References

[1] S. Nagano and H. Kondo, "Highly stabilized half-watt IMPATT oscillator," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Microwave Circuit Aspects of Avalanche-Diode and Transferred Electron Devices*), vol. MTT-18, pp. 885–890, Nov. 1970.

[2] H. Komizo *et al.*, "K-band high power single-tuned IMPATT oscillator stabilized by hybrid-coupled cavities," *1972 G-MTT Dig. Tech. Papers*, pp. 176–178.

[3] H. J. Thaler, G. Ulrich, and G. Weidmann, "Noise in IMPATT diode amplifiers and oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 692–705, Aug. 1971.

[4] I. Tatsuguchi, N. R. Dietrich, and C. B. Swan, "Power-noise characterization of phase-locked IMPATT oscillators," *IEEE J. Solid-State Circuits* (*Special Issue on Solid-State Microwave Circuits*), vol. SC-7, pp. 2–10, Feb. 1972.

[5] H. Komizo, Y. Ito, H. Ashida, and M. Shinoda, "A 0.5-W CW IMPATT diode amplifier for high-capacity 11-GHz FM radio-relay equipment," *IEEE J. Solid-State Circuits* (*Special Issue on Microwave Integrated Circuits*), vol. SC-8, pp. 14–20, Feb. 1973.

[6] F. Ivanek, "Single-sideband amplitude modulation in microwave transmission systems," *Microwave J.*, pp. 27–36, Apr. 1972.

[7] R. J. Trew *et al.*, "Intermodulation characteristics of X-band IMPATT amplifiers," *1972 G-MTT Dig. Tech. Papers*, pp. 182–184.

[8] H. Seidel, "A feedforward experiment applied to an L-4 carrier system amplifier," *IEEE Trans. Commun. Technol.*, vol. COM-19, pp. 320–325, June 1971.

Analysis of Phase Characteristics as a Function of Ambient Temperature of IMPATT Amplifiers

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***Abstract*—Experimental data on phase characteristics as a function of ambient temperatures for GaAs IMPATT amplifiers are presented. An evaluation is given to show the impact of ambient temperature on an amplifier design used in phased-array radars.**

Introduction

It has become apparent that, to avoid network feed loss in some phased-array applications, individual amplifiers for each antenna element would be desirable. However, this requires amplifiers of small size, low cost, and high reliability which, at the same time, have characteristics that are well understood. It is especially important with IMPATT-diode amplifiers used in airborne environments, since the RF phase in these devices is quite susceptible to changes in ambient temperature.

The purpose of this paper is to provide empirical data on solid-state amplifiers which have been designed for phase-array applications.

Experiment

The objective of the experiment was to precisely measure the phase of the forward transmission coefficient of the avalanche diode amplifier (ADA) while monitoring the ambient temperature of the diode. A Hewlett-Packard network analyzer was used for measuring the transmission coefficient. The normal equipment configuration had to be modified in order to supply the desired input power to the amplifier. Fig. 1 depicts the setup employed. The system is basically a standard microwave bridge. The technique is used with the network analyzer in the reference arm, but which bypasses part of the test arm of the analyzer.

During testing, the amplifier was mounted on a water-bath heat sink. The baseplate temperature of the amplifier was controlled by varying the temperature of the water into the heat sink. The cooling equipment used permitted continuous water temperature regulation from 0 to 70°C, which resulted in measured temperatures at the diode mount of 11.7–69.7°C. Ambient temperature of the diode was monitored by a thermocouple attached to the diode mount. The amplifier/heat-sink assembly was mounted in a box to isolate the diodes from possible air drafts.

The amplifiers tested were GaAs ADA's made under Air Force contract F33615-69-C-1830. These 4-stage circulator-coupled reflection amplifiers were designed in alumina-substrate microstrip circuits with each diode individually biased and tuned. The nominal output power from each amplifier was 1 W from 9.0 to 9.6 GHz with a gain of 17 dB.

All operating points for these tests were chosen to be within the amplifier design criteria. Input power was selected as +8.5 dBm. The oscillator was set to sweep from 9.0 to 9.6 GHz. Table I lists the pertinent device parameters. Fig. 2 is a photograph of the amplifier.

Five of these amplifiers were to be tested but one of them failed in test. Of the four remaining amplifiers all showed the same experimental results in relative phase shift versus change in ambient temperature.

