A 12-W GaAs Read-Diode Amplifier at *X* Band

HUA QUEN TSERNG, MEMBER, IEEE, DONALD J. COLEMAN, JR., FRIEDRICH H. DOERBECK, MEMBER, IEEE, DON W. SHAW, AND WILLIAM R. WISSEMAN, SENIOR MEMBER, IEEE

***Abstract*—Multiple-mesa GaAs Read diodes have been incorporated in a single-stage microstrip amplifier module at *X* band. Stable CW amplification with an output power of 12 W at 4-dB gain and 23.5-percent power-added efficiency has been demonstrated. Design considerations for the amplifier circuits along with the microwave performance results are presented.**

I. Introduction

EFFICIENT amplification of microwave power using GaAs single-drift IMPATT and Schottky–Read diodes has been reported for operating frequencies from *C* through *Ku* bands [1]–[5]. CW output powers on the order of ~5 W and efficiencies greater than 20 percent with 4–5-dB gain have already been achieved at *X* band for a single-stage single-mesa microstrip amplifier [4], [5]. This paper reports the development of high power (10–12 W) high-efficiency (>20-percent) Read-diode amplifiers suitable for applications as the output stage in an amplifier chain at *X* band [6]. A description of the techniques for active device evaluation and the approach for the power amplifier design is given. Circuit description and microwave performance are also presented.

II. Device Characterization

The diodes used in the amplifiers reported here were plated heat-sink multiple-mesa devices fabricated with plated Pt Schottky barrier contact to the active surface of the GaAs wafer [7]. A high-low doping profile is used with the high layer doped about 6×10^{16} cm^{-3} and the low layer doped about 2×10^{15} cm^{-3} as determined by differential capacitance versus voltage analysis. To obtain high efficiency a surface layer thickness of about 0.5 μm before metallization of the wafers is necessary. A post fabrication burn-in at 350°C was utilized to react a small additional portion of the surface high layer with the Pt contact. Since the Pt/GaAs reaction is diffusion limited [8], the 350°C burn-in will slow the rate of reaction for improved device reliability.

The devices used in the amplifier development effort were composed of individual mesas whose diameters were about 6 mil. Initial microwave evaluation of the diodes was performed in the conventional waveguide hat circuit with packaged single-mesa devices. Efficient oscillation over a wide frequency spectrum was observed. Devices could be tested at frequencies as high as 13 GHz and showed efficiencies of 20 percent with power in excess of 1 W.

To design an optimum amplifier circuit, it is essential to characterize the diode in a microstrip circuit under large-signal operation to ensure proper harmonic terminations. Although the use of a network analyzer has been a common practice to measure the small- and large-signal impedance of a Read diode, it is not completely satisfactory for characterizing the large-signal operating characteristics because of the fixed harmonic impedances (~50 Ω) of the measuring system. Due to the nonsinusoidal RF waveforms of the diodes, it has generally been observed that the high-power high-efficiency operation of Schottky–Read diodes requires special attention to the circuit impedances at the subharmonic and harmonic frequencies in addition to the provision of optimum loading at the fundamental frequencies. It has also been determined empirically that circuits with relatively low harmonic impedances are less susceptible to the premature power saturation effect and to the parametric instabilities [9]–[12].

In an effort to understand the large-signal behavior of GaAs high-low Schottky–Read diodes and to demonstrate the possibility of a high-power high-efficiency operation with no discontinuous jumps with the input dc level, a microstrip oscillator circuit has been built with special attention to the harmonic and subharmonic impedances. The detailed circuit topology will be described later. It suffices to say that using this basic circuit topology oscillators with output powers of 8–10 W in the 8–10-GHz frequency range can be achieved. Fig. 1 shows the power-efficiency characteristics of a three-mesa diode operating in one of the *X*-band microstrip circuits. An output power of 8 W with 23-percent efficiency has been achieved at 9.5 GHz. An edge-coupled microstrip dc block is incorporated in the oscillator circuit, eliminating the requirement for a discrete blocking capacitor.

By designing an oscillator with known impedance versus frequency characteristics, the impedance of the diode can be obtained as the negative of the circuit impedance. The characterization of the Read diode in a microstrip oscillator circuit not only predetermines the

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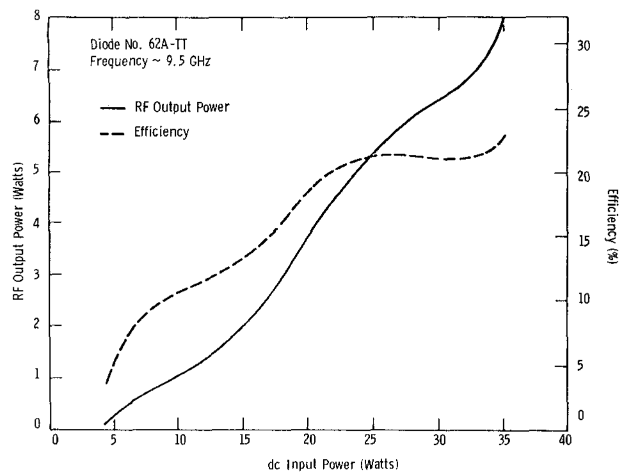

Fig. 1. Microwave performance of a Schottky–Read oscillator.

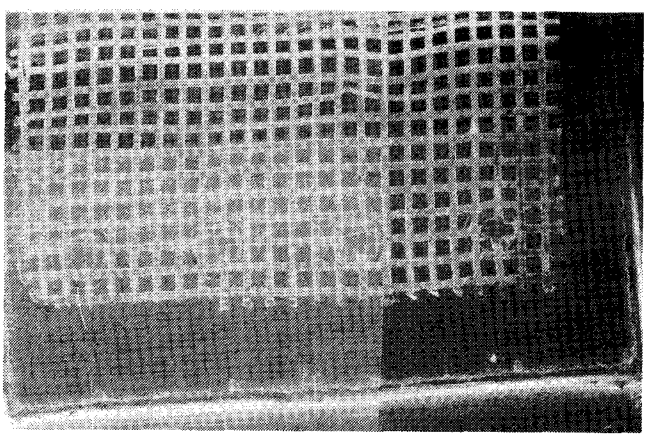

Fig. 2. SEM picture showing a four-mesa Schottky–Read diode bonded to a microstrip circuit with a gold mesh ribbon.

power-generating potential of a diode to be used in an amplifier circuit but also provides crucial information with regard to the proper impedance level required for reflection amplifier operation.

The diode size and the interconnection scheme for multimesa diodes can also be optimized for the amplifier design. To achieve the highest possible output power, either a single-mesa diode with a large junction area or a multiple-mesa diode with the same total area may be used. Because of its thermal advantage, the multiple-mesa approach has been pursued for this work. Fig. 2 shows a scanning electron micrograph (SEM) of a four-mesa diode bonded to a microstrip circuit. Each mesa has a nominal diameter of 6 mil. The separation between two mesas is approximately 12 mil. This distance represents a compromise between the avoidance of thermal crowding and the requirement for tight electrical coupling. A gold-plated copper block is used for mounting the diode. To reduce the bondwire inductance, a gold mesh ribbon is used for interconnecting the mesas and bonding to the microstrip circuit. The bonding scheme is shown in Fig. 2.

III. Amplifier Circuit Design

In addition to the diodes, the key amplifier components are the diode carriers, dc block, the microