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A 10-W, 6-GHz, GaAs IMPATT Amplifier for Microwave Radio Systems

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An experimental 10-W, three-stage, GaAs IMPATT amplifier has been developed with transmission characteristics suitable for use in 6-GHz long-haul radio-relay systems. The amplifier uses five flat-doping-profile GaAs IMPATT diodes in three cascaded, circulator-coupled stages. The dc input power is 153 W with a nominal 10 W of output power and an overall noise figure of less than 35 dB. The overall amplifier efficiency is 6.5 percent. The major portion of the amplifier is constructed in strip transmission line using suspended alumina substrate in an aluminum housing. Small, integrated, coaxial sections with coaxial transformers connect the diodes to the strip transmission line circuits. The amplifier is cooled by free convection.

I. INTRODUCTION

IMPATT diodes provide a practical means of generating watts of cw microwave power. These devices are now commonly used in transmitter power amplifiers at 6 GHz and higher frequencies. For short-haul radio systems, an output power of 1 to 2 W, which can be obtained using a single diode,[1] is often sufficient. However, for long-haul systems, 10 W is a typical output power requirement, and the traveling-wave tube has been the indispensable selection. This much power can be obtained from multiple-IMPATT-diode circuits, especially when GaAs diodes are used. GaAs diodes have greater efficiency and lower noise than Si diodes, and this latter quality is equally important in meeting long-haul objectives.

This paper describes the circuit configuration used to meet the long-haul transmission objectives with a minimum number of IMPATT diodes, corresponding to highest overall efficiency. The diodes have conventional flat-doping profiles. The higher-efficiency, modified-Read-profile diodes were not available at the onset of this development, so they are not included in this study.[2]

II. MICROWAVE RADIO SYSTEM

The microwave radio system under consideration is a 6-GHz FM system with 1800-message circuit capability. It currently uses a 10-W traveling-wave tube as an rf amplifier in the transmitter. The thermal noise for a typical hop with 1800-message circuit loading should not exceed 15 dBrnc0.* The contribution of the amplifier to the total thermal noise level should be less than 6 dBrnc0. This corresponds to a double-sideband carrier-to-noise ratio, C/N (DSB-FM, 1-Hz BW), of 147 dB. N is defined as the total noise power in two 1-Hz bands, 8.5 MHz on each side of the carrier, whose power is C.

The performance of the amplifier in the system can be evaluated by the use of system thermal noise performance contours. These contours were derived assuming average values for all parameters in a single hop of a typical radio repeater system. Such contours in dBrnc0 as a function of rf output power and C/N of the transmitter amplifier[4] are given in Fig. 1. These curves assume that the amplifier contributes only thermal noise, with essentially no contribution of intermodulation and cross-modulation noise. The horizontal and vertical asymptotes of the curves of Fig. 1 indicate the regions of receiver noise and transmitter noise domination, respectively. When transmitter noise dominates (vertical asymptotes), improving the output power of the amplifier does very little to improve the system performance. Similarly, if the receiver noise is the dominant factor, improving the noise of the transmitter amplifier does not improve the overall performance.

The curves indicate that 15 dBrnc0 can be achieved with an amplifier whose C/N is 147 dB and output power is 40 dBm. It also indicates the power and noise trade-off that can be made and still get the overall performance of 15 dBrnc0.

III. CALCULATED PERFORMANCE

The design goals of the amplifier were a C/N of 147 dB with an output power of 40 dBm. Such a performance cannot be realized with a single-stage device. The power-noise characteristic of a typical GaAs diode is given in Fig. 2 for 32-W dc input power. Maximum power and minimum noise cannot be realized simultaneously. The maximum usable added power of a reliable flat-doping-profile 6-GHz GaAs diode is on the order of 36 dBm with a corresponding noise figure of approximately 51 dB and an efficiency of about 12.5 percent.

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* dBrnc0 is a measure of message circuit noise expressed in decibels relative to a reference level of −90 dBm. It is measured using a C-message weighting network and referred to the 0 transmission level point (Ref. 3).

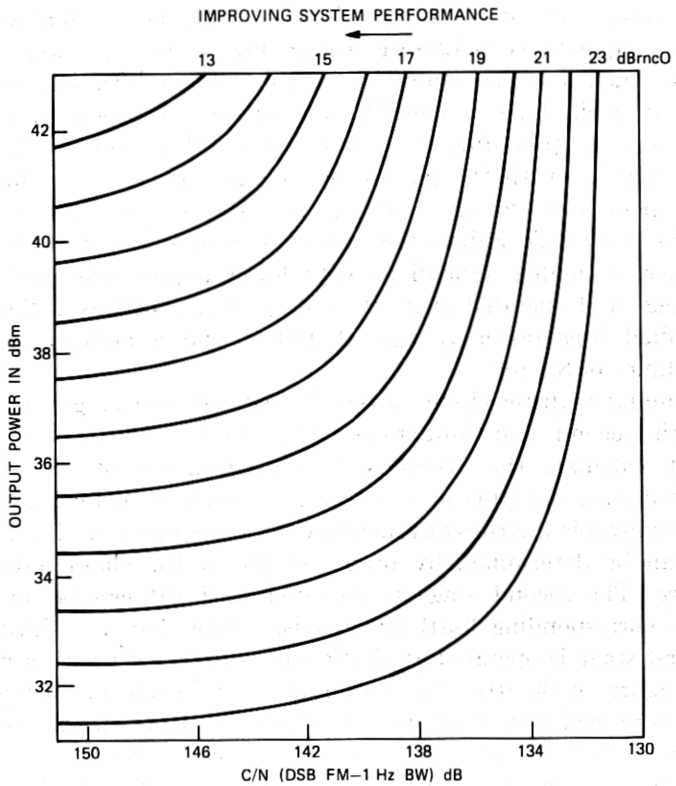

Fig. 1—Lines of constant system thermal-noise performance appropriate for evaluating the output amplifier for a 6-GHz long-haul microwave radio system.

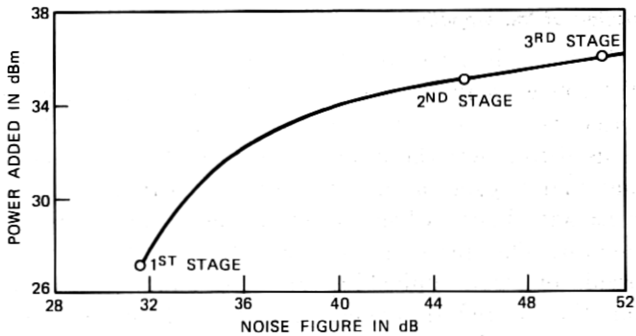

Fig. 2—Power-noise characteristic of a typical 6-GHz GaAs diode with 32 watts dc input showing the operating levels used in the three-stage amplifier.

The nominal breakdown voltage is 83 V, and the nominal zero-bias junction capacitance is 12.5 pF. Using these diodes, a power of 10 W can be realized by cascading two stages of amplification with two diodes in each stage. A suitably low overall noise performance can be obtained by preceding the power stages with a low-noise high-gain stage. A diode with the power-noise characteristic shown in Fig. 2 when operated at 27 dBm output in the first stage will meet the noise objective. To reduce the overall dc power requirement for the amplifier, a smaller area diode with lower doping was used in the first stage and operated at 21 W of dc power. This was a diode with a nominal breakdown voltage of 100 V and a nominal zero-bias capacitance of 8.5 pF.

Assuming realistic circuit losses (1 dB) between stages and operating the second- and third-stage diodes at the levels shown in Fig. 2, we can calculate the overall system performance of the amplifier. The diodes are operated in a conventional single-tuned coaxial circuit using a movable quarter-wavelength coaxial transformer. The nominal gain can be determined by proper choice of the characteristic impedance. The second stage is operated at 1 dB less power added with a corresponding 6-dB lower noise figure than the third stage. The first stage is operated at 27 dBm of added power with a nominal noise figure of 30 dB. The optimum second-stage operating point was determined from a series of calculations made with a fixed first- and third-stage power added and noise and a variable power and noise combination of the second stage. The overall calculated output power was 40.3 dBm with a noise figure of 33 dB. This corresponds to a C/N of 146.5 dB when the input power is 8.5 dBm, the nominal input level available. The corresponding system performance is better than 15 dBrnc0.

IV. THREE-STAGE AMPLIFIER

4.1 Description of the amplifier

Figure 3 is a schematic of the amplifier. The input and output are in WR-159 waveguide. To satisfy the input match requirement, a terminated circulator is used as an isolator. A 10-dB directional coupler is used to power the input monitor diode. This diode provides a dc signal that triggers a squelch network to remove the dc power from the IMPATT diodes when the input signal decreases a predetermined amount. This prevents the first stage, which is an injection-locked oscillator, from unlocking and free-running at a frequency other than the desired frequency. The first stage consists of a circulator and the diode network. A terminated circulator is used as an isolator between the first and second stages to provide isolation

