Ka-Band MMIC Beam Steered Transmitter Array

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A 32-GHz six-element linear transmitter array utilizing Monolithic Microwave Integrated Circuit (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

Downlink communication systems for NASA deep-space missions presently operate at X-band (8.5 GHz). However, in the mid-1990s, advanced deep-space missions may utilize Ka-band systems (32 GHz downlink, 34 GHz uplink) to achieve communications enhancement on the order of 8 dB. A receiver Monolithic Microwave Integrated Circuit (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 initial 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-scanning capability of the phased array will allow the narrow beam ($\approx$ 0.2 deg) of the large reflector to perform fine beam pointing toward the Earth ($\pm$1 deg). 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 article reports the performance results and mathematical modeling of the JPL linear transmitter array 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 photograph of a phase shifter is shown in Fig. 1. A single phase shifter contains 12 MESFETs in a three-bit switched-line configuration and 2 MESFETs in an analog loaded-line configuration. The switched-line circuit provides nominal phase changes of 45, 90, and 180 deg. The loaded-line design provides a nominal continuous phase variation from 0 to 45 deg. 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]. A photograph of an amplifier is shown in Fig. 2.

The devices used in the array were two-stage amplifiers utilizing GaAs MESFETs with a 0.25-μm 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. 3, 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 6 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. Thus as improved MMIC devices become available or evaluation of different antenna elements is desired, the devices or elements may be readily integrated into this test-bed.

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-deg branch-line couplers with compensating lengths of microstrip interconnecting transmission lines to produce equal amplitude and phase at all six outputs. A close-up of the divider is shown in Fig. 4. 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-wave-length radial line open-circuit stub. The power divider was designed using the EEsof Touchstone simulation and MiCAD layout systems. A table of simulated versus measured data for all six ports at 32 GHz is shown in Table 1.

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 waveguide-to-microstrip transitions to the carrier as shown in Fig. 5. The carrier strips consisted of laser cut, 0.25-mm-thick alumina substrates with etched TiW/gold circuit metalization 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 MMICs were attached to the carriers with silver epoxy and wire bonded to the alumina substrates with 25-μm-diameter gold wire.

The antenna array, consisting of six pairs of microstrip radiators that 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.

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, shown in Fig. 6, 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 ease of assembly so that DIP sockets could be used at each MMIC position. Since only ± 10 deg of beam scan is needed for the array to achieve the required reflector fine beam pointing of less than 1 deg, the relatively wide subarray spacing did not generate any serious grating lobe problems. Figure 7 is a calculated far-field pattern [7] of the 12-patch linear array with a 10-deg beam scan and 1.08-wavelength subarray spacing.

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 calculation as shown in Fig. 8. It demonstrated excellent pattern performance. The measured array gain, excluding the power divider loss, was 15.9 dBi, which indicates an efficiency of 83 percent. Individual measurements of single and double patches preceded the 12-patch array measurement, and Table 2 shows a comparison of the radiator efficiencies in these three cases.

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. Figure 9 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 and standard deviation of the phase shift was 7.0 ± 1.6 percent over the range 0 to 300 deg. Attenuation as a function of nominal phase angle is shown in Fig. 10. The mean attenuation at zero phase shift is 10.4 dB for the first group and 8.0 dB for the second. The attenuation changed at a rate of approximately 0.8 dB/100 deg and 2.8 dB/100 deg for the two groups. For phase settings larger than 250 deg, two units fail to track the other four, and their attenuations become larger. This large variation in attenuation performance is partially explained by the fact that these devices were originally designed for a lower frequency, 30 GHz, and 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. 11. The six amplifiers were fabricated from the same wafer and have a low power-gain mean and standard deviation of 13.7 ± 1.7 dB. The mean and standard deviation of output power at 1-dB gain compression is 13.6 ± 0.3 dBm. 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 its beam steering pattern. This pattern, shown in Fig. 12, 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 1-deg intervals from -25 deg to 25 deg. 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 deg to 25 deg, our primary interest is in the ± 10-deg region. Nevertheless, excellent comparison between the calculated and measured results can be observed in Fig. 12. The relatively high sidelobes 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. If all the six subarrays were functioning properly, the calculation predicted that the sidelobes are -12 dB below the beam peak. The array had a beamwidth of 7.5 deg and demonstrated acceptable beam steering over ± 8 deg.

