Development of a 24- to 44-Gigahertz (Ka-band) Vector Modulator Monolithic Microwave Integrated Circuit (MMIC)

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A low-power, broadband (24-to 44-GHz), versatile vector modulator monolithic microwave integrated circuit (MMIC) has been developed using TriQuint's high-reliability 0.15-μm gallium arsenide (GaAs) pseudomorphic high electron mobility transistor (pHEMT) process. This small, low-mass, low-power, cost-effective MMIC simplifies communication system architectures, reduces parts count, increases reliability, and enables extremely high data rates to enable advanced transponder designs. The design of the vector modulator is presented along with the measured performance, including the development of a hermetic 24 to 44 GHz (Ka-band) MMIC package.

I. Introduction

A 24 to 44 GHz (Ka-band) vector modulator (VM) monolithic microwave integrated circuit (MMIC) was developed to support deep-space and near-Earth missions as part of a future deep-space transponder capable of supporting high data rates of hundreds of Mb/s. These rates could not be supported with current 8-GHz (X-band) channel bandwidth (BW) constraints. Applications for high data rate modulators include Mars missions, lunar missions, astronaut video, high-definition television (HDTV), satellite communications, and local area microwave network links. As data rates and frequencies are increasing to support more capabilities for data and video transfer, and as higher levels of integration are needed to reduce size, weight, and power consumptions, MMICs are ideally suited for the high capability requirements of high data rate Ka-band communications.

The development needs for a future advanced transponder, particularly a Ka-band transponder, were discussed in [1]. One task within the Mars Advanced Technology Program was to develop state-of-the-art Ka-band MMICs for advanced transponder designs, with a goal of reducing transponder mass, power, and cost. This vector modulator MMIC was a high-priority design based on several criteria:

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(1) Increase the science return (higher bandwidth) with NASA's Deep Space Network (DSN) moving to Ka-band in order to provide data rates greater than a hundred Mb/s.

(2) Simplify the transponder hardware by modulating directly at Ka-band.

(3) Support Ka-band phased-array applications by providing amplitude and phase control to steer the beam.

(4) Support phase modulation—binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), quadrature amplitude modulation (QAM), Gaussian minimum shift keying (GMSK).

(5) Provide the same functionality as a linear phase modulator and a QPSK modulator.

The data throughput needs of future missions have increased to hundreds of Mb/s, typically with a QPSK modulation scheme. Current modulation requirements are BPSK or QPSK and use of a linear modulator or a BPSK/QPSK modulator. Future modulation schemes may extend the number of bits per symbol or may use Gaussian modulations (GMSK) to reduce noise or control the spectrum. A high-speed simultaneous amplitude and phase control vector modulator would be ideal for current and future modulation methods.

II. Design Goals/Specifications

A. Ka-Band Vector Modulator for Linear-Phase Modulation and GMSK/QPSK Modulation Applications

Table 1 lists the overall system-level goals of a Ka-band vector modulator for a future transponder design. Some of the goals include the driver circuits in addition to the Ka-band vector modulator. The design was intended to meet all of the requirements listed in Table 1 but is not limited to this application. For instance, the broad bandwidth of the vector modulator MMIC would allow its use in other applications from 24 to 44 GHz.

The predominate factors that affect the amount of data that can be transmitted are the modulator design, the bandwidth of the frequency channel assigned for communications, the power radiated, and the modulation scheme. Assuming sufficient channel bandwidth and radiated power, a vector modulator is capable of transmitting more than one bit of information for each clock cycle, or symbol. For simple modulation schemes such as BPSK, one bit of information is transmitted for each data clock such that a 300-MHz capability results in 300 Mb/s of information. For the popular QPSK modulation, there are four states, or symbols, that can be transmitted on each clock, resulting in 600 Mb/s of information for a 300-MHz clock. Astronaut and satellite communications with strong signal power could use the vector modulator to transmit multiple bits per symbol such that the actual data rate would be many times the clock/symbol rate. As an example, using a 300-MHz modulation clock with a 64-symbol modulation scheme would produce a data rate of 1.8 Mb/s without requiring additional spectrum bandwidth. Depending on the application, a vector modulator operating on a 300-MHz Ka-band channel is capable of transmitting up to 500 Mb/s of data using various multi-bit per symbol modulation schemes. For the rest of this article, modulation rates will be specified as "b/s" (bits per second), assuming a BPSK-type modulation so as not to confuse "symbol rate" and "data rate." The following contains a description of the vector modulator development, design trade-offs, performance summary, additional hermetic Ka-band package development, and conclusions.

Table 1. Specification of Ka-band vector modulator for linear-phase modulation and GMSK/QPSK modulation applications.

Parameter	Specification[a]
Frequency range	31.8 to 33 Gz
Linear-phase shift range	0 to 360 deg
Deviation from linear phase	±1 deg maximum
Modulation bandwidth at modulator input port:	
−0.25-dB bandwidth	±100 MHz minimum
−3-dB bandwidth	±300 MHz minimum
Data rate	1 kb/s to 100 Mb/s
Insertion loss	10 dB maximum
Insertion-loss flatness	±0.3 dB maximum over phase-shift range
	±1 dB maximum over tuning and temperature range
Phase quadrature	88.4 ± 0.3 deg minimum
I/Q balance	±0.25 dB maximum
RF port return loss	15 dB minimum
Input IP3 (pin = −10 dBm)	30 dB minimum
Input 1 dB compression	10 dBm minimum
Control voltage/current range	TBD[b] [goal: +0.5 V to 2 V]
DC power consumption	TBD [goal: <200 mW]
Design temperature range	−55 deg C to +75 deg C

[a] System-level goals, including the effects of the digital modulation controller.

[b] TBD = to be determined.

III. Design Approach

Low power, small size, and weight are important in space applications favoring MMICs as a means to integrate capability while increasing reliability and efficiency. Before designing this vector modulator MMIC, various foundries were explored before choosing the TriQuint Texas 0.15-μm gallium arsenide (GaAs) pseudomorphic high electron mobility transistor (pHEMT) process. TriQuint was chosen for the quality of their foundry services, space-qualified parts history, low cost prototyping services, foundry libraries, and service. Several NASA missions have flown TriQuint Texas GaAs pHEMT devices, such as the MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) mission to Mercury.