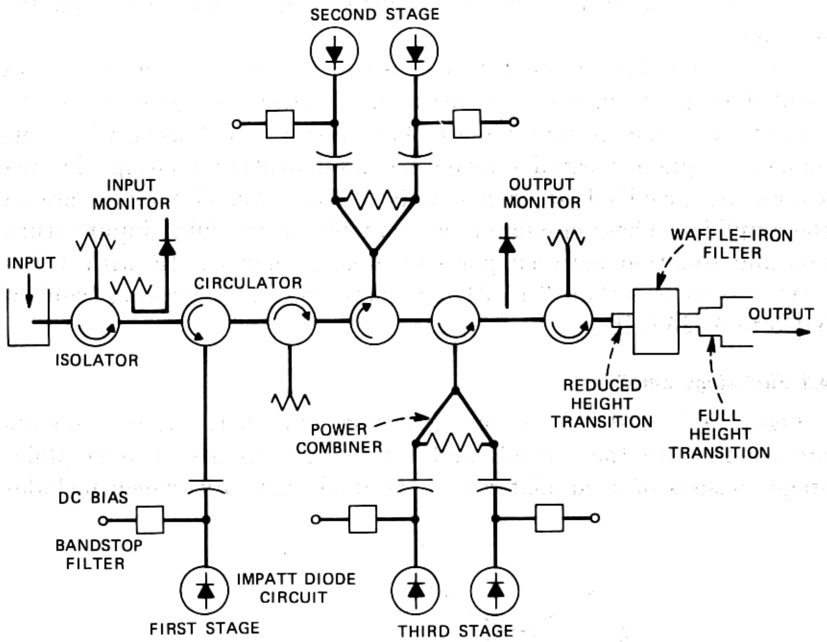

Fig. 3—Schematic representation of a three-stage, five-diode, 6-GHz IMPATT amplifier.

between them. This is especially important here because of the relatively high gain of the first stage. Any doubly-reflected amplified signal from the first stage could combine with the low-level incoming signal and introduce distortion.

The second and third stages are similar. Each consists of a circulator, resistively terminated power-combiner network, and a diode network. There is no isolator between the second and third stages because of the relatively low gain of the second stage.

The output circuit consists of an output monitor, a terminated circulator used as an isolator, a stripline-to-reduced-height transition, a waffle-iron filter, and a full-height transition. The waffle-iron filter is used to prevent any higher harmonic signals from appearing at the output.

4.2 Circuit fabrication

The circuit is fabricated on 24-mil-thick alumina substrate suspended between ground planes spaced 124 mils apart. The thin-film transmission line pattern is deposited on the ceramic substrate using photolithographic techniques. The ceramic substrates are suspended in a channel 0.580-in. wide to prevent moding and cross-coupling problems.

The Y-junction circulator[5] consists of yttrium-iron-garnet discs bonded to both sides of the ceramic, filling the space between the ceramic and the ground planes. The ferrites are biased with permanent magnets located outside the ground-plane housing. Tuning screws are provided at each circulator port. Six circulators are in the amplifier. These circulators are capable of providing input return loss and isolation between ports of greater than 33 dB with a forward loss of less than 0.15 dB per pass over the operating band of 5.925 to 6.425 GHz.

4.3 First-stage amplifier

Figure 4 is a sketch of the first-stage amplifier. Many elements are common to the second- and third-stage circuits. The amplifier stage consists of a circulator and the diode network, which includes

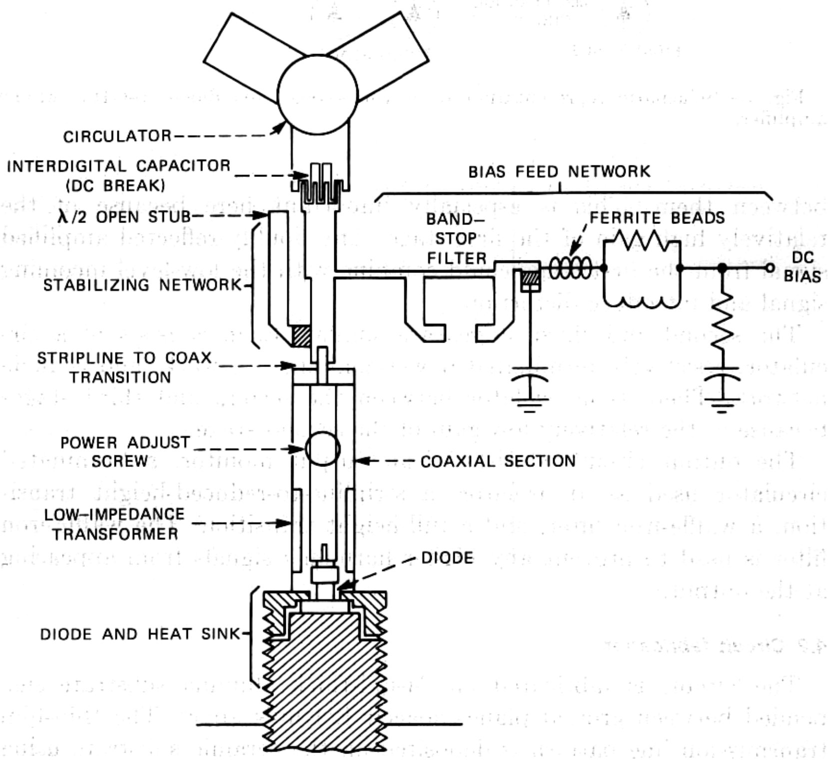

Fig. 4—Components of the first stage of the amplifier.

a dc break, a bias-feed network, a stabilizing network, a stripline-to-coax transition, a low-impedance transformer, and the diode.