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 switched-line phase shifters were accurate to within 7 percent on average and the power amplifier 1-dB compressed output power varied over 0.3 dB. The array had a beamwidth of 7.5 deg and demonstrated acceptable beam steering over ± 8 deg.

From the above results, it can be concluded that this MMIC phased array has adequate beam-scanning capability for use in the 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

The authors wish to acknowledge the contributions of C. Cruzan for his efforts in assembling the array.

References

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Table 1. Simulated versus measured data for six-way power divider

	Simulated							
Out Port	1	2	3	4	5	6	*Avg.*	σ
MAGS21	−10.6	−10.7	−10.6	−10.5	−10.6	−10.6	−10.6	0.1
ANGS21	−11.0	−9.0	−9.0	−10.0	−8.0	−8.0		
adjANG	0.0	1.0	1.0	1.0	2.0	2.0	1.0	1.0
	Measured							
Out Port	1	2	3	4	5	6	*Avg.*	σ
MAGS21	−11.1	−10.9	−11.3	−11.9	−11.5	−11.8	−11.4	0.4
ANGS21	71.0	52.0	77.0	77.0	54.0	75.0		
adjANG	0.0	−19.0	6.0	6.0	−17.0	3.0	−4.0	11.0
	|Measured−Simulated|							
Out Port	1	2	3	4	5	6	*Avg.*	σ
MAGS21	−0.5	−0.2	−0.6	−1.4	−0.9	−1.2	−0.8	0.4
ANGS21	0.0	−20.0	4.0	5.0	−20.0	1.0	−5.0	11.0

Table 2. Ka-band microstrip antenna gain and efficiency

Parameter	Single Patch	Two-Patch Array	12-Patch Array
Calculated directivity, dBi	7.3	10.7	16.7
Measured gain, dBi	6.9	10.2	15.9
Efficiency, percent	91	89	83

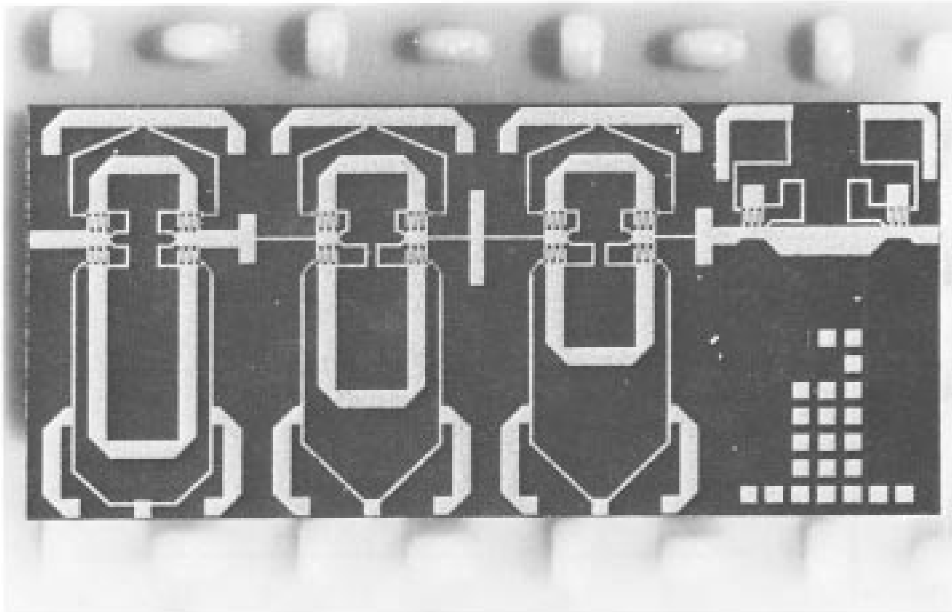

Fig. 1. Honeywell MMIC phase shifter.

