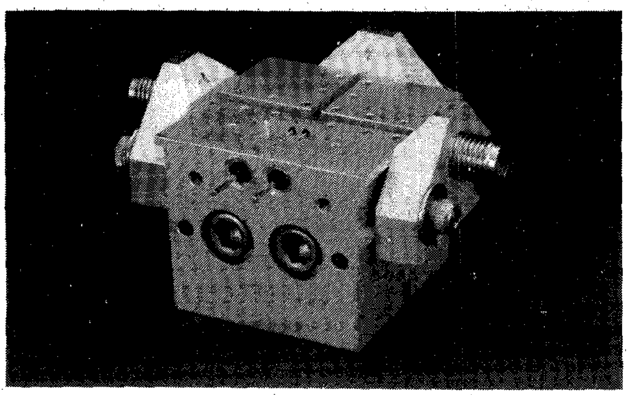

Fig. 6. Microstrip test fixture for high power testing.

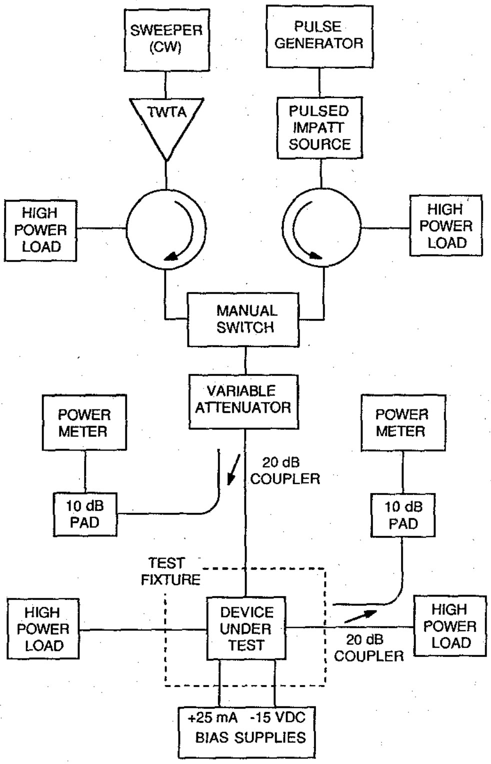


Fig. 7. High power test stand block diagram.

Switching speed measurements were performed on the design with via hole grounds. The 10 to 90 percent RF and 90 to 10 percent RF rise and fall times are 2 ns. The 50 percent TTL to 90 percent RF and 50 percent TTL to 10 percent RF times are 10 ns. The Alpha 66245 inverting driver that applied +10 mA and −12 V to the switch has a 7 ns delay between the 50 percent TTL and 50 percent output drive levels. Photographs of the measurement are given in [7].

## VI. Conclusion

The monolithic *Ka*-band p-i-n diode switches described here have demonstrated excellent millimeter-wave characteristics under high power conditions. The radial stub grounded design does not match the broad-band performance of the via hole design, but the elimination of back-side wafer processing simplifies fabrication. Insertion loss for the via hole grounded design is 0.7 dB at 35 GHz and isolation is better than 32 dB from 30 to 40 GHz. The switch is capable of handling +38 dBm pulsed and +35 dBm CW, which were the maximum power ratings of the test equipment available. Switching speed is 2 ns.

## Acknowledgment

The authors are grateful to I. Crossley and T. Duffield for their support of this work. Thanks are also due to R. Cox, J. DeAngelis, D. Donoghue, S. Gray, and J. Ladd for their assistance with measurements and to R. E. Goldwasser and B. Golya for technical discussions.

