High-Power *C*-Band Multiple-IMPATT-Diode Amplifiers

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Abstract—**The design considerations and performance characteristics of two high-power microwave reflection amplifiers that use multiple silicon IMPATT diodes are presented. The amplifiers employ microstrip hybrid-circuit-type power combiners to combine the individually matched IMPATT diodes. The first unit, a single-stage 4-diode amplifier, produced 8-W output with 6-dB gain while the second 12-diode amplifier gave 15.8-W output at about 9-dB gain. FM and AM noise added by these amplifiers has been measured with each amplifier driven to nearly full output. Use of microstrip hybrid-circuit power combiners appears to offer a simple and economical design approach for the implementation of microwave solid-state power amplifiers using multiple active devices.**

I. Introduction

SEVERAL AUTHORS [1]–[3] have demonstrated techniques of combining IMPATT-diode oscillators to achieve increased power output at microwave frequencies. Similar approaches have also been applied to IMPATT-diode reflection amplifiers [4]–[7] in order to enhance their output power capabilities. This paper details the results obtained using simple microstrip hybrid circuits to combine the output from several individually matched IMPATT diodes that act together to form a reflection amplifier having much higher output than is available from a single diode. The amplifier units are based on use of a specially designed 4-way hybrid combiner circuit that acts as a building block allowing multiples of four diodes (i.e., 4, 8, 12, etc.) to be combined. The single-stage amplifier used a single 4-way hybrid circuit to combine four diodes while the 2-stage amplifier used three 4-way hybrid circuits (one in the preamplifier stage and two in the output stage) to combine 12 diodes.

Both of the amplifiers that were constructed utilized commercially available high-power single-drift silicon IMPATT diodes,[1] similar to those described by Cowley and Patterson [8]. Each diode consists of an array of four mesas connected electrically in parallel and mounted in a microwave diode package. These diodes typically produced a maximum output power of from 1.75 to 2.0 W at a frequency of 5.6 GHz when operated as an oscillator. Tests showed that these individual IMPATT diodes were capable of delivering from 2.2- to 2.4-W output (or 1.7- to 1.9-W power-added) at 6-dB gain with 5- to 6-percent power-added efficiency when operated as an unconditionally stable reflection amplifier.

It is well known [9] that IMPATT diodes operated at high average junction temperatures suffer degraded output power, increased noise, and reduced lifetimes. Thus, in all of the amplifiers built and tested, care was taken to adequately heat-sink the diodes. This entailed mounting them on massive copper blocks having integral cooling fins and circulating air onto the heat sink.

The dc input to each IMPATT was passed through a stabilization circuit composed of a two-section low-pass filter and a ferrite RF termination in order to assure adequate isolation between the power supply and the active devices (i.e., to prevent bias-circuit interactions).

II. Power-Combiner Circuit

A microstrip hybrid-circuit combiner scheme was chosen because of its simplicity and ease of fabrication. The 4-diode amplifier was used as a basic building block for more complex amplifier structures because: 1) it lends itself to production using a cascade of three 3-port hybrids; and 2) the 4-diode amplifier is more easily evaluated and optimized than amplifiers that combine more diodes in a single unit. The power-combiner circuit design was based upon the theory of 3-port TEM-mode hybrids developed by Cohn [10]. Both 1-section and 2-section hybrids have been designed and built, and the choice is determined by the bandwidth required from the combiner circuit to satisfy the needs of the particular amplifier.

The starting point of the 4-way combiner circuit design was the approach given in [10]. However, the basic theory in [10] is not adequate for microstrip circuits with chip resistors at the frequencies of interest (~5.1 GHz). Therefore, computer analysis and optimization were required to design these circuits. Our analysis took into account the following factors: 1) the finite coupling between pairs of microstrip transmission lines in the combiner (i.e., the even- and odd-mode impedances Z_{0e} and Z_{0o} were considered), 2) the finite inductance and capacitance contributed by the isolation (chip) resistors, and 3) the finite Q of the microstrip transmission lines. Fig. 1 shows the design values of the 2-section, 2-way power-combiner circuit that was computer-optimized to yield minimum input VSWR over the frequency band of interest. The computed performance expected from this design is also listed. The 4-way combiner is achieved by interconnecting three of the 2-way combiners as illustrated in Fig. 2. The microstrip circuit of Fig. 2 was

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[1] Hewlett-Packard IMPATT diodes #5082-0467, Hewlett-Packard Associates, Palo Alto, CA 94304.