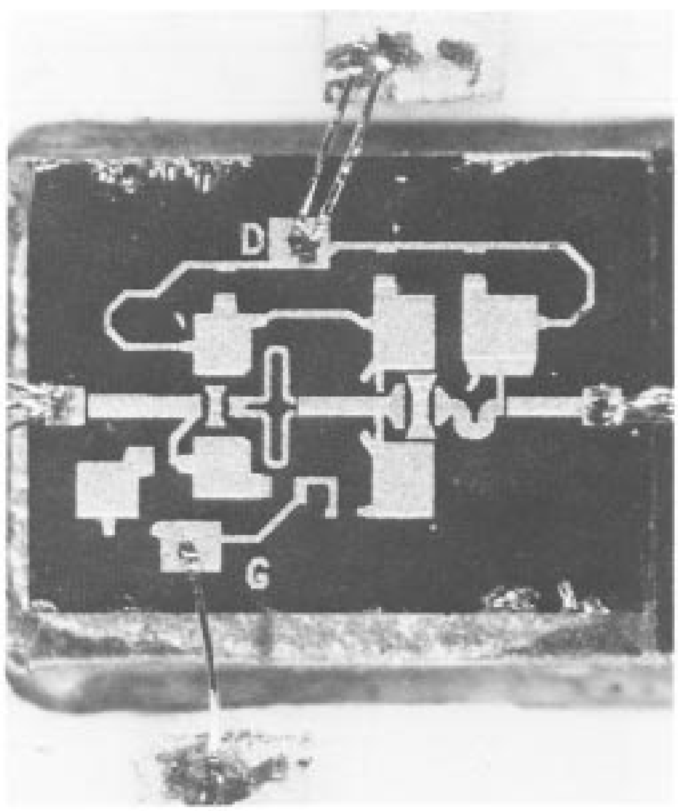

Fig. 2. Texas Instruments MMIC power amplifier.