4.3.1 DC break

An interdigital capacitor is used to provide a dc break, keeping the high voltage confined to the diode circuit. A detailed view is shown in Fig. 5. The total capacitance measured at 1 MHz was approximately 2.3 pF. This series reactance is incorporated into the circulator design such that, at point A, the impedance looking toward the circulator is 50 ohms. When the interdigital capacitor is used in the circuit, resonances can exist when the gap length is a multiple of a half wavelength. This can be acceptable if these resonances can be made to straddle the operating frequency band. The resonance

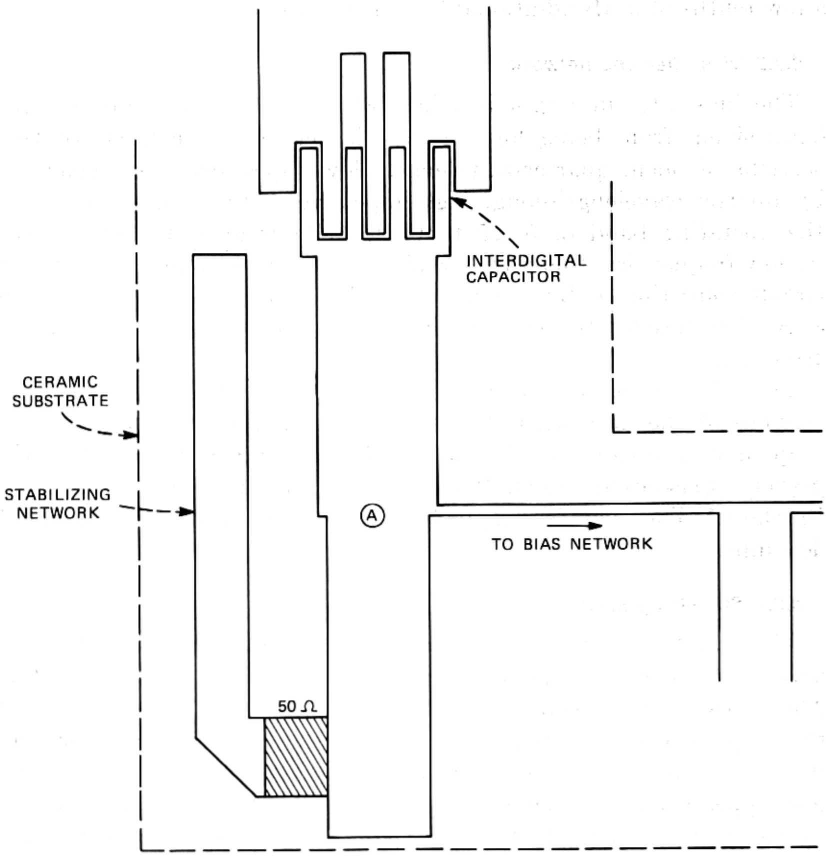

Fig. 5—Conductor pattern on ceramic substrate showing detail of the interdigital capacitor and the stabilizing network.

can be controlled by adjusting the total length of the gap, but this length also determines the total capacitance, which in turn affects the impedance match of the circulator. A simpler means of controlling the resonant frequency is to reactively load the gap.[6] This is shown in the figure as the slot in series with the transmission line formed by the gap. If the length of the slot is less than a quarter-wavelength long, the gap is inductively loaded, which essentially increases the gap length and thereby lowers the resonant frequency. By such a technique, the slot resonant frequency can be controlled without affecting the total gap capacitance. The gap was coated with a dielectric material to prevent any accidental short circuit. The coating increased the total capacitance slightly. A method of actually eliminating the slot resonance is to resistively load the series slot.[7] This is the most satisfactory method if one can tolerate a few tenths of a dB additional loss in the circuit.

4.3.2 Bias filter and network

The bias filter in Fig. 4 is a band-stop filter. It prevents any in-band signal from being lost to the bias circuit. It consists of two sections of open, quarter-wavelength, low-impedance lines separated by quarter-wavelength-long, high-impedance lines. The rejection in the operating band of 5.925 to 6.425 GHz is greater than 40 dB. At low frequencies, this filter circuit can be represented as a low-pass circuit consisting of L-C components. The circuit is terminated with a 50-ohm resistor in series with a 22-pF chip capacitor, which is grounded.

The bias network continues further in lumped elements. The purpose of the network is to provide a high resistance in the low-frequency spectrum together with a low resistance at dc. This will prevent bias-circuit oscillations of the type described by C. A. Brackett.[8] The bias is supplied from a constant-current-regulated dc supply.