## References

[1] G. H. Nesbit, J. C. Chen, C. P. Wen, and D. C. Wong, "Monolithic transmit/receive switch for millimeter-wave application," in *IEEE GaAs IC Symp. Tech. Dig.*, Oct. 1987, pp. 147–150.
[2] D. J. Seymour, D. D. Heston, and R. E. Lehmann, "*X*-band and *Ka*-band monolithic GaAs PIN diode variable attenuation limiters," in *1988 IEEE MTT-S Int. Microwave Symp. Dig.*, May 1988, pp. 255–258.
[3] G. L. Lan, D. L. Dunn, J. C. Chen, C. K. Pao, and D. C. Wong, "A high performance V-band monolithic FET transmit-receive switch," in *1988 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.*, May 1988, pp. 99–101.
[4] R. Tayrani and R. W. Glew, "Ultrafast GaAs microwave PIN diodes," *Electron. Lett.*, vol. 19, no. 13, pp. 479–480, June 1983.
[5] R. Tayrani, D. C. Bartle, and N. J. Barrett, "GaAs surface oriented microwave PIN diodes," in *Proc. 1984 IEEE GaAs Integrated Circuit Symp.*, Oct. 1974, pp. 85–87.
[6] J. F. White, *Microwave Semiconductor Engineering*. New York: Van Nostrand Reinhold, 1982, pp. 83–91.
[7] J. V. Bellantoni *et al.*, "A monolithic high power *Ka* band PIN switch," in *1989 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.*, June 1989.

# *Ka*-Band MMIC Beam-Steered Transmitter Array

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***Abstract*—A 32 GHz six-element linear transmitter array utilizing MMIC phase shifters and power amplifiers has been designed and tested as part of the development of a spacecraft array feed for NASA deep-space communications applications. Measurements of the performance of individual phase shifters, power amplifiers, and microstrip radiators were carried out and electronic beam steering of the linear array was demonstrated.**

## I. Introduction

Communication systems for NASA deep-space missions presently operate at *X*-band (8 GHz). However, in the mid-1990's, advanced deep-space missions will utilize *Ka*-band systems (32 GHz down-link, 34 GHz up-link) to achieve communications enhancement on the order of 8 dB. A receiver MMIC array at *Ka*-band has been reported [1], but a transmitter array, a critical element in these systems, has not.

At JPL a 32 GHz solid-state transmitter is under development utilizing state-of-the-art GaAs MMIC devices. The inital goal of this work is to produce a *Ka*-band planar phased array with 5 W output power to feed a 4 m reflector system. The electronic beam

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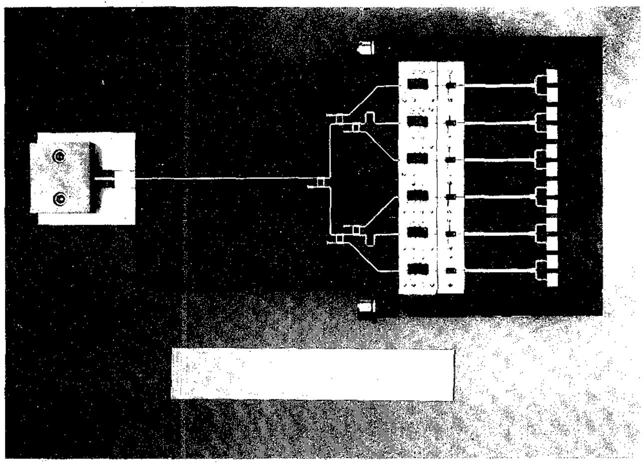

Fig. 1. Six-element linear transmitter array.

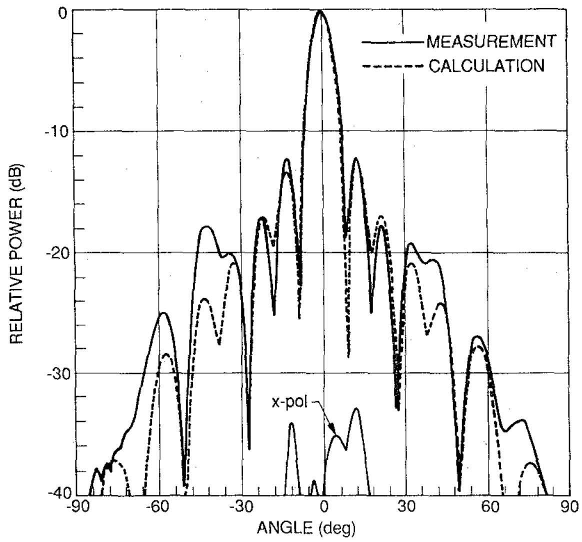


Fig. 2. Calculated and measured broadside, nonscanned far-field patterns for the linear array without MMIC's.

scanning capability of the phased array will allow the narrow beam ( ~ 0.2°) of the large reflector to perform fine beam pointing toward the earth (±1°). As a first step in this effort, a linear array composed of six subarrays of microstrip radiators, six MMIC switched line phase shifters, and six MMIC power amplifiers was designed and tested. The MMIC devices were developed under programs funded by the NASA Lewis Research Center. This paper reports on the expected and actual performance of the JPL linear array transmitter incorporating these devices.