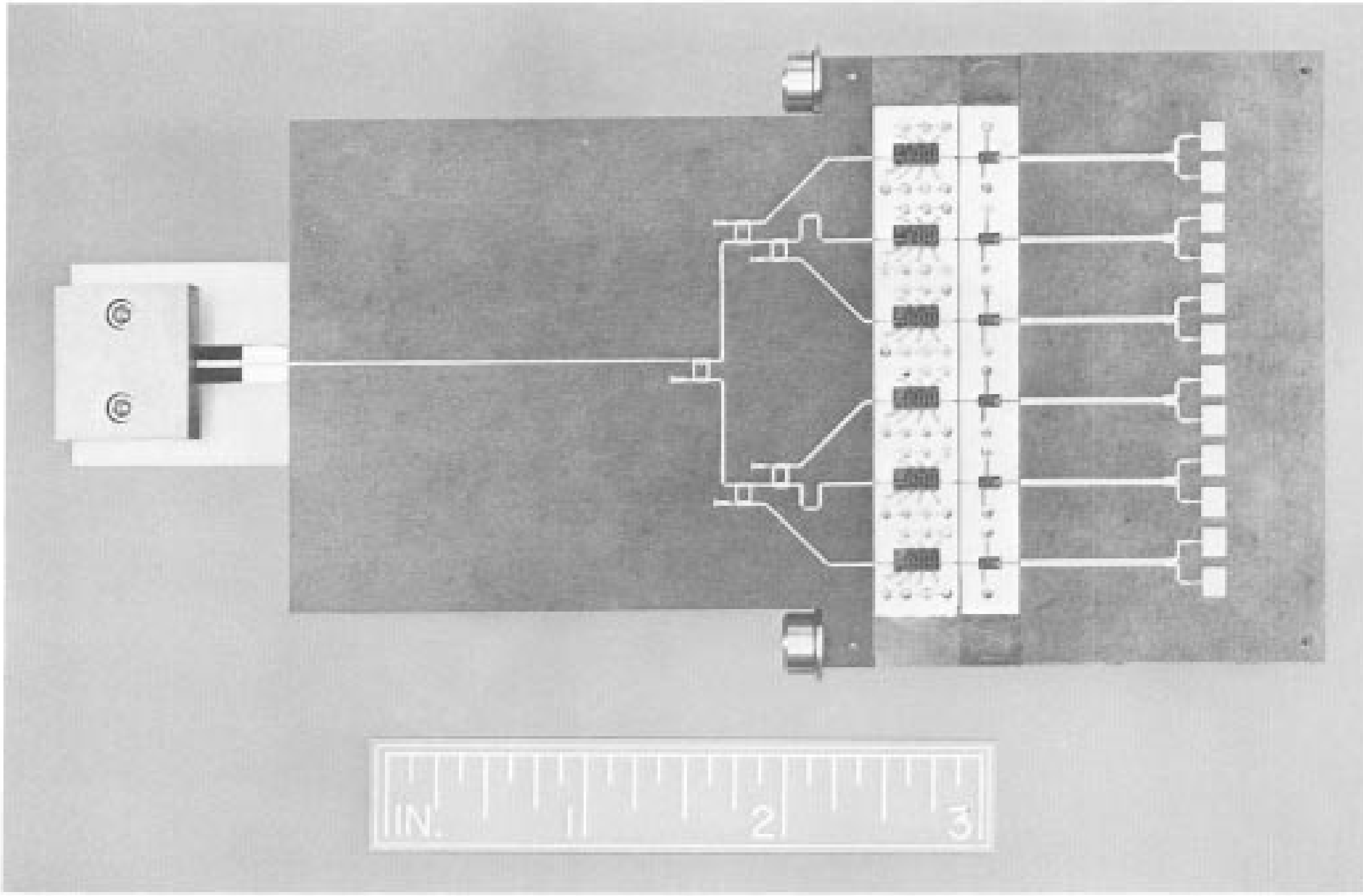

Fig. 3. Six-element linear transmitter array.

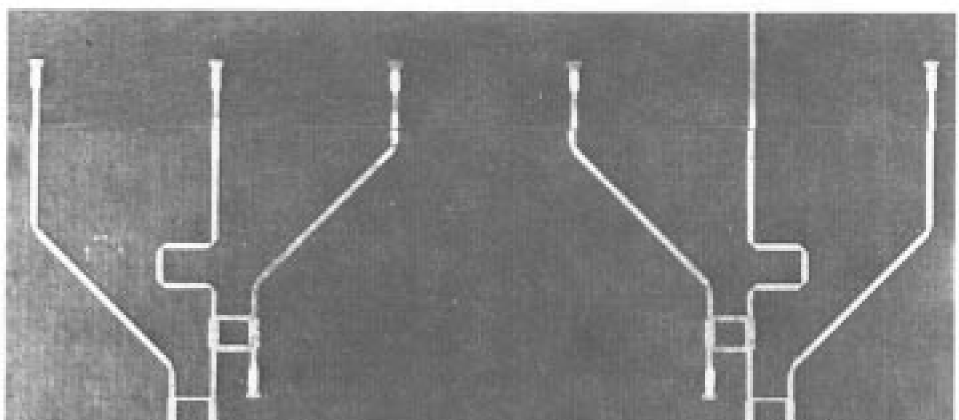

Fig. 4. Six-way microstrip power divider.