A small gate-length switch device, such as a TriQuint 0.15-μm GaAs pHEMT, has desirable low-resistance and low-capacitance switch characteristics coupled with high-frequency performance. The early availability of some switch devices from TriQuint's 0.15-μm pHEMT process allowed initial modeling and characterization prior to the release of a design library. Power consumption is negligible since the switches are voltage driven with virtually zero gate current, typically less than one pA. Unlike an amplifier device, there is no temperature increase above the base temperature, resulting in longer life and increased reliability. Any DC consumption would be required only by an external driver circuit modulating the pHEMT switches at up to hundreds of Mb/s.

Various approaches for a vector modulator MMIC chip were explored before deciding on a simple distributed architecture. Figure 1 shows the chosen architecture, where the radio frequency (RF) input splits into an in-phase (I, 0-deg) and quadrature phase (Q, 90-deg) component. Each I and Q component then is attenuated and summed with a combiner to produce a vector sum (amplitude and phase control). Since $\lambda/4$ structures at Ka-band easily fit on a GaAs MMIC die, distributed Lange and Wilkinson couplers were used for the attenuators and combiner. A simple reflective attenuator used a Lange coupler and two identical variable resistive switch elements to control the attenuation. Ideally, the amplitude would be a maximum value at a low resistance, decreasing to zero amplitude as the resistance is increased to 50 ohms. As the resistance is increased from 50 ohms to a high resistance, the amplitude would increase to a maximum "negative" value (i.e., 180-deg phase shift).

Using this architecture, two vector modulator designs were created. One vector modulator used simple narrowband resonated resistive attenuators to compensate for device parasitics that are significant at Ka-band. The second broader-band design used balanced attenuators (see [2]), which are insensitive to switch parasitics. Each balanced attenuator consists of two complementary uncompensated switch attenuators connected by Lange couplers.

A test chip (Fig. 2) was designed to evaluate both the narrowband and broadband vector modulator architectures as well as various switch device sizes, both attenuator subcircuits, and some other test circuits. The narrowband design occupies ~1.4 mm square with only two control inputs (I, Q) while the broadband design occupies ~2 mm square with four control inputs (I, I*, Q, and Q*). Measurements of these circuits allowed a comparison of the two Ka-band vector modulator architectures—the narrowband and broadband designs—in addition to optimization of the vector modulator MMIC.

Evaluation of the test chip structures revealed that both vector modulator architectures had potential. The 150-μm switch device used for both vector modulators appeared to be a good compromise between loss and bandwidth. Both vector modulator architectures were fabricated as individual 2 mm $\times$ 2 mm GaAs MMIC dies with subtle changes from the original layouts.

IV. Ka-Band Narrowband Vector Modulator Design

A narrowband vector modulator was fabricated using the TriQuint Texas 0.15-μm pHEMT process and their low-cost prototype chip option (PCO). Since the 2 mm $\times$ 2 mm die size was the smallest PCO size available, the additional space was used for test circuits. Figure 3 shows the layout of the narrowband vector modulator. The dies were tested on a Cascade Microtech probe station along with an Agilent 8510 network analyzer (NWA). S-parameters were measured for various I and Q DC bias voltages. Figure 4 shows the measured performance (S_{21}) at 36 GHz with I and Q stepped over 8 bias voltages. Insertion loss for a general-purpose vector modulator is about 11 dB at 36 GHz and about 12 dB at 32 GHz. When used as a BPSK or QPSK modulator, insertion loss is improved by about 3 dB.

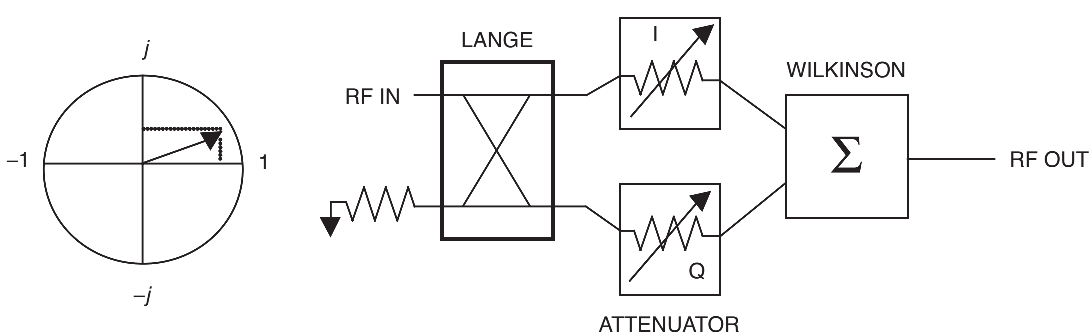

Fig. 1. The vector modulator architecture: the RF input splits into I and Q phases, which are attenuated and summed (RF out) to allow simultaneous amplitude and phase modulation.

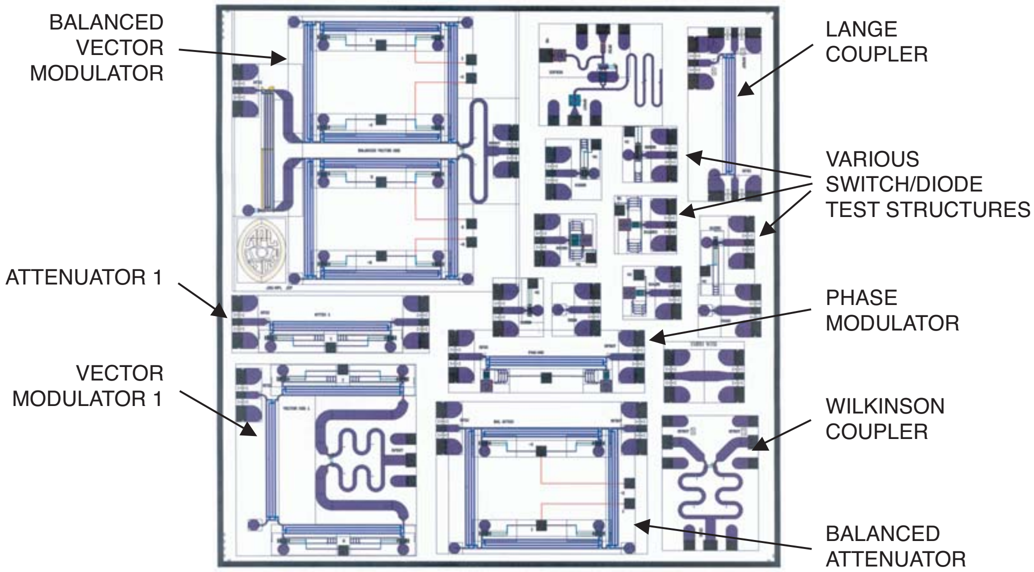

Fig. 2. Test chip to evaluate switch devices and vector modulator architectures.