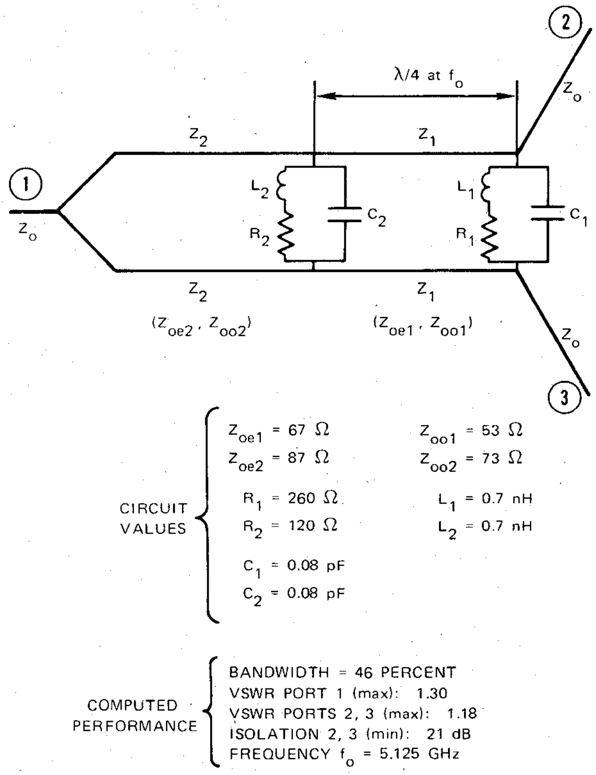

Fig. 1. Modified design values and characteristics of a two-way hybrid combiner circuit obtained from computer analysis.

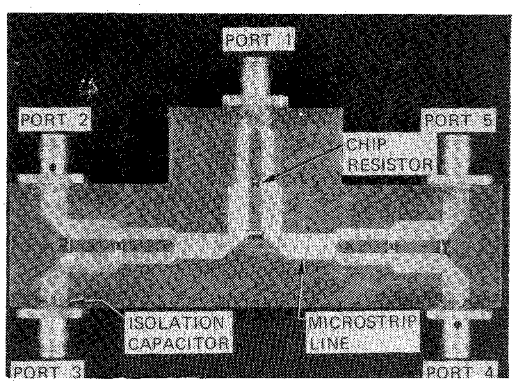

Fig. 2. Photograph of the four-way microstrip power-combiner circuit.

fabricated on $\frac{1}{16}$-in-thick Duroid circuit board ($\varepsilon_r = 2.53$). The thin copper transmission-line sections were produced by standard photolithographic and etching techniques and the chip isolation resistors (of the appropriate value) were solder-mounted directly onto the printed lines. Chip capacitors were also connected in series at each port of the power combiner (under the SMA connector tabs) to isolate the RF output (Port 1) from the dc bias that is applied to the IMPATT diodes (attached to Ports 2 through 5). To minimize the losses, it was found necessary to enclose the circuit with a metal cover. This tended to cause deterioration in the isolation and power-division properties of the combiner owing to waveguide modes propagating in the closed metal case. To circumvent this problem, two short-circuit posts were used to suppress these disturbances or shift them outside the frequency band of interest.

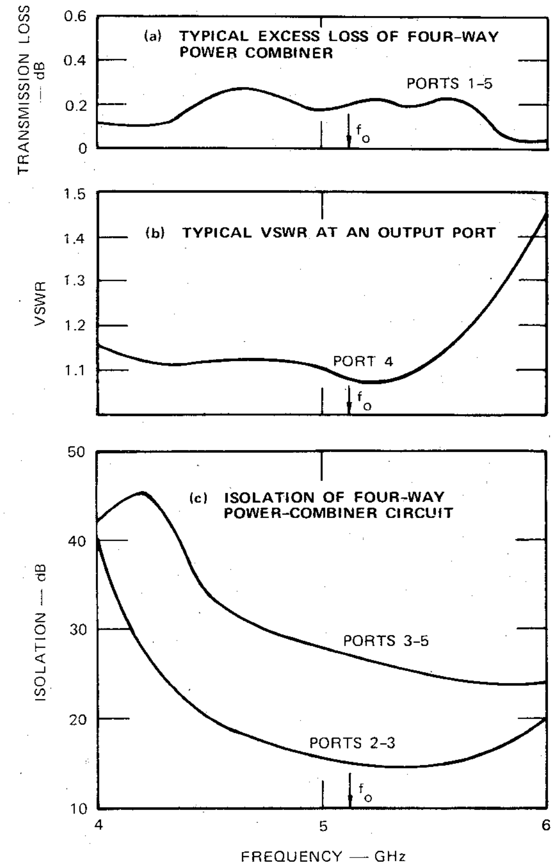

Fig. 3. Performance of the hybrid power combiner.