## II. MMIC Devices

The MMIC phase shifters were designed and fabricated on GaAs by the Honeywell Sensors and Signal Processing Laboratory [2], [3]. A single phase shifter contains 12 MESFET's in a 3-bit switched-line configuration and two MESFET's in an analog loaded-line configuration. The switched-line circuit provides nominal phase changes of 45, 90, and 180°. The loaded-line design provides a nominal continuous phase variation from 0 to 45°. These devices were originally designed for operation at 30 GHz for NASA's ACTS program rather than at the slightly higher Deep Space Network frequency of 32 GHz.

The MMIC power amplifiers were designed and fabricated by the Texas Instruments Central Research Laboratory [4]. The devices used in the array were two-stage amplifiers utilizing GaAs MESFET's with a 0.25 $\mu$m gate length and gate widths of 0.1 mm and 0.3 mm for the first and second stages, respectively. The design goal of this device was to produce 20 dBm of output power.

## III. Array Design

The linear phased array, shown in Fig. 1, is composed of four major "building blocks": 1) a six-way microstrip power divider; 2) a carrier strip of six MMIC phase shifters; 3) a carrier strip of six MMIC power amplifiers; and 4) an antenna array of six pairs of microstrip patch radiators. All blocks were separately fabricated and tested to allow evaluation of the performance of each device and for building a detailed model of the linear array. This "building block" design approach of the array also allows for ease of replacement of any of the major components.

The RF input to the array is through a WR-28 waveguide-to-microstrip transition of the Van Heuven [5] antipodal finline type. The double-sided transition pattern is etched on 0.25-mm-thick Rogers 5880 Duroid and attached to the gold-plated aluminum housing using Indalloy 121 solder.

The six-way microstrip power divider consists of a set of 90° branch line couplers with compensating lengths of microstrip interconnecting transmission lines to produce equal amplitude and phase at all six outputs. The divider pattern was etched on 0.12-mm-thick Rogers 5880 Duroid laminated on an aluminum carrier. Each coupler was terminated by a 50 Ω TaN thin-film chip resistor connected to an approximately quarter-wavelength radial line open-circuit stub.

The MMIC carrier strips were designed to permit measurement of each MMIC device and to interface with the array. Individual devices were measured by attaching a pair of waveguide-to-microstrip transitions to each side of the carrier. The carrier strips consisted of laser-cut, 0.25-mm-thick alumina substrates with etched TiW/gold circuit metallization that were soldered to gold-plated Kovar carrier strips. The dc and control lines were brought through the carrier and substrate via miniature coaxial feedthroughs mating on the underside with dual in-line pair (DIP) socket connectors. The MMIC's were attached to the carriers with silver epoxy and wire bonded to the alumina substrates with 25-$\mu$m-diameter gold wire.

The antenna array, consisting of six pairs of microstrip radiators which radiate in a direction normal to the plane of the dielectric, was designed using the multimode cavity theory [6]. This theory assumes that the electric field in the cavity underneath the patch can be precisely modeled by a series of cosine modal functions. Since the fundamental mode, as well as the higher order modes, can all be included in the analysis, accurate prediction of the resonant frequency, copolarization and cross-polarization radiations, input impedance, and bandwidth effect can be achieved [7].