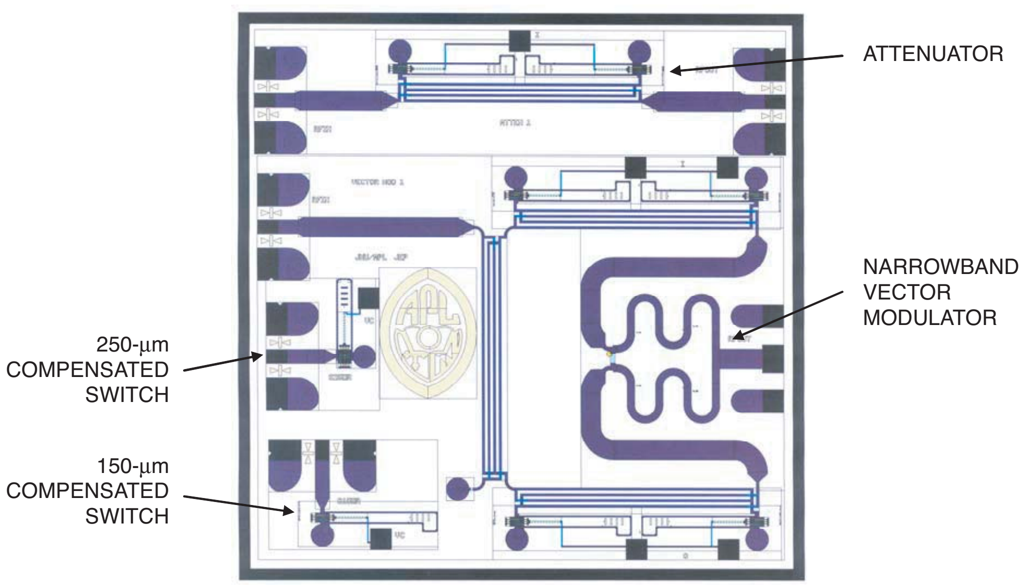

Fig. 3. Narrowband vector modulator (plus test circuits).

V. Ka-Band Broadband Vector Modulator Design

The broadband vector modulator also was fabricated on a 2 mm × 2 mm die using the TriQuint 0.15-μm GaAs pHEMT process (see Fig. 5). A single 150-μm switch circuit was squeezed in the corner for additional verification tests. S-parameter measurements on the vector modulator showed a wideband insertion loss of less than 11 dB from 24 to 44 GHz. The minimum insertion loss is about 10.4 dB at 32 GHz as a general-purpose vector modulator (see Fig. 6). Likewise, a BPSK or QPSK modulation results in a 3-dB improvement in insertion loss. Input and output return loss was better than 10 dB from 24 to 44 GHz (see Fig. 7).

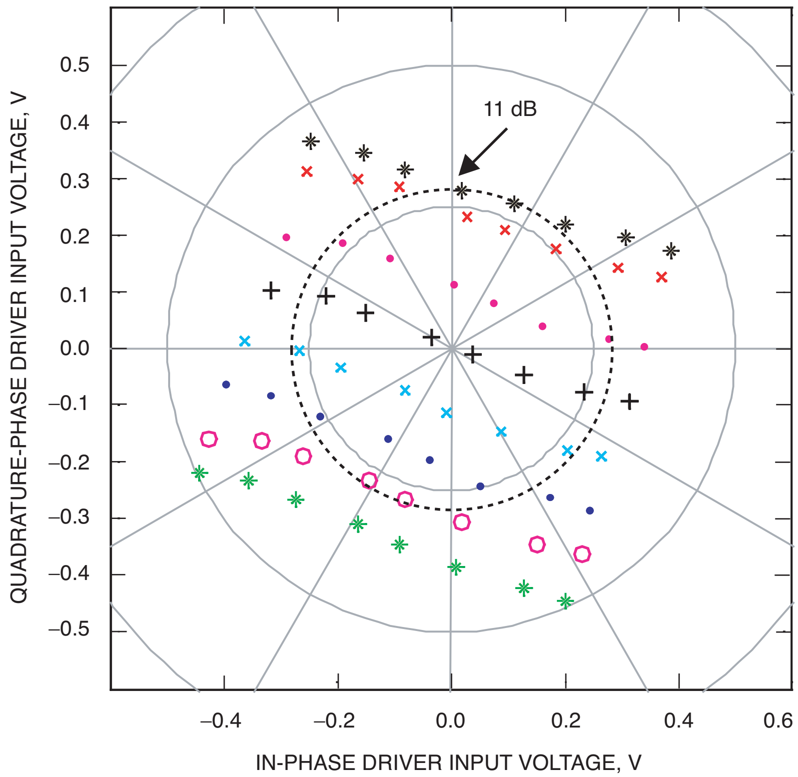

Fig. 4. Measured S_{21} of narrowband vector modulator (36 GH, 8 × 8 array).

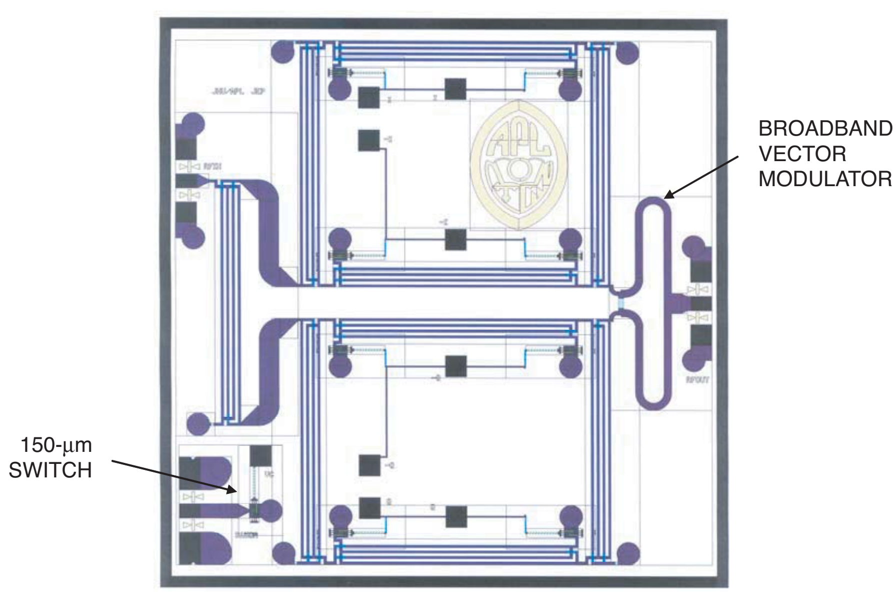

Fig. 5. Broadband vector modulator (plus test switch).