4.3.3 Stabilizing network

The stabilizing network shown in Fig. 5 consists of a half-wavelength, open-circuited line connected in series with a 50-ohm resistor. This network is in shunt with the main line and helps to control the impedance presented to the oscillator outside the operating frequency band. At the operating frequency, the half-wavelength line appears as an open circuit and the resistor is essentially not connected to the circuit. At the half frequency, the line is a quarter-wavelength long and presents a short circuit to ground behind the resistor. The circuit is then shunted by the 50-ohm resistor. This network lowers the impedance presented to the diode at the subharmonic frequency and helps to increase the margin of stability when properly located in the circuit.[9,10] It takes a larger rf drive before spurious oscillations appear. The penalty paid using this network is the addition of about 0.15-dB insertion loss at the band edges. The stability margin can be increased further by adding a second resistor-stub network but at the expense of additional loss.

4.3.4 Coaxial circuit

Figure 6 is the side view of the coaxial circuit. A transition is made from stripline to coax at the end where a dielectric bead is located. A tuning screw is provided for matching purposes. The diode is located at the end of the 50-ohm coaxial circuit whose center conductor is spring-loaded to take up variations owing to mechanical tolerances. A movable transformer is located in the 50-ohm coaxial circuit. The characteristic impedance of the transformer is chosen to provide the correct resistive load component to the diode. The reactive load is varied by moving the transformer to cancel the reactance of the diode. To adjust the oscillation rf level for different diodes, the resistive component is made adjustable by adding a capacitive screw approximately an eighth wavelength from the nominal end position of the transformer. As the screw penetration is increased, the equivalent transformer characteristic impedance is increased by a factor of up to 1.6.

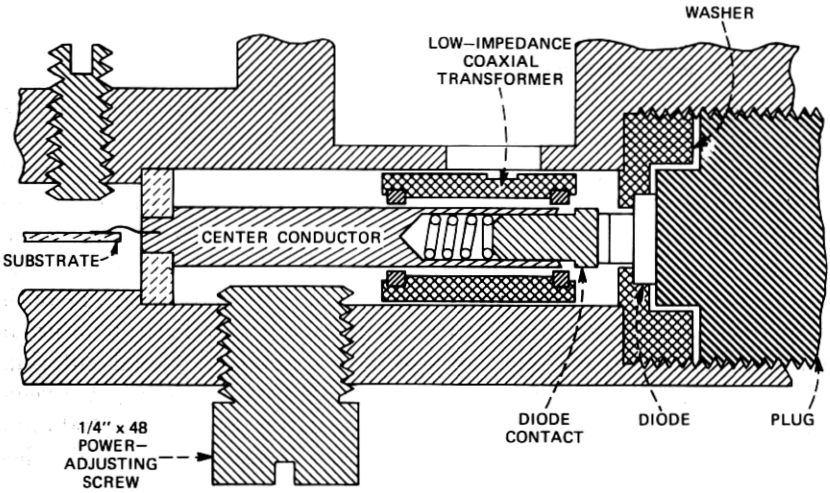

Fig. 6—Cross-sectional view of the coaxial amplifier circuit.

The diode rests in a diode washer which is screwed into the housing. A plug is screwed into the housing behind the diode, and the front surface makes contact to the back surface of the diode. One major problem of the amplifier is heat transfer from the diode to the housing. The heat must be transferred from the diode to the plug and through the threads to the housing. Some heat is transferred from the diode to the washer to the housing. The threaded washer is made as short as possible, permitting a short length for the narrow tip of the threaded plug. The plug is made as large in diameter as possible. To ensure good heat transfer, heat-sink compound is used in the threads.

4.3.5 Transformer

Figure 7 is a photograph of the coaxial transformers. The first-stage transformer is a noncontacting transformer with Teflon* beads located at both ends to center the center conductor. The transformer is insulated from ground with three Teflon strips placed longitudinally on the outer circumference spaced 120 degrees apart. The other transformers have only one Teflon bead used for centering the center conductor. The Teflon strips are located on the circumference of the transformers. An additional slot is cut in the outer circumference for the purpose of moving the transformer in the line. The characteristic impedances of the first, second, and third stage transformers were 8.3, 11.8, and 20.0 ohms, respectively. Noncontacting types of transformers were used instead of the spring-finger contacting type because of the cost advantage.

4.4 Second- and third-stage amplifiers

The second- and third-stage amplifiers are similar. Each consists of a circulator, hybrid power-combiner, dc break, bias-feed network, stabilizing network, and a coaxial section containing the IMPATT diode. Other than the hybrid power-combiner, the elements are similar to those of the first stage. The conductor pattern on ceramic substrate is shown in Fig. 8. In the hybrid power-combiner, the connecting lines are 70.7-ohm characteristic impedance and are both a quarter-wavelength long. A 100-ohm resistor provides an internal termination. All ports are matched to 50 ohms. A signal entering the port connected to the circulator (input) divides equally between the other two arms with no signal appearing across the 100-ohm resistor. A signal applied to either of the latter two arms divides

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* Trademark of Dupont Corporation.