The antenna array was etched on a 0.25 mm Rogers 5880 Duroid substrate. Each etched radiator pair consists of two rectangular microstrip patches combined by a two-way reactive power combiner. A typical input return loss for a two-patch array at 32 GHz was nominally −20 dB with 2.5 percent bandwidth. The separation between radiator pairs was 1.08 free-space wavelengths. This spacing was chosen to allow for ease of assembly so that DIP sockets could be used at each MMIC position. Since only ±10° of beam scan is needed for the array to achieve the required reflector fine beam pointing of less than 1°, the rela-

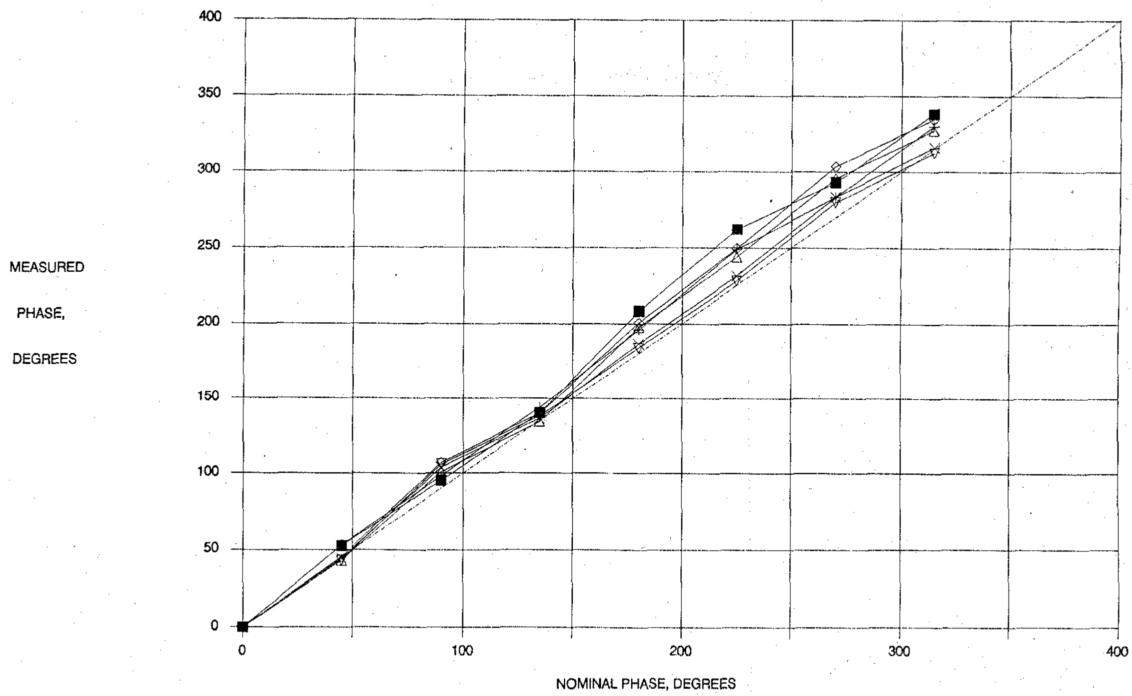


Fig. 3. Measured phase of six phase shifters.