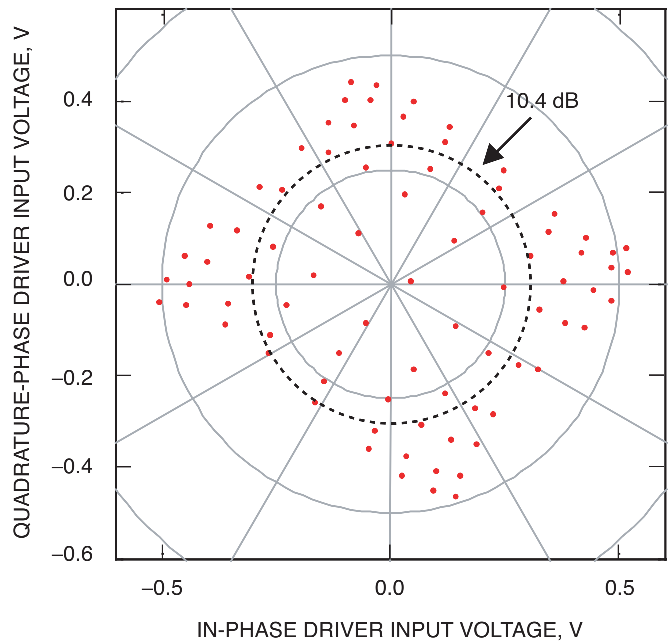

Fig. 6. Measured S_{21} of broadband vector modulator (32 GH, 9 × 9 array).

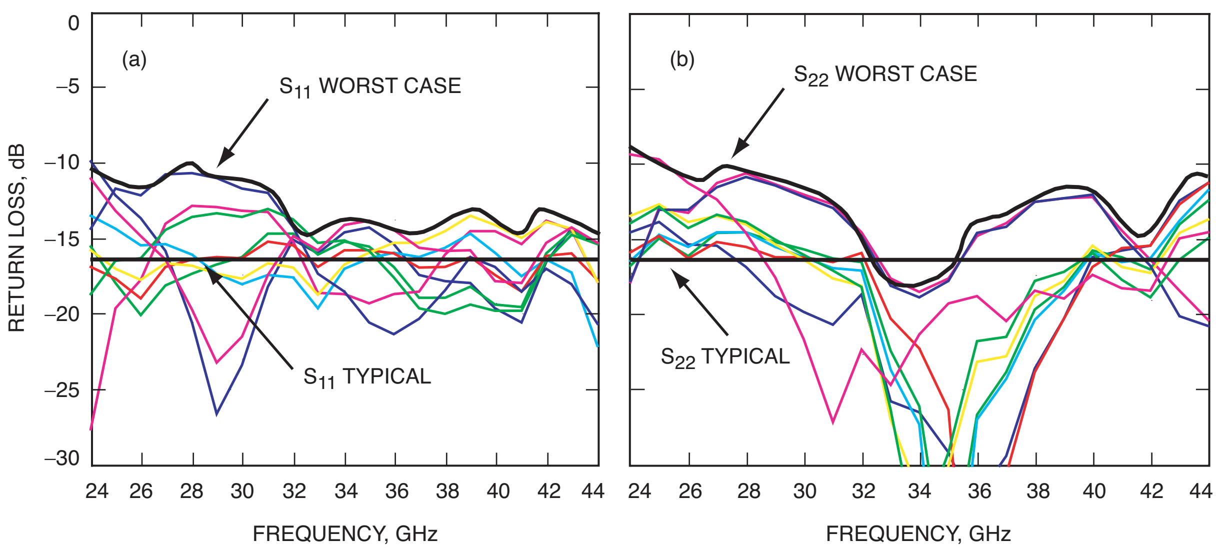

Fig. 7. Measured input/output match for the broadband vector modulator (24 to 44 GHz): (a) S_{11} and (b) S_{22}.

VI. Performance Testing

Temperature measurements (from −55 deg C to +75 deg C) of packaged vector modulator MMICs were completed, including 1-dB power compression capability, insertion loss, and modulation bandwidths. A simple test fixture using K-connectors, coaxial connectors (I/Q inputs), and a thin-film circuit with 50-ohm microstrip traces was created for performance testing of the MMICs. Figure 8 shows the MMICs' silver epoxy attached to the test block with wire bonds to the microstrip traces. Since the wire bonds of the test block at Ka-band have significant mismatch losses, the insertion loss of the probed die compared

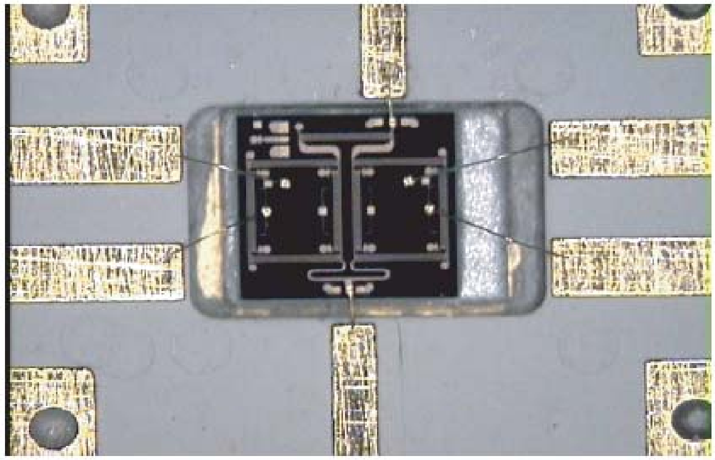

Fig. 8. The MMIC die attached to the test block for performance testing.

favorably with the packaged die after subtracting mismatch loss. The temperature range of −55 deg C to +75 deg C was chosen to verify compatibility with a typical Mars environment and should not be construed as a design limit. GaAs devices can operate reliably at 150 deg C or higher, albeit with a slight increase in insertion loss as resistances increase with temperature. Plots of the measured vector modulator in the test package are shown in Fig. 9. The constellation plots are similar to previous die measurements but were numerically created by sweeping the I and Q inputs separately while the other input was fixed (red and green points), and then summing the points to create a vector matrix.