Phase measurements on the amplifier were taken every 9°C over the temperature range with zero reference phase arbitrarily taken near room temperature (26.3°C) Thermal expansion of the microstrip circuit and circulators were expected to contribute to the amplifier phase shift. To isolate this factor the circulator strip was removed from one of the amplifiers and phase measurements taken over the temperature range 26.3–71.1°C. No practical method was avail-

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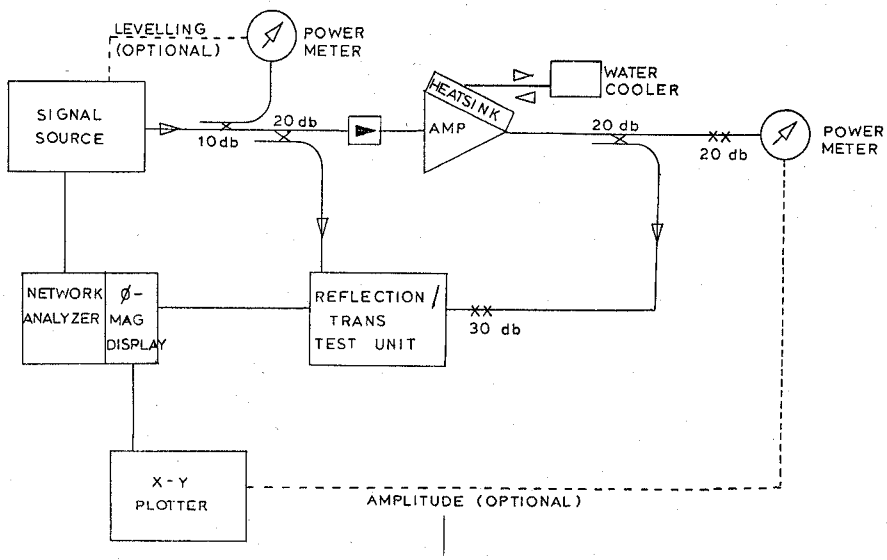

Fig. 1. Diagram showing the experimental configuration.

TABLE I
DEFINITION OF DEVICE PARAMETERS

Parameter	Value
Input Power Operating Point	+8.5 dbm
Diode Biasing	+85V; 0.65 - 0.68A
Frequency Range	9.0 - 9.6 GHz
Temperature Range	11.7 - 69.7°C
Device Area	10^{-4} cm^2
Doping Profile	1.4 x 10^{16} flat
Capacitance	5.0 - 5.5 pf
Power Output (Nominal)	1 watt
Gain (Nominal)	17 db

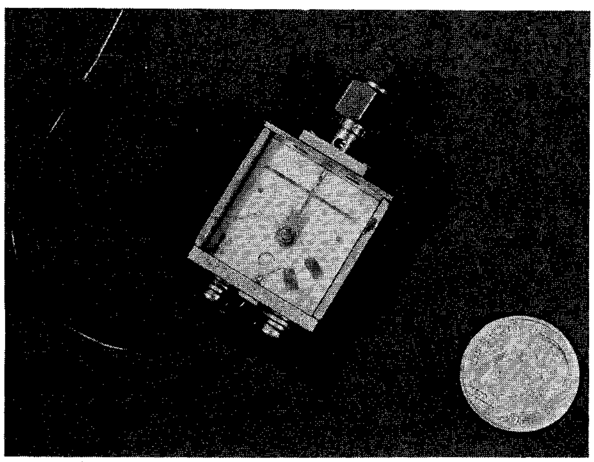

Fig. 2. The ADA.

able to measure the effect of this expansion on the microwave integrated circuit (MIC) matching network. However, estimation of electrical-length changes in alumina-substrate microstrip circuits over this temperature range indicate that it is negligible. Therefore, the effect of the matching network upon phase was assumed to be small as compared to the effect of the diodes and circulators.

TABLE II
PHASE MEASUREMENTS OF THE AMPLIFIER[a]

Temp °C	Frequency (GHz) 9.0	9.1	9.2	9.3	9.4	9.5	9.6
11.7	+67	69	78	75	66	65	62
12.8	65	67	76	73	63	61	58
15.6	48	51	59	57	46	45	44
18.3	44	35	48	47	35	32	33
21.1	25	18	32	32	23	18	21
23.1	8	5	19	19	11	7	10
26.3	-1	9	16	15	5	1	2
29.4	-14	-3	2	1	-9	-11	-10
32.2	-13	-7	-2	-3	-16	-21	-20
35.0	-27	-18	-13	-13	-26	-31	-30
37.8	-37	-27	-21	-21	-35	-42	-40
40.6	-51	-49	-34	-36	-48	-55	-54
43.3	-75	-61	-53	-56	-65	-71	-69
46.1	-100	-81	-74	-76	-82	-88	-85
48.9	-126	-97	-89	-91	-95	-101	-98
51.7	-139	-107	-100	-100	-105	-111	-107
54.4	-152	-120	-114	-113	-117	-123	-120
57.2	-172	-139	-135	-131	-134	-139	-134
60.0	-183	-151	-147	-143	-145	-150	-146
62.8	-193	-163	-163	-153	-155	-162	-157
65.6	-205	-173	-172	-165	-167	-172	-169
69.7	-220	-190	-191	-181	-183	-188	-186

[a] Zero phase reference—+26.3°C.

RESULTS

The tables and graphs are prepared for data points selected 100 MHz apart from 9.0 to 9.6 GHz. Table II presents amplifier phase values at given temperatures and frequencies. As noted earlier, the phase is measured from a zero phase reference selected at 26.3°C. Measurement repeatability was gauged by the capability of the system to closely duplicate the reference curve. Using this criterion, the data are repeatable within ±5 deg.

It can be seen from the data in Table II that the change in phase, at a given frequency, with temperature is approximately linear. The linear correspondence is somewhat better at the higher frequencies than at the lower frequencies. The

TABLE III

PHASE MEASUREMENTS OF THE CIRCULATOR STRIP[a]

Temp			Frequency	(GHz)			
°C	9.0	9.1	9.2	9.3	9.4	9.5	9.6
26.3	0	+9	+6	+5	+9	+9	+1
37.8	-22	-15	-17	-14	-9	-7	-20
48.9	-47	-40	-41	-38	-29	-33	-44
60.0	-70	-64	-62	-56	-47	-52	-67
71.1	-97	-93	-83	-75	-66	-72	-90

[a] Zero phase reference—+26.3°C.

TABLE IV

PHASE CHANGE RATES (DEG/°C)

Freq (GHz)	Amplifier	Circulator	Diodes
9.0	-5.06	-2.14	-2.92
9.1	-4.63	-2.22	-2.41
9.2	-4.65	-1.98	-2.67
9.3	-4.43	-1.80	-2.63
9.4	-4.32	-1.69	-2.63
9.5	-4.43	-1.84	-2.59
9.6	-4.27	-2.07	-2.20

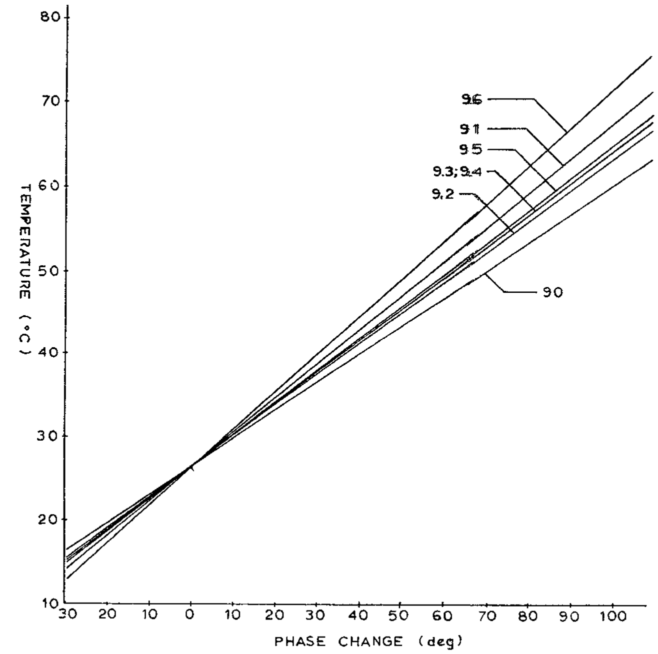

Fig. 3. Phase change as a function of temperature for the selected frequencies for the diodes.

data in Table II are for the amplifier which includes the diodes, circulators, and matching networks. Isolating the phase shift attributable to the diodes requires the elimination of the phase shift contributed by those other factors. Table III shows the phase data for the circulators. To calculate the phase shift caused by the diodes, the phase change per degree centigrade is evaluated for both the amplifier and the circulators. This data together with the rate of change of phase per degree centigrade of the diodes are tabulated in Table IV. Assuming the phase at 26.3°C was precisely zero for all frequencies, Table IV may be plotted as in Fig. 3.

CONCLUSIONS

An experimental factor which should be noted is the relation between the diode temperature and the water temperature in the heat sink. The water temperature was varied from 0 to 70°C, while the diodes varied only from 11.7 to 69.7°C. It is immediately apparent that the diode temperature and water temperature converge at higher values. The greater difference at low temperatures leads to the observation that the diode heat-sink gradient was greater at lower temperatures, and hence the conclusion that the diodes were at a higher temperature than measured. This factor will tend to bring up the lower temperature end of the rate of phase-change lines.

The rate of change of phase as a function of ambient temperature in the ADA's is nearly constant at a given frequency for all the amplifiers measured. This predictability, therefore, lends itself to simple temperature compensating techniques which would eliminate a critical potential problem in distributed power-source phased-array systems.

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REFERENCES

[1] C. K. Kim *et al.*, "Avalanche diode amplifier development," Air Force Avionics Lab., Air Force Systems Command, Wright-Patterson AFB, Ohio, Tech. Rep. AFAL-TR-71-219, Aug. 1971.