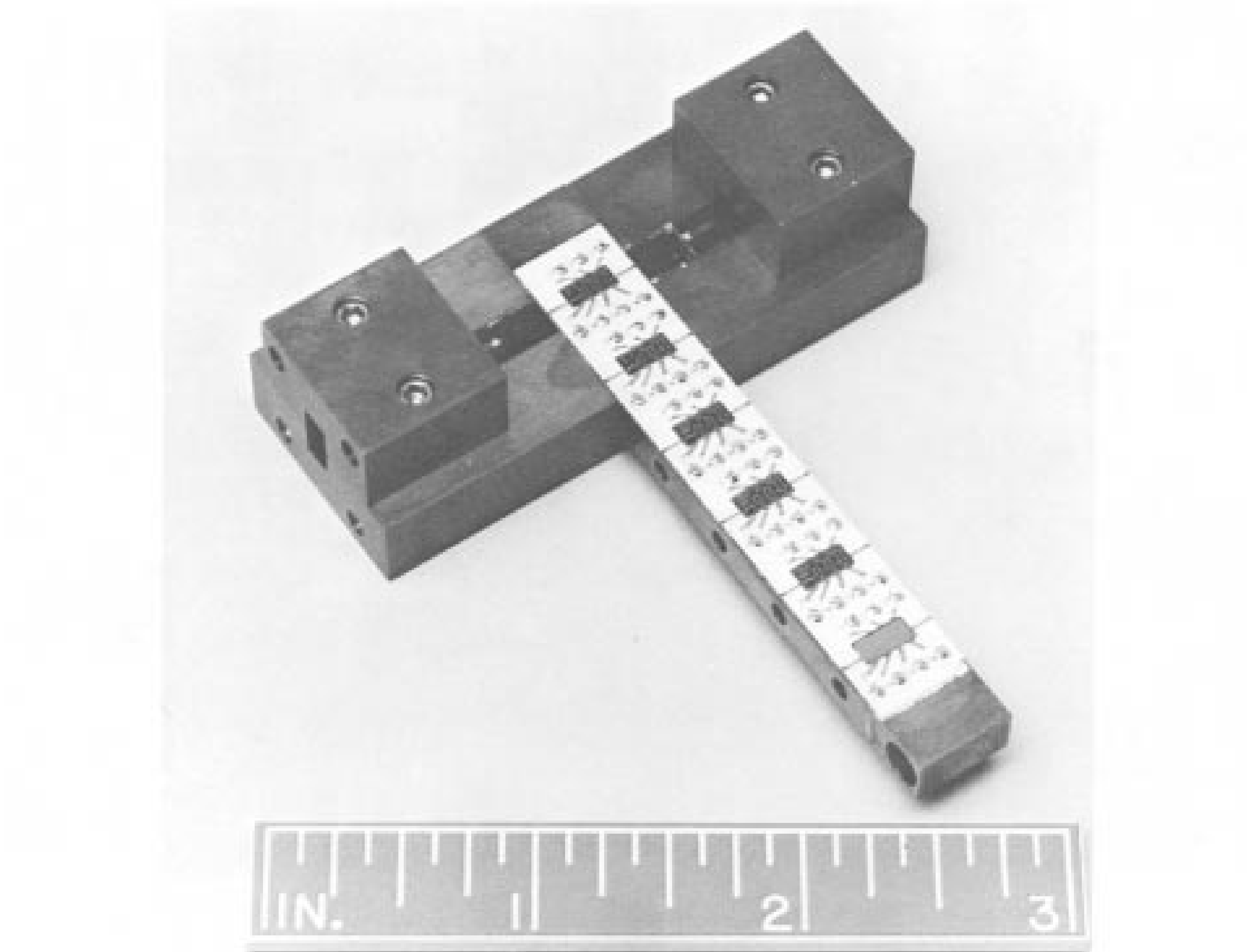

Fig. 5. MMIC phase-shifter carrier strip between two waveguide-to-microstrip transitions.

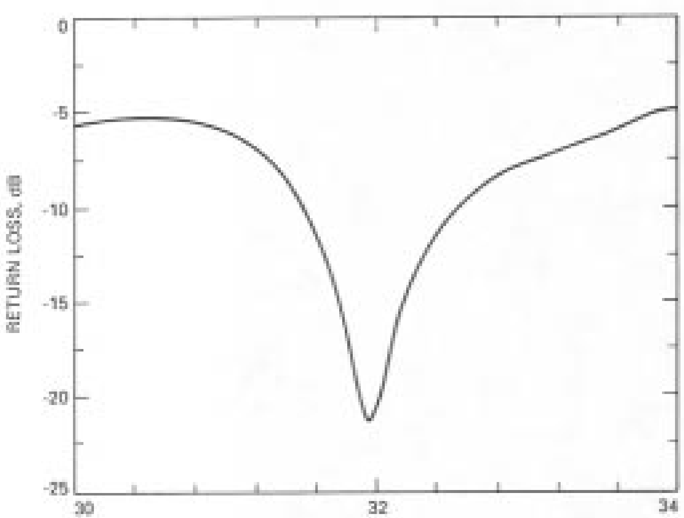

Fig. 6. Measured input return loss for a two-patch array.