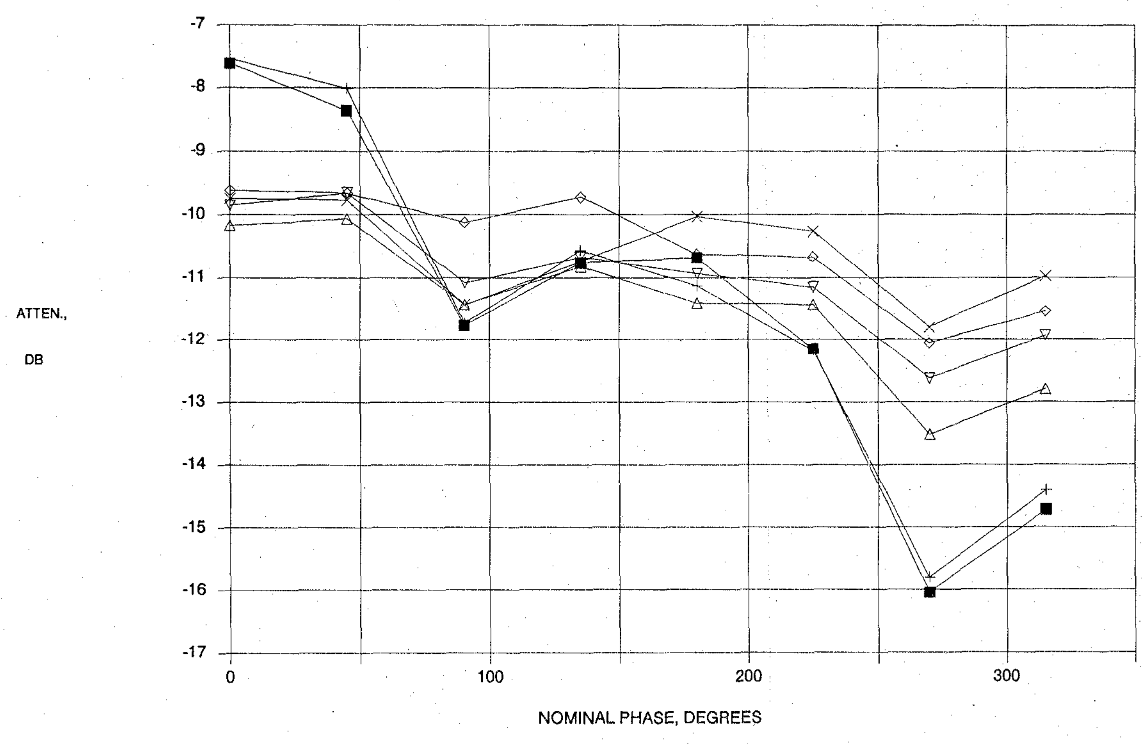


Fig. 4. Measured attenuation of six phase shifters.

tively wide subarray spacing did not generate any serious grating lobe problems.

## IV. Test Results

To ensure that the microstrip array gives adequate performance, the six pairs of patches were connected directly to the six-way power divider without the amplifiers and phase shifters. The far-field pattern was measured and compared with the calculated pattern [7], with the results shown in Fig. 2. It demonstrated excellent pattern performance. The measured array gain, excluding the power divider loss, was 15.9 dBi with an efficiency of 83 percent.

The MMIC devices were measured on an extended HP8510 at 32 GHz in the carriers. Phase shift measurements were referred to the nominal zero phase state of each device, and attenuation was referred to back-to-back waveguide-to-microstrip transitions.

Fig. 3 is a plot of nominal phase versus measured phase for six phase shifters. The devices used in the array were from two wafers, each made with slightly different mask sets. The mean phase shift was 7.0 percent, with a standard deviation of 1.6

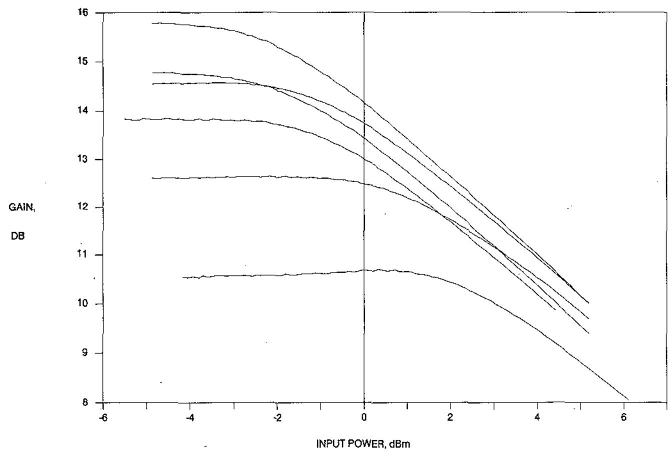


Fig. 5. Measured gain versus input power of six power amplifiers.