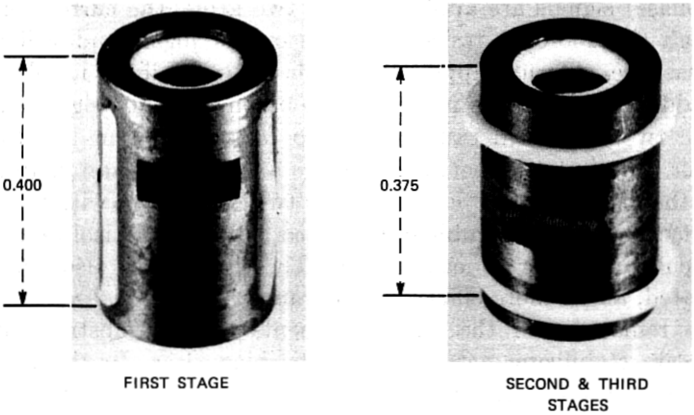

Fig. 7—Photograph of the low-impedance, noncontacting-type coaxial transformers.

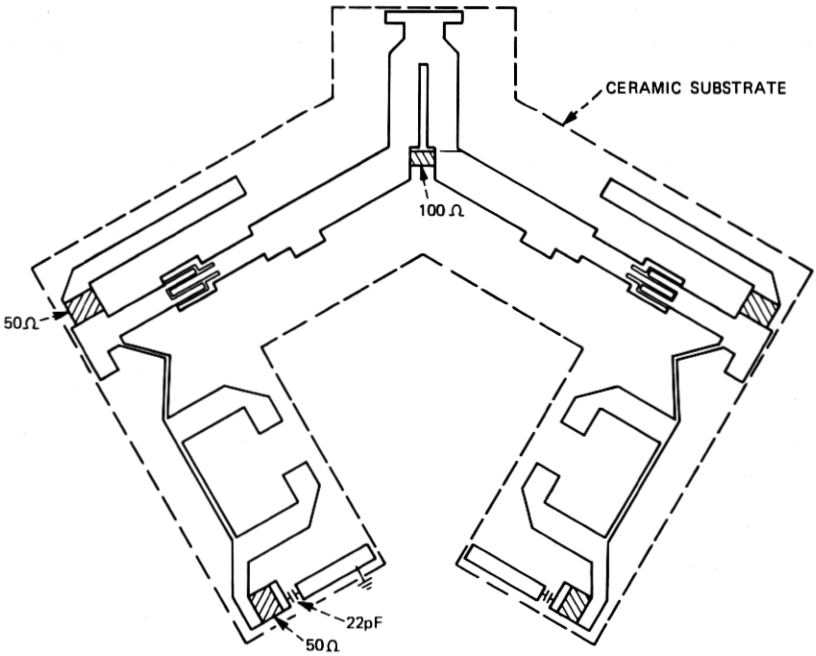

Fig. 8—Detail of the conductor pattern showing the hybrid power-combiner, interdigital capacitors, stabilizing networks, and bias networks used in the second and third stages of the amplifier.

between the 100-ohm resistor and the input. If equal (amplitude and phase) signals are applied to the two arms, the currents flowing through the 100-ohm resistor will be out of phase and will cancel, whereas the currents appearing at the input will be in phase and will add. Any difference in magnitude or phase of the signals applied to the two arms will cause power to be absorbed in the 100-ohm resistor. The isolation between the two arms was greater than 27 dB, with the balance from input to the two side arms within 0.1 dB. This type of power-combiner was used because the isolation allows independent tuning of each diode. The diodes are also physically separated, and a more efficient heat transfer can be realized.

The remainder of the circuit elements on the substrate are the dc break, stabilizing network, and the bias filter. In the bias-filter network at the dc bias-connection point, a chip capacitor is soldered onto the conductor and a spring-finger grounding clip is used to provide a connection to both ground planes.

V. PERFORMANCE OF THE AMPLIFIERS

Six prototype amplifiers were built for system evaluation and tested at two frequencies. Figure 9 shows the result of the measurement at 6.125 GHz as plotted on the power—C/N coordinates.