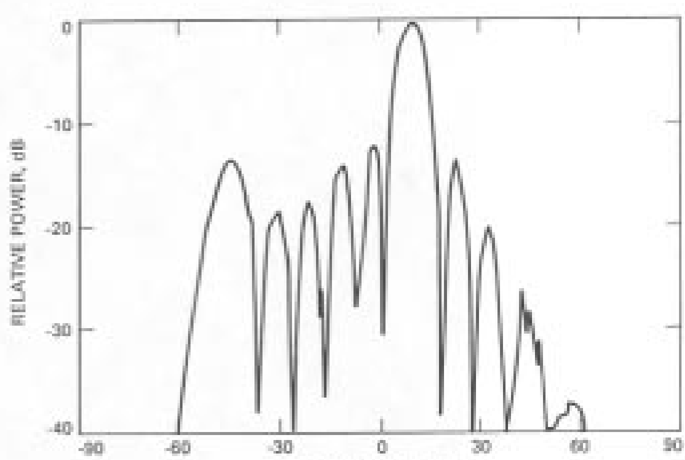

Fig. 7. Calculated far-field pattern of the 12-patch array with a 10-deg beam scan.

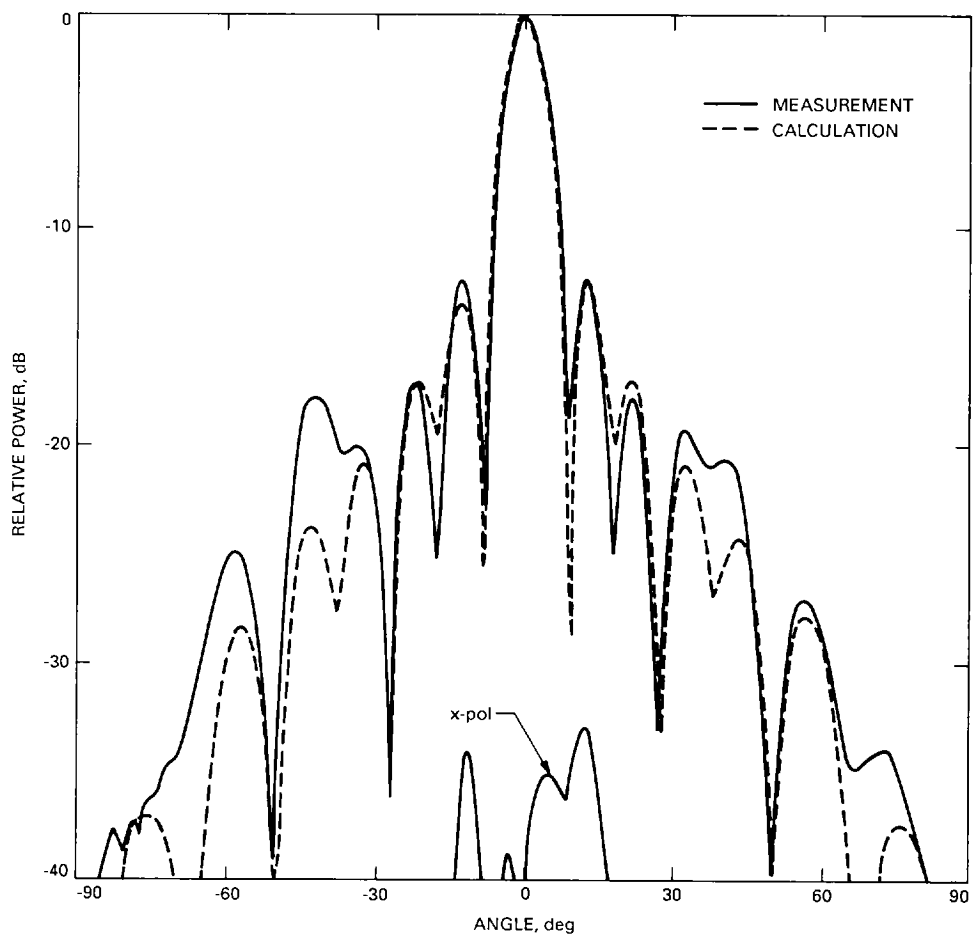

Fig. 8. Comparison of calculated and measured far-field pattern for the linear array without MMIC carrier strips.