Modulation bandwidths of both the narrowband and broadband vector modulators were verified with the MMICs in the test fixture while modulating the I and Q inputs and measuring the attenuation using a spectrum analyzer. The 3-dB attenuation point was verified to exceed 300 Mb/s. Figure 10 shows the

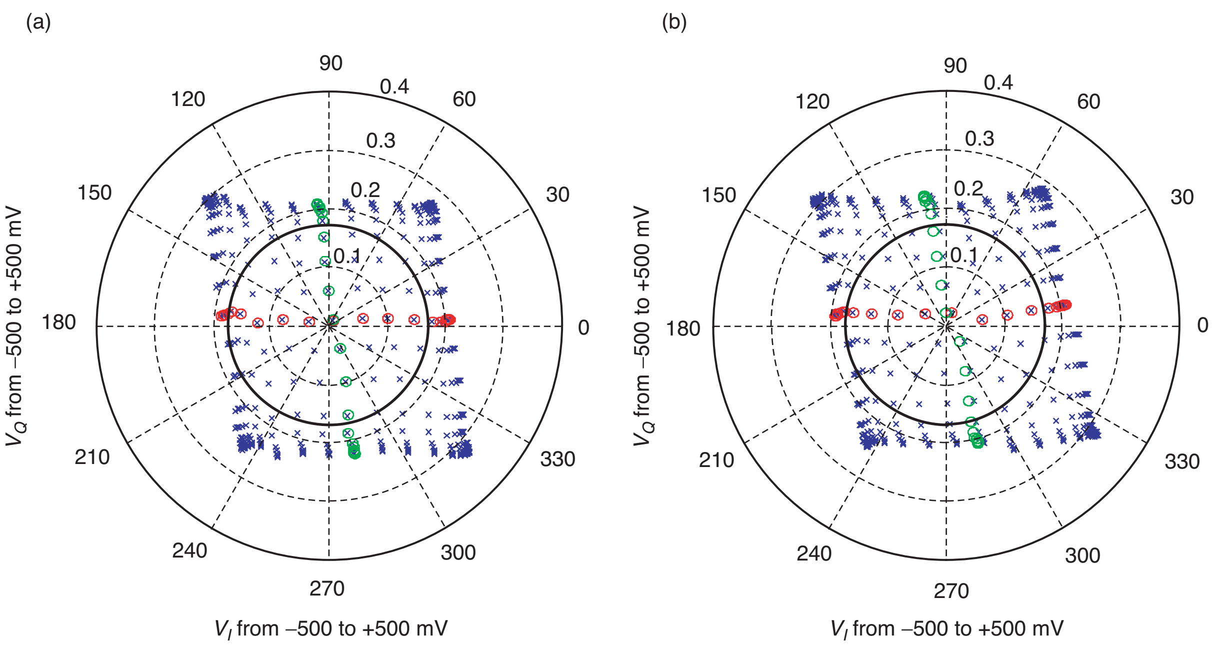

Fig. 9. Constellation of swept I/Q for a broadband vector modulator (in the test package): (a) 32 GHz and (b) 36 GHz.

