitally-controlled attenuator

The DCA Series attenuators (Figure 5) combine fast switching, full monotonicity, and low power consumption that was previously unavailable in FET-based or PIN diode based DCAs. The series includes 2-b, 3-b, and 6-b models in frequency ranges of DC to 6 GHz or DC to 18 GHz. They consume only 50 mW from their +/-5 VDC power supplies, far less than DCAs employing PIN diode switches. The 6-b model measures only 2.2 x 0.84 x 0.38 in. and weighs 1.1 oz. In addition to the standard 2-b, 3-b, and 6-b models that have operating frequencies up to 18 GHz, custom versions can be created that optimize specific performance parameters. The attenuators have a resolution of 1 dB, guaranteed monotonicity over their entire attenuation range, and typical step accuracy of +/-0.25 dB. Hermetic sealing is offered as an option that together with an operating temperature range of -55º C to +95º C make the DCA Series compatible with aerospace and defense applications.

Enhancing DCA fabrication

In traditional DCAs, cavities are machined into each side of the aluminum housing, which creates a “floor” that separates the RF and control functions. Instead, the housing of the DCA Series attenuators is machined all the way though and the entire circuit is fabricated as a multi-layer circuit board with a thick metal core (plate) separating RF components on one side, and the control, switching, and power components on the other (Figure 6). Isolated “through-plate” vias are used to make the connections between the two, which eliminates the need for wire bonds and terminals to facilitate feedthroughs.

Of the PIN diodes, FETs, or pHEMTs employed in DCAs, the PIN diode switches fastest but consumes the most power. FET- and pHEMT-based switches use much less power and have claimed settling times as fast as 3 ns. However, these seemingly fast settling times are generally specified at 20% to 80% of final value. To reach 98% of final value can take tens or even hundreds of microseconds. In a 6-stage DCA application, 12

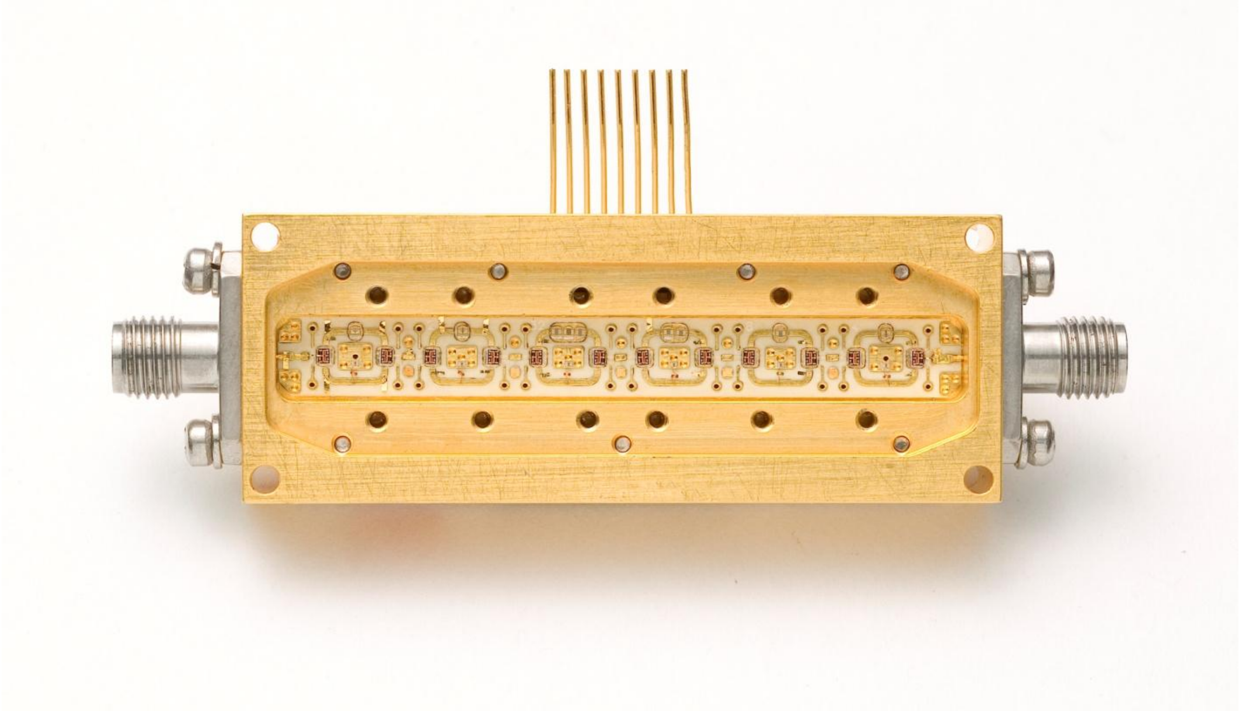

Figure 6 - Construction of the DCA Series attenuator combines analog, digital, and microwave components to achieve high performance and low power consumption in a small enclosure

switches (2 per stage) are cascaded. For a change in attenuation from 31 dB to 32 dB, all six stages are switched at once and the DCA settles to within 1 dB of final value when each of the 12 switches has reached its 98% point. To achieve the best combination of fast switching speed and low power consumption, Narda evaluated a variety of FET and pHEMT switches and identified a family of pHEMT-based types that achieve 1-dB, 100-ns settling time in a six-stage DCA design.

SUMMARY

Contrary to the opinion of many in the microwave industry, the MIC still has much to offer. Like so many technologies whose development path has been labeled “mature”, the MIC can with innovative design and fabrication techniques achieve dramatic improvements in most areas of interest to manufacturers of microwave systems. The Model 10512 and DCA Series assemblies are just two of the numerous products to which Narda has applied “new thinking” to reduce size and weight, increase functionality within a given footprint, enable multiple variations of a design to be easily created, and reduce manufacturing cost, all while simultaneously increasing performance of many parameters.