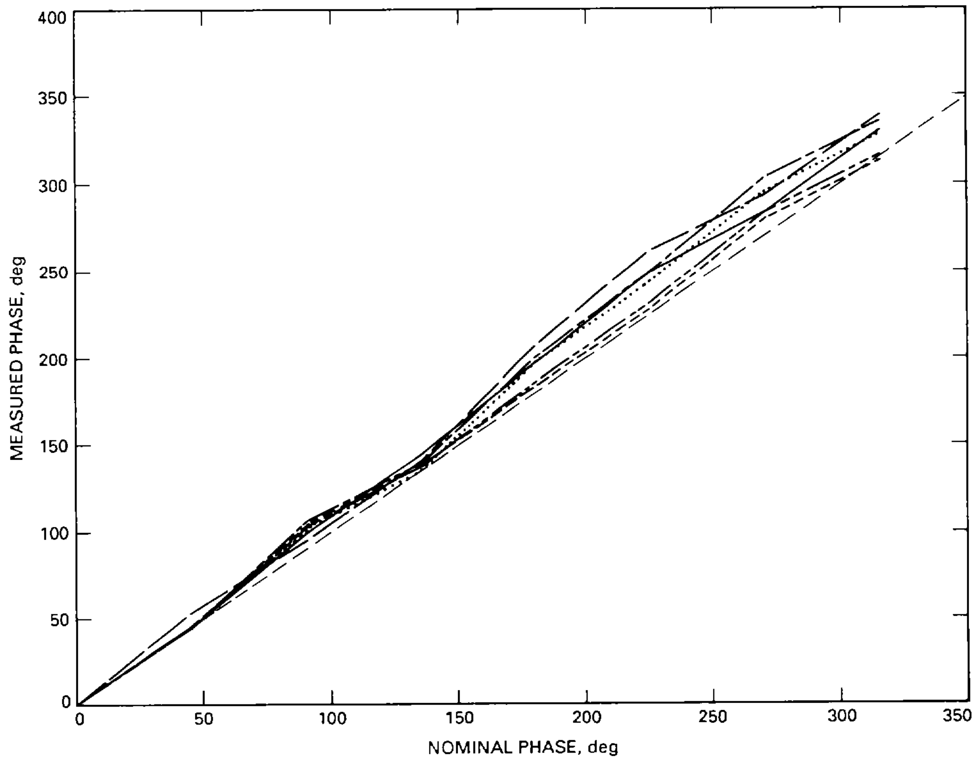

Fig. 9. Phase deviations measured against the nominal phase shift (dashed line) for six phase shifters.

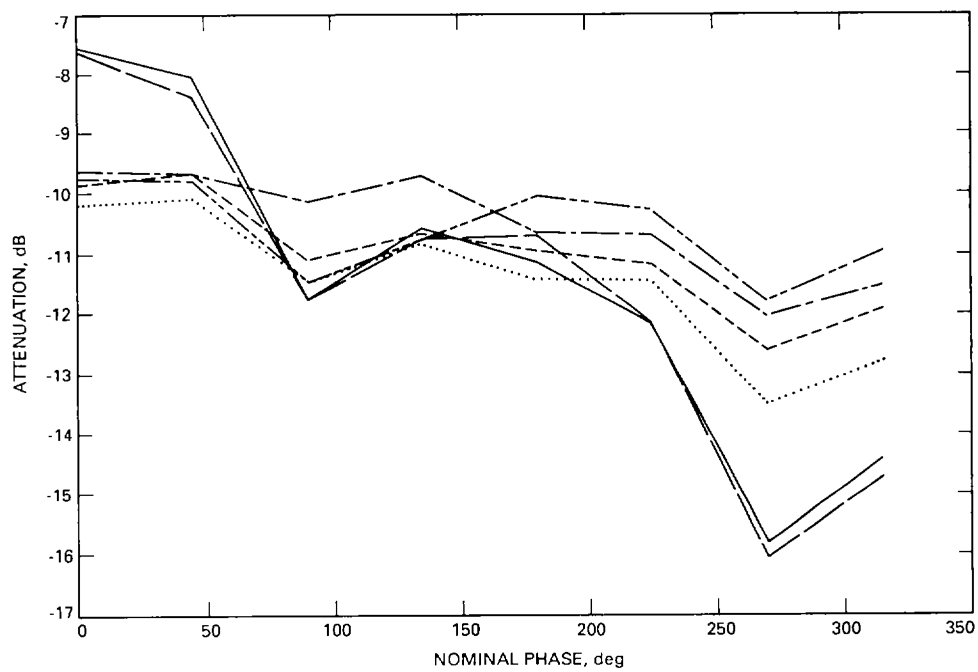

Fig. 10. The spread in measured attenuation for six phase shifters.