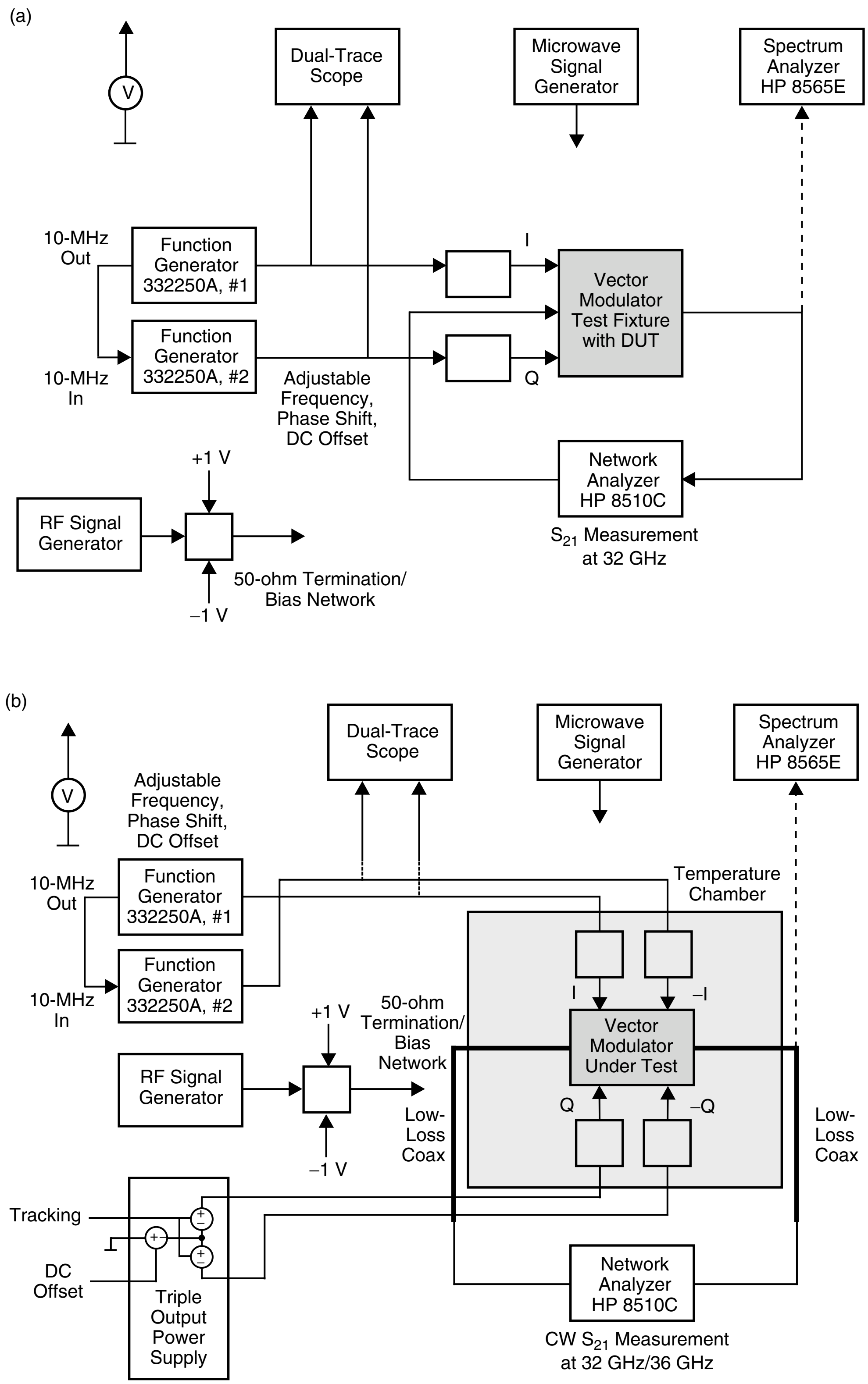

Fig. 10. Test setup for vector modulator bandwidth characterization: (a) narrowband and b) broadband. Small rectangles represent bias/termination boards.

test setup used to characterize the bandwidth of both vector modulators. Unused control inputs were tied to a fixed DC bias (decoupled with a 3.9-nF capacitor). Each input under test was terminated with a 50-ohm resistor using the termination circuits shown in Fig. 11.

Table 2 shows the 3-dB modulation bandwidth results at room temperature for the average of three narrowband MMICs at carrier frequencies of 32 GHz and 36 GHz, and for three input power levels. The design easily supports modulations exceeding 300 Mb/s.

Table 3 shows 3-dB modulation bandwidth results for the broadband vector modulator at several temperatures (−55 deg C, −30 deg C, 25 deg C, and 75 deg C), two carrier frequencies (32 GHz and 36 GHz), and various power levels.

Figure 12 shows a typical frequency response plot with a 50-ohm termination resistor installed on the bias board versus terminating on the test fixture closer to the MMIC die. This would seem to indicate a need to properly terminate the modulation drivers at high frequencies (a few hundred Mb/s) to reduce mismatch reflections. This termination resistor easily could be incorporated into a future MMIC fabrication to provide modulation rates up to a few Gb/s.

Input power handling capability was measured in the test fixtures by increasing the input power level until the insertion loss increased by 1 dB for the QPSK corners. The broadband vector modulator was greater than 12 dBm while the narrowband vector modulator was somewhat less at about 6 dBm.

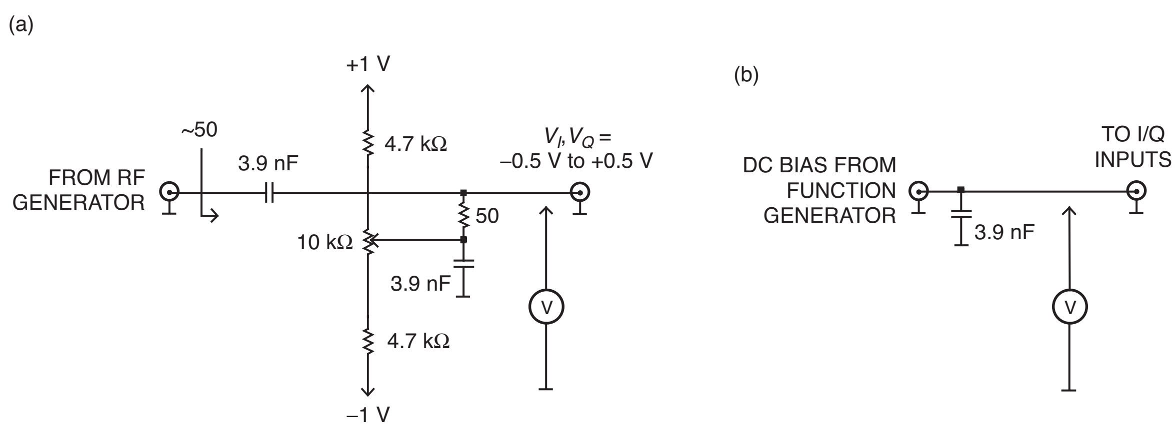

Fig. 11. Termination circuits: (a) 50-ohm termination/bias network used on modulated input and (b) fixed DC bias/decoupling network on other input.

Table 2. Bandwidths of narrowband vector modulators 1 through 3.

Input RF power, dBm	Modulation bandwidth I/Q input, MHz	
	32 GH	36 GHz
−20	∼485	∼550
−10	∼480	∼650
0	∼680	∼815

Table 3. Bandwidths of the broadband vector modulator.

Power on input under test, dBm	3-dB modulation bandwidth, MHz I/I*/Q/Q* 32 GHz				3-dB modulation bandwidth, MHz I/I*/Q/Q* 36 GHz			
	−55 deg C	−30 deg C	25 deg C	75 deg C	−55 deg C	−30 deg C	25 deg C	75 deg C
−20	—	665	475	420	—	615	460	400
−10	—	620	435	320	—	640	465	330
0	480	875	585	440	550	810	620	450

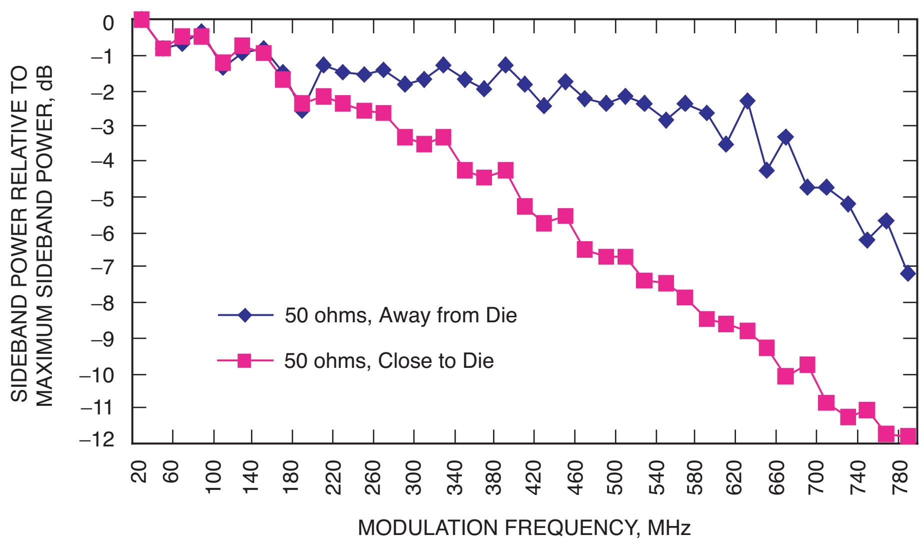

Fig. 12. Measured bandwidth versus location of a 50-ohm termination resistor.