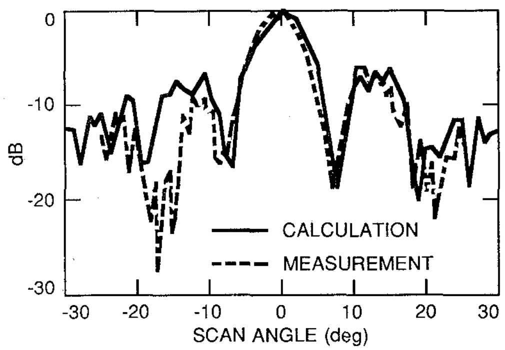


Fig. 6. Measured and calculated relative power received at the detector due to beam scanning of the transmitter array.

percent, of the nominal phase for the range of nominal phase states from 0 to 315°. Attenuation as a function of nominal phase angle is shown in Fig. 4. The mean attenuation at zero phase shift is 10.4 dB for the first wafer and 8.0 dB for the second. This large variation in attenuation performance is partially explained by the fact that these devices were originally designed for a lower frequency, 30 GHz, for another application. Despite this variation in attenuation, however, reasonable array beam steering was obtained.

The gain versus input power of the MMIC power amplifiers is shown in Fig. 5. The six amplifiers were fabricated from the same wafer and have a small-signal gain mean of 13.7 dB with standard deviation of 1.7 dB. The mean output power at 1 dB gain compression is 13.6 dBm with a standard deviation of 0.3 dB. Several amplifiers were externally tuned and were found to be capable of producing as much as 21.5 dBm with an efficiency of 14.5 percent at 1 dB gain compression.

The complete integrated linear phased array was tested by measuring transmitted power under electronic beam steering. This pattern, shown in Fig. 6, was measured with a different technique from the conventional method. Both the receive antenna, which was a 10 cm reflector, and the test transmit array were placed in fixed positions facing each other. Then the array's phase shifters were adjusted to scan the beam at one degree intervals from $-25°$ to 25°. Both the measurement system and the phase shifter bias switching system were controlled by a PC. A program was written to set the phases based on keyboard entries of beam steering angles. The pattern was then recorded with the received power versus the scan angles. Although the pattern was measured from $-25°$ to 25°, our primary interest is in the $\pm 10°$ region. Nevertheless, excellent comparison between the calculated and measured results can be observed in Fig. 6. The relatively high side lobes were caused by improper operation of one of the middle amplifier modules. The calculation included the effect of the failed module as well as randomized errors in both phase and amplitude. With all six subarrays functioning properly, the calculation predicted that the side lobes are $-12$ dB below the beam peak. The array had a beam width of 7.5° and demonstrated acceptable beam steering over $\pm 8°$.

## V. Conclusions

A 32 GHz six-element linear transmitter array utilizing MMIC phase shifters and power amplifiers has been developed and tested as a precursor to the design of a two-dimensional array for use in a NASA spacecraft array feed. The array had a beam width of 7.5° and demonstrated acceptable beam steering over $\pm 8°$, which is adequate for the future two-dimensional array. The areas that need to be improved are the efficiency of the MMIC power amplifier and the insertion loss of the MMIC phase shifter.

## Acknowledgment

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## References

[1] Honeywell Physical Sciences Center, "Electronically steerable patch panel array antenna," Final Report 1 (Oct. 1985–30 Sept. 1986). AFATL-TR-87-19, USAF Armament Laboratory, Eglin AFB.
[2] V. Sokolov *et al.*, "A GaAs monolithic phase shifter for 30 GHz application," in *1983 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.*, pp. 40–44.
[3] P. Bauhahn, C. Butter, V. Sokolov, and A. Contolatis, "30 GHz multi-bit monolithic phase shifters," in *1985 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.*, pp. 4–7.
[4] P. Sanier, H. Q. Tserng, N. Camilleri, K. Bradshaw, and H. D. Shih, "A high efficiency *Ka*-band monolithic GaAs FET amplifier," in *GaAs IC Symp. Tech. Dig.*, 1988, pp. 37–39.
[5] J. H. C. Van Heuven, "A new integrated waveguide–microstrip transition," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 144–147, Mar. 1976.
[6] W. F. Richards *et al.*, "An improved theory for microstrip antennas and applications," *IEEE Trans. Antennas Propagat.*, vol. AP-29, pp. 38–46, Jan. 1981.
[7] J. Huang, "The finite ground plane effect on the microstrip antenna radiation patterns," *IEEE Trans. Antennas Propagat.*, vol. AP-31, pp. 649–653, July 1983.