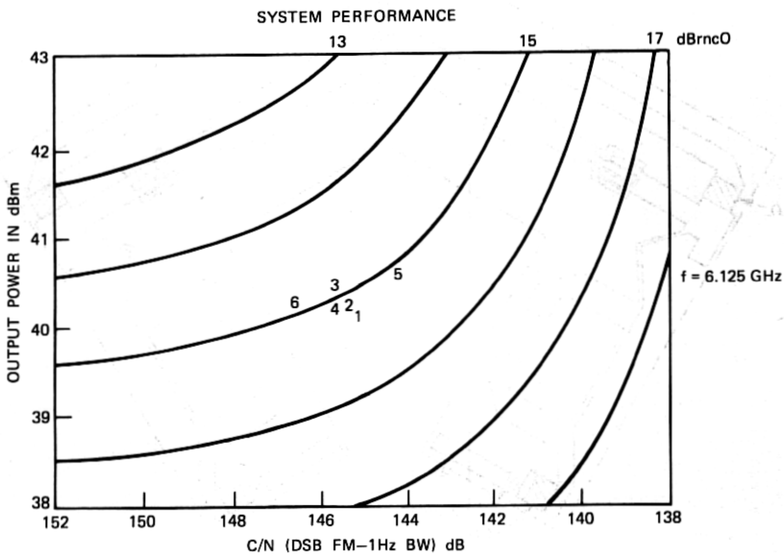

Fig. 9—Measured power and noise characteristics of the six amplifiers and their corresponding one-hop system thermal-noise performance. The numbers represent the measured data points.

(C/N of 147 dB corresponds to a noise figure of 32.5 dB for an input power of 8.5 dBm.) The numbers on the figure indicate the measured performance of each amplifier. The average power output and noise figure were 40.4 dBm and 34.1 dB, respectively. When tuned for the other test frequency, 6.375 GHz, the power output was lower but the noise was better. The average power output was 39.6 dBm with an average noise figure of 32.6 dB. The locking bandwidth of all the amplifiers was greater than ± 60 MHz. The average one-hop system thermal noise performance at both frequencies was about 15 dBrnc0. System tests indicated that the amplifiers were thermal-noise limited with negligible intermodulation distortion.

The amplifier is retuned for each channel frequency. Tuning consists of:

(*i*) Tune power output and free-running frequency on the first stage.
(*ii*) Adjust gain and center frequency of second stage. This required iteration of the four adjustments to obtain a prescribed output power.
(*iii*) Adjust center frequency of the third stage for maximum power output.

The power and overall noise figure were measured at other frequencies in the operating band, and Fig. 10 shows the results for one amplifier. The power output of the first stage alone, P_1, and first and second stages alone, P_{1-2}, are also shown. The power decreases at the high end of the band with an improvement in noise performance. The noise peak near the high end of the band was due to a subharmonic oscillation. In all the amplifiers, a subharmonic oscillation was generated in the third stage when driven by a high-level signal. The subharmonic oscillation introduces some excess noise but, because of the high gain existing before the third stage, the overall effect on the amplifier noise performance is minimal if the subharmonic oscillation is well established. In some amplifiers, the subharmonic does not exist at the low end of the frequency band, but it does exist at the high end of the band. At some intermediate frequency, a threshold of subharmonic oscillation is encountered. The noise at this threshold point is high enough to have an effect on the overall amplifier noise in spite of the high gain preceding the third stage. The solution to the problem is to eliminate the subharmonic oscillation completely or, if this is not easily accomplished, to have it well established at all times.

All measurements were made at room temperature ambient. The output power decreased with increasing ambient temperature at a

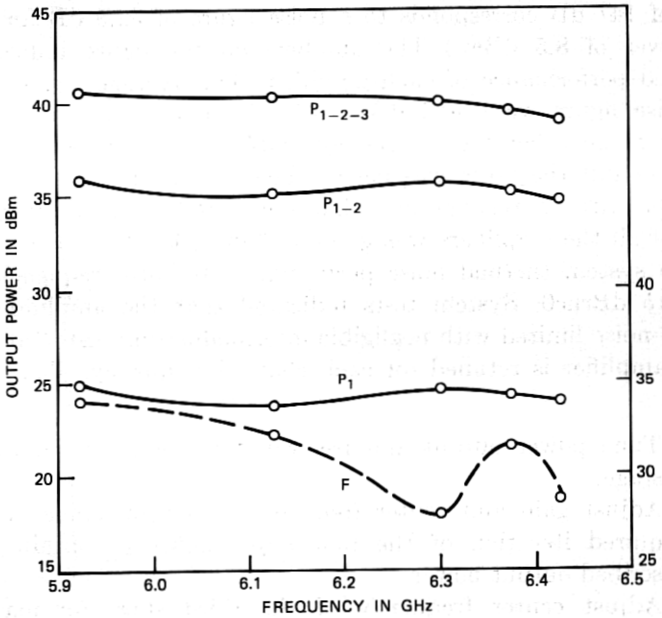

Fig. 10—Power and overall noise figure of a prototype amplifier measured as a function of frequency. $P_n (n = 1, 1\text{–}2, 1\text{–}2\text{–}3)$ indicates the output power with only the n stages turned on.

rate of about 0.05 dB/°F. This decrease was almost entirely due to variation of the first-stage amplifier gain. Temperature compensation of the first-stage gain would be necessary for uncontrolled environments.

Figure 11 is a photograph of the amplifier showing the top and bottom housing with the ceramic substrate and circuit elements. The amplifier is 11 in. wide × 14 in. long × 5 in. thick and weighs 12.5 lbs. The cooling fins can be seen on the top housing. Similar fins are also located on the bottom housing. The fins are spaced at three fins per in. The total surface area is 1286 sq. in. The measured thermal impedance of the amplifier from diode case to air was 1.5°C per W for free-convection cooling. With a diode junction-to-case thermal impedance of 5°C per W and a 25°C ambient, the junction temperature would be about 210°C. From aging studies, the predicted life would be in the order of 10^6 hours per diode. Even with five diodes, the amplifier should provide adequate reliability.

VI. CONCLUSIONS

A 10-W IMPATT amplifier has been developed whose transmission characteristics are suitable for use in 6-GHz long-haul radio relay

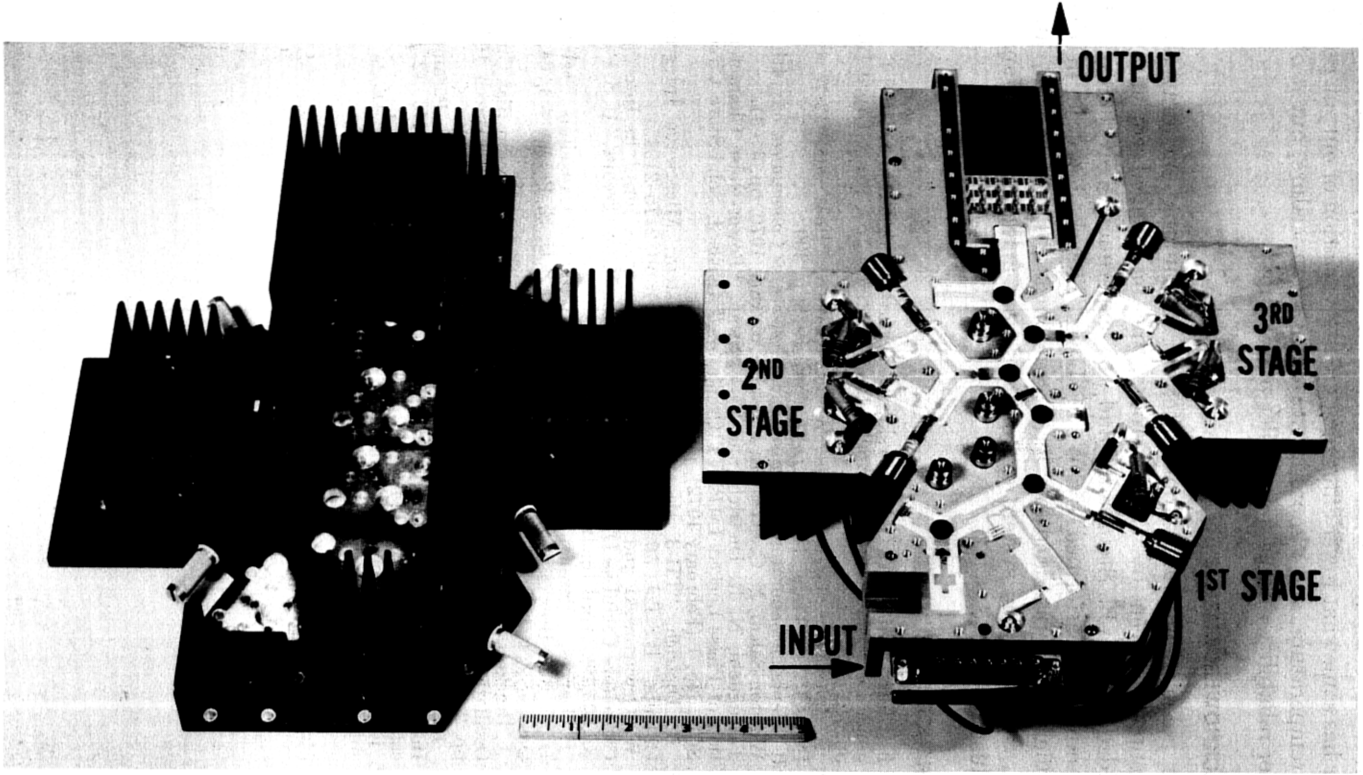

Fig. 11—Top and bottom housing of the amplifier with the ceramic substrate, diodes, and circuit elements shown.

systems. As compared with a traveling-wave tube, the IMPATT amplifier has somewhat lower efficiency, greater variation of output power with temperature, and a more intricate tuning procedure, but it offers greater reliability and uses a simpler power supply.

VII. ACKNOWLEDGMENTS

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