VII. Vector Modulator Comparison

A comparison of the narrowband design to the broadband modulator reveals many similarities and a few significant differences. Power consumption for both designs is negligible (μW) due to the low currents required to switch the 0.15-μm pHEMT devices. While the narrowband design requires two inputs for I and Q controls, the broadband design requires four inputs for the complementary I and Q controls (I/I* and Q/Q*). The additional broadband complementary inputs can be generated simply, and they allow more flexibility in compensating the design over temperature and frequency. Except for the attenuator approaches, both vector modulators are similar in measured return loss and modulation bandwidth. The narrowband design has slightly higher insertion loss, and this varies with frequency. In contrast, insertion loss for the broadband balanced vector modulator is a consistent 10.4 to 10.9 dB from 24 to 44 GHz, with little variation over frequency due to bias. Lastly, the broadband vector modulator design is robust to processing variations because of the balanced attenuators that compensate for switch parasitics. One can read more about the broadband vector modulator in [3].

Although the narrowband design had good performance, the broadband design was more linear, had less insertion loss, and would be less sensitive to process variation for future fabrications. A brief comparison of the two vector modulator designs appears in Table 4.

Table 4. Condensed summary of narrowband versus broadband design performance.

Parameter	Narrowband	Wideband
Frequency	35–40 GHz	24–44 GHz
Return loss	>11 dB	>10 dB
Insertion loss	VM: ~11–11.5 dB	VM: ~10.5–11 dB
	QPSK: ~7.5–8.5 dB	QPSK: ~7 dB
Modulation BW (3 dB)	>300 MHz	>300 MHz
Power consumption	<1 mW	<1 mW
Sensitive to fabrication process	Yes	No

A summary of the comprehensive performance of the broadband vector modulator compared to the original system-level specifications is given in Table 5. Many of these overall system specifications include a control circuit for the vector modulator that may be specific to each application. There are no known limitations in the vector modulator MMIC that would preclude achieving these linearity specifications.

VIII. Hermetic Package Development

A hermetic Ka-band package was explored for use with this Ka-band vector modulator and also for other future applications with Ka-band MMICs. Stratedge Inc. modified a standard SE40 (up to 40 GHz) ceramic package to allow for a hermetic solder lid attachment in place of the typical epoxy non-hermetic lid attachment. A few packages were sealed to test hermeticity. Several additional packages were assembled with Ka-band vector modulator MMICs, a thin-film (alumina) microstrip transmission line, and wire bonds for RF performance measurements.

Wire-bond lengths must be very short for Ka-band applications or their inductance must be compensated in both the thin-film network and the MMIC RF pads. The intent was to keep the wire bonds in the Stratedge package from 6 to 7 mils in length, but x-rays showed that the actual wire bonds in these assemblies were three times as long. Re-simulations of the package with 15- to 18-mil wire bonds compared well with the measured results (see Fig. 13). For future use, a custom thin-film network could be created using careful tolerance control to keep the wire bonds at 6 to 7 mils long. Short wire bonds would yield a better return loss with this vector modulator MMIC and would reduce mismatch losses.

Table 6 shows a comparison of return loss due to wire-bond length with ideal 50-ohm matches. With no compensation of the wire bonds, a 0.1-nH wire bond at 32 GHz is equivalent to about a 14.1-dB return loss, equating to 0.2 dB of mismatch loss. This small inductance equates to a very short 6- to 7-mil wire-bond length. A typical 15-mil wire bond attached to a 50-ohm microstrip represents a 19.5-dB return loss (0.05-dB mismatch loss) at 8 GHz (X-band) but has a poor 8.2-dB return loss at 32 GHz—equivalent to about 0.7 dB of mismatch loss. Both the packaged MMICs in the hermetic Stratedge package and in the test blocks had poor return losses, yielding significant mismatch losses (i.e., greater than 1 dB).

The development of a hermetic package for MMICs in space applications was an additional benefit of this task. A few sealed packages easily passed MIL-STD-883D hermeticity requirements. In spite of the long wire bonds, the hermetic packaged vector modulator MMICs were shown to be usable at Ka-band. A redesign of the thin-film network and careful control of its placement in the package cavity should allow for shorter wire bonds, resulting in better return loss and lower mismatch losses. This would improve the performance of the modified hermetic SE40 package from Stratedge at Ka-band. Figure 14 shows the packaged MMICs with a ruler for scale.

Table 5. Performance summary of the broadband vector modulator MMIC.

Parameter	Specification[a]	Measurement test data
Frequency range	31.8 to 33 GHz[b]	Tested from −55 deg C to 75 deg C in device under test (DUT) over 20–40 GHz. Measured MMIC dies show good performance from 24–44 GHz.
Phase shift range	0–360 deg	0–360 deg.
Modulation BW at I/Q ports: −0.25 dB BW −3 dB BW	 100 MHz minimum 300 MHz minimum	1 dB/3 dB modulation BWs vary with DC bias and RF power level on I/Q input, but are consistently higher than 100 MHz (for 1 dB) and 300 MHz (for 3 dB).
Insertion loss	10 dB maximum (measured versus frequency)	Measured/estimated/corrected insertion loss ∼11 dB for the general case, VM 24–40 GHz. For the QPSK/BPSK case, loss is ∼8 dB.
Phase error	+20 deg maximum (error relative to ideal)	See S_{21} versus I/Q transfer characteristic. To meet 2-deg specification, I/Q will require predistortion.
Amplitude error	+1 dB maximum (error relative to ideal)	<1 dB.
RF port return loss	15 dB minimum (measured versus frequency)	Measured as <10 dB at die levels from 24–44 GHz. Loss was worse in the DUT test package.
Input 1 dB compression	10 dBm minimum	Input 1 dB compression point was measured to be 17 dBm at 32 GHz and 16 dBm at 36 GHz (DUT).
Control voltage/current range	TBD [goal: +0.5 V to 2 V]	−0.6 V to +0.6 V.
DC power consumption	<1 mW (zero bias current)	At 0 dBm input RF power and 10 dB insertion loss, power dissipation can be calculated to be about 1 mW.
Design temperature range	−55 deg C to +75 deg C	DUT tested at −55 deg C, −30 deg C, 25 deg C, and 75 deg C.