Fig. 3 gives a summary of the measured performance of the complete 4-way power-combiner circuit. Over the frequency range 5.0–5.3 GHz, the typical excess loss of the combiner circuit from the sum port, Port 1, to any output port, Ports 2 through 5, is less than 0.25 dB. The VSWR of the sum port with all the other ports terminated in 50 Ω was less than 1.2. The VSWR of any of the four output ports, with all other ports terminated was less than 1.13. Fig. 3 also gives the measured isolation between two opposite amplifier ports (2 and 3) and two diagonal ports (3 and 5) across the frequency band of interest. The greater than 18-dB isolation between any two amplifier ports is substantially above the gain available from any IMPATT diode, and this ensures stable amplifier operation when the four IMPATT amplifiers are combined.

The measured performance of the 4-way power combiner is in good agreement with the computed results. This implementation of a power-combiner circuit is desirable because: it uses microstrip lines and thus is easy to fabricate, all dimensions and resistor values are easily achievable, and the circuit can be produced by standard printed-circuit manufacturing techniques. Since the circuit is planar, it is an easier geometry to fabricate than other combiner circuits, such as the N-port Wilkinson type [11]. A disadvantage of this combiner is the limited power-dissipation capability of the chip resistors used in the combiner circuit. In the case of a diode failure that unbalances the combiner, significant amounts of power will be dissipated in the resistors. An isolation-resistor failure can be prevented with

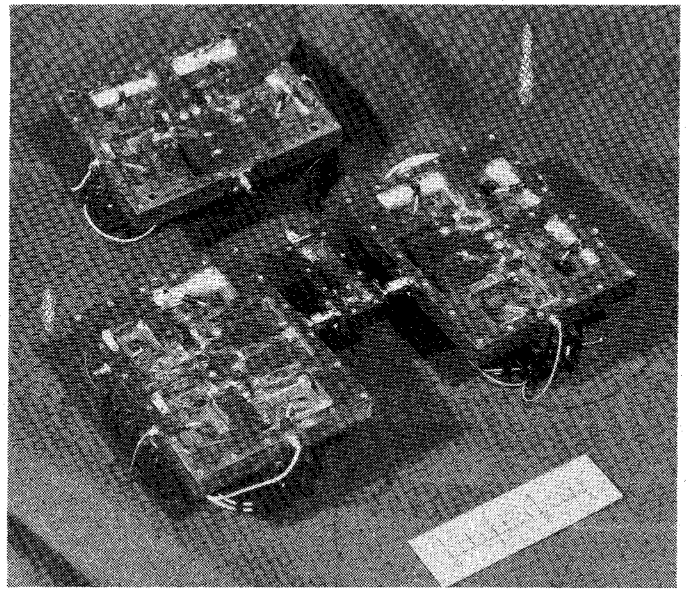

Fig. 4. Internal construction of the 12-IMPATT-diode amplifier (all-microstrip construction).

TABLE I
PERFORMANCE OF 4-DIODE IMPATT AMPLIFIER AT THREE DIFFERENT INPUT DRIVE LEVELS[a]

Maximum Output Power (watts)	Power Added (watts)	Gain (dB)	Power-Added Efficiency (percent)	Bandwidth -1 dB Level Relative to 5.23 GHz (MHz)
8.17	6.16	6.08	5.08	350
9.12	6.43	5.31	5.30	365
9.60	6.50	4.98	5.37	400

[a] These test measurements were made using Microwave Associates Model 7K128 circulator.

high-power resistors or a modified combiner circuit that permits the use of external loads with adequate heat-dissipation capability [12].

III. Four-Diode-Amplifier Performance

The 4-diode amplifier circuit was completed by attaching four individually matched IMPATT-diode amplifier modules to each of the output ports of the combiner (Ports 2 through 5) and attaching a 3-port circulator, which serves to separate the input from the output RF signal, to the sum port (Port 1). The IMPATT diodes were individually matched by their associated RF circuitry so that each module possessed nearly the same tuned-amplifier properties (i.e., power gain and bandwidth). Each amplifier module was composed of an IMPATT diode mounted at the end of a single-tuned quarter-wavelength coaxial matching section with characteristic impedance of 14.2 Ω. The outer conductor around the diode was increased in diameter over a short length to adjust (tune) the center frequency of the diode amplifier module to the desired value. The performance of the 4-diode IMPATT amplifier unit measured at its optimum operation frequency of 5.23 GHz is summarized in Table I.