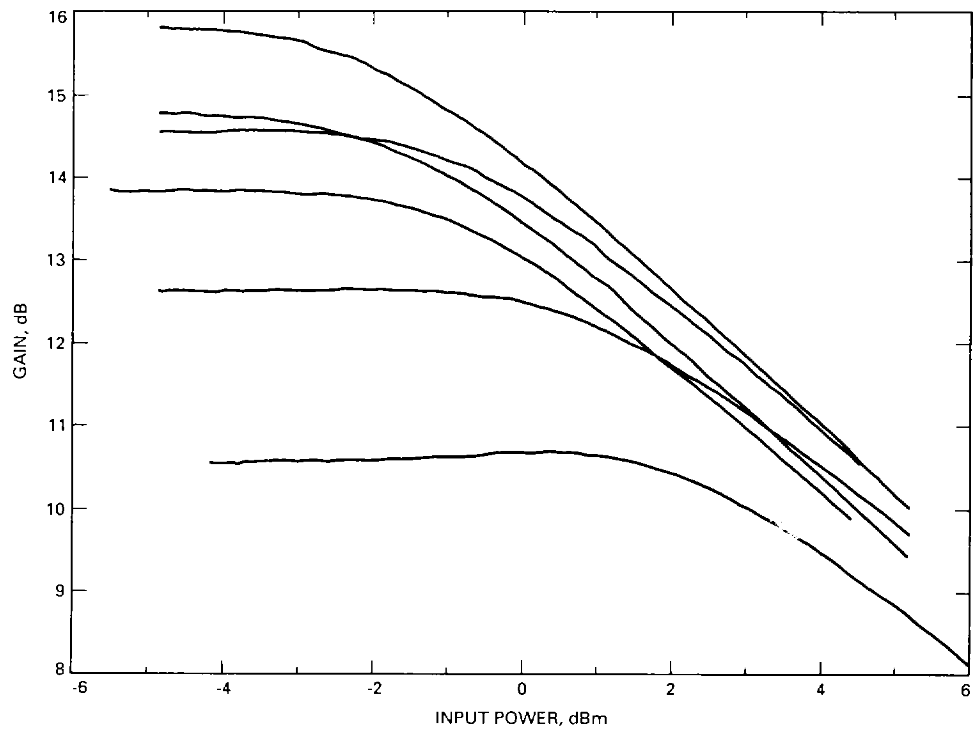

Fig. 11. The spread in measured gain-versus-input power of six power amplifiers.

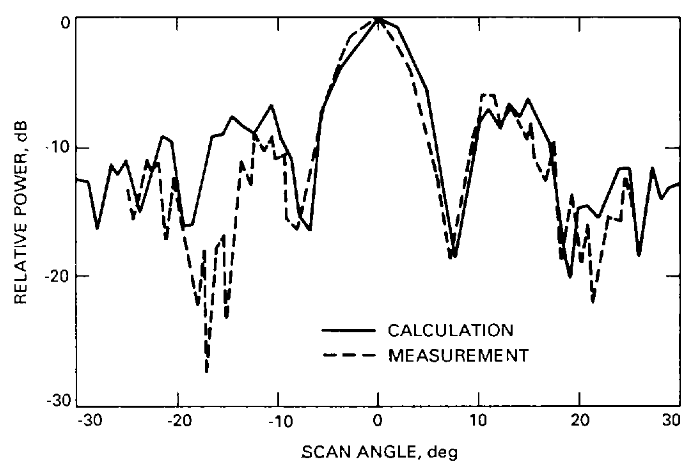

Fig. 12. Measured and calculated beam-scanning patterns for the transmitter array.