[a] These apply at the system level, including the JPL linearizer.

[b] Note: all measurements to be made at a center frequency of 32.0 GHz except as noted.

IX. Summary

The broadband vector modulator MMIC is a versatile design with good performance and excellent bandwidth and is "robust" to MMIC processing variations. MMICs were fabricated using the TriQuint Texas 0.15-μm pHEMT GaAs process (see [4]). TriQuint Texas was chosen due to its ability to produce high-reliability MMICs for space, its low-cost prototyping option, and the availability of test and inspection services for future fabrications. Many space-qualified designs, such as for NASA's MESSENGER mission to Mercury, have been fabricated using TriQuint's pHEMT GaAs processes.

X. Conclusions

A low-power, high-modulation bandwidth, highly integrated MMIC vector modulator was developed under the Mars Advanced Technology Program for Ka-band operation. The design is capable of space

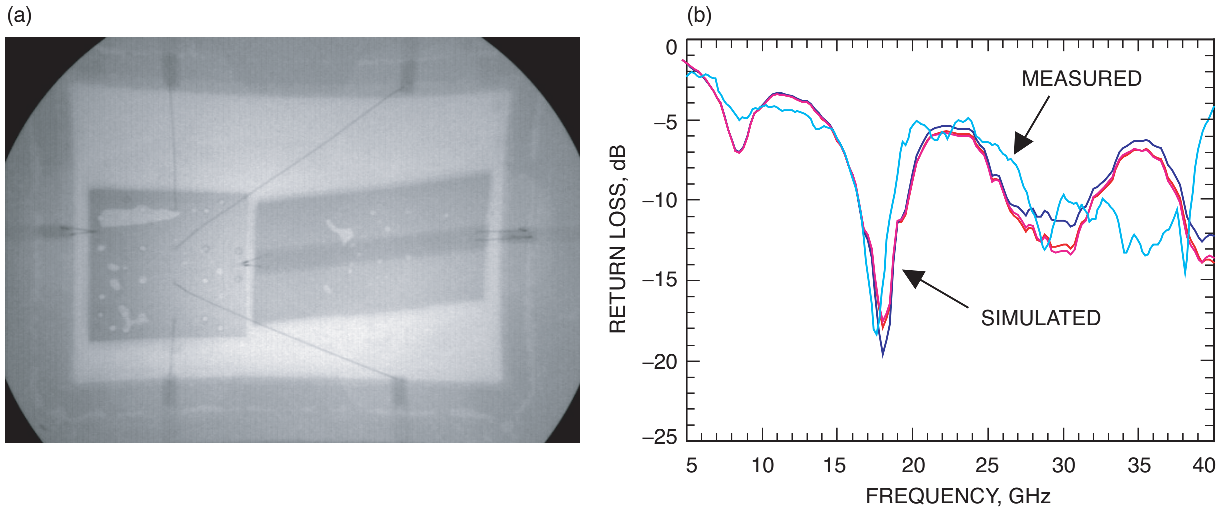

Fig. 13. Simulation of packaged MMIC to verify performance with relatively long wire bonds: (a) x-ray of packaged MMIC and (b) simulation versus measured S_{11}.

Table 6. Wire bonds and return loss.

Wire-bond length, nH	Return loss at X-band (8 GHz), dB	Return loss at Ka-band (32 GHz), dB
6–7 mil wire bond $= > \sim 0.1$	26	14.1
15 mil wire bond $= > \sim 0.21$	19.5	8.2
20 mil wire bond $= > \sim 0.3$	16.4	5.8

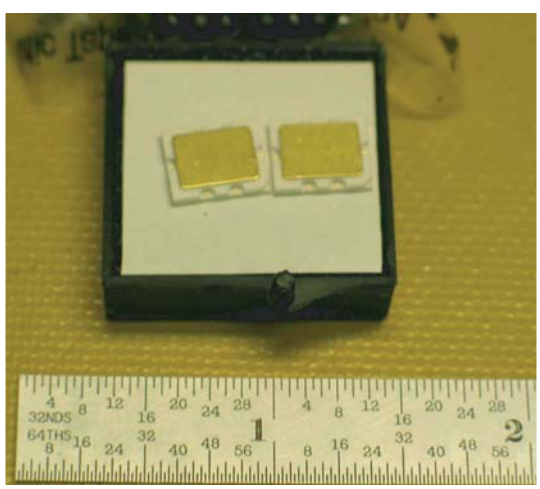

Fig. 14. Two hermetic Stratedge packages containing Ka-band vector modulator MMICs.

applications from 24 to 44 GHz but was initially developed for a future Ka-band transponder around 32 GHz. Performance testing to verify the design over expected space environmental conditions has been completed. Specific future missions may require additional die fabrications if more parts or additional qualification tests are needed. Currently a hundred dies are set aside for additional future testing and qualification as needed. TriQuint easily could fabricate a few hundred additional dies using their low-cost PCO or thousands of dies using the slightly more expensive full wafer fabrication option (WFO). The design would not need to change unless there were a future requirement for modulations of more than 1 Gb/s. This could be accommodated by a very minor change to the control input resistors that limit the modulation to several hundred Mb/s. Replacing those resistors with a matched 50-ohm impedance should allow modulations of a few Gb/s and is easily accomplished with a future PCO or WFO TriQuint fabrication.

In addition, a modified commercial Stratedge package was tested and shown to be hermetic and could be used with this MMIC or others for space applications to Ka-band. There is ongoing work and future development to be done in the areas of improving Ka-band MMIC packaging, system-level testing, and evaluation of the vector modulator MMIC, including data transfer and bit-error testing with linear phase, QPSK, GMSK, and M-ary quadrature amplitude modulation (M-QAM) modulations.

Acknowledgments

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