The total dc input power to the amplifier under these test conditions was 121.1 W. Swept-frequency measurements conducted on the 4-diode unit show that the amplifier -1-dB bandwidth centered around 5.23 GHz was between 350 and 400 MHz. Extensive tests showed that no spurious interactions occur between the four single-diode amplifier modules (i.e., the devices were well isolated), and each unit performs as if it were operated in an isolated 50-Ω test system. The swept-frequency measurements also revealed the output RF signal to be free from any unwanted "jumps" or spurious triggered responses observed in some avalanche-diode amplifiers [13]. Thus, to summarize, an 8-W output reflection amplifier was developed, using four IMPATT diodes, that was capable of 6-dB gain and 5-percent power-added efficiency at the frequency of $\approx$5.2 GHz.

IV. Twelve-Diode-Amplifier Performance

The operation of the 4-diode amplifier unit which has been described validated the concept of using a simple microstrip hybrid-circuit power combiner to achieve substantial microwave power by combining several individually matched IMPATT diodes. The coaxial amplifier modules used in the 4-diode amplifier were too complex and bulky to be used in the 12-diode design, and thus a singly tuned microstrip version of the amplifier module was developed. Tests on a single-diode microstrip amplifier module showed that it was capable of 1.6–1.8-W power-added at 6-dB gain (slightly lower output was produced due to the lower Q of the microstrip relative to the coaxial circuit).

In order to achieve a higher gain amplifier, the 12 diodes were configured into a 2-stage design. The first stage was composed of four individually matched diodes and a 4-way single-section microstrip combining circuit. The output stage utilized 8 diodes in two 4-diode arrays that were subsequently power-combined in a 2-way hybrid. Fig. 4 shows the layout of the 12-diode amplifier with the preamplifier situated at the top left and the two drivers located at the bottom right side. Not shown in the figure is the 4-port circulator that was used to both separate the input and

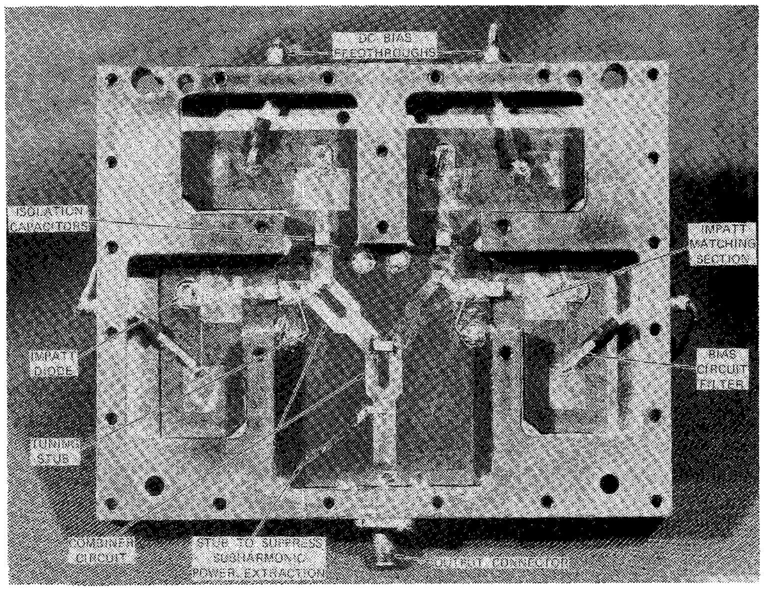

Fig. 5. Four-IMPATT-diode hybrid circuit amplifier module.

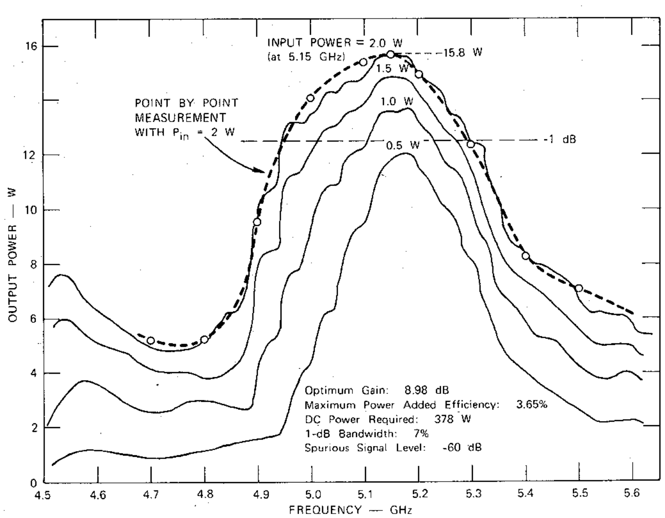

Fig. 6. Performance of 12-diode high-power IMPATT-diode amplifier.

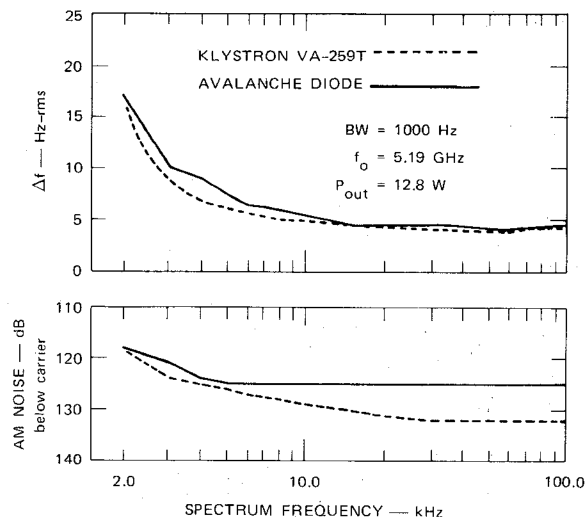

Fig. 7. Comparison of FM and AM noise measured on a klystron driver and on 12-diode-IMPATT amplifier.

output signals and couple the signal between the two stages. The total amplifier gain of ~9 dB is derived by summing the 5.5-dB gain of the first stage and the 4.3-dB gain of the driver stages, and subtracting about 0.8-dB circulation loss (at the midband frequency of 5.125 GHz). Fig. 5 shows a close-up photograph of one of the 4-diode amplifier modules used as the basic amplifier building block. The various components are detailed in the picture. Single-section hybrid combiner circuits were used because they gave sufficient bandwidth for the amplifier design and had slightly less line loss than the 2-section design previously used. The IMPATT diodes are situated in a recessed cutout area in the metal base in order to suppress spurious diode interactions. Circuit modes that can occur when a metal lid is used to enclose the circuit were effectively suppressed by incorporating shorting pins into the enclosure design.

The swept-frequency performance of the 12-diode amplifier is given in Fig. 6. The insert of Fig. 6 gives the amplifier performance at the optimum operation frequency of 5.15 GHz. The frequency of maximum gain shifts to slightly lower frequencies as the drive level is increased. At 15.8-W output the amplifier is nearly saturated (i.e., a fourfold increase in drive power from 0.5-W to 2-W increases the output by slightly over 1 dB). Both of these characteristics are common for amplifiers which use IMPATT diodes [14].

The noise characteristics of the 12-diode amplifier were ascertained by a comparative technique[2] routinely used in the evaluation of low-gain high-power microwave amplifiers [15]. In this technique, measurements of FM and AM noise close to the carrier were made on the amplifier when it was driven to nearly full output by a klystron source.[3] The results of these measurements are plotted in Fig. 7(a)

[2] Noise measurements conducted in the Environmental Test Section of Varian, Inc., Palo Alto, CA.
[3] Varian Model VA-259T.

and (b) along with the noise from the klystron (for comparison). These figures show that the 12-diode amplifier adds little extra FM noise over that of the klystron driver alone in the frequency range 2–100 kHz from the carrier. Also the IMPATT amplifier contributes little excess AM noise, being more than 115 dB below the carrier, over the measurement range. It should be noted that in both tests a 1000-Hz measurement bandwidth was used rather than the more usual 100-Hz bandwidth. This 12-IMPATT-diode amplifier is designed to operate in conjunction with a high-gain lower noise preamplifier unit (having 2-W output), and thus this first preamplifier stage should essentially determine the noise of the amplifier chain.

The completed amplifier unit was assembled on a common chassis and four rotary fans were incorporated for cooling the amplifier during operation.

V. Conclusions

A 12-diode IMPATT amplifier constructed using microstrip circuit and hybrid power combiners was capable of a maximum output of 15.8 W at a 2-W drive. The -1-dB bandwidth was 350 MHz. The measured noise characteristics show that the amplifier contributes little FM or AM noise over that produced by a medium-power klystron. The amplifier was unconditionally stable for all drive levels from zero up to 2.5-W input, and measurements of the swept-frequency response and output-signal spectrum showed that the amplifier produces clean RF output signals with no spurious frequencies generated other than noise and the harmonics of the input signal. It is clear that this amplifier design could yield much higher output power if recently developed GaAs IMPATT's [16] were substituted for the single-drift silicon IMPATT's used in the present amplifier.

The microstrip hybrid circuits have thus proven to be easy and convenient techniques for fabricating amplifiers using multiple discrete devices. The planar circuit format should lead to reduced complexity and decreased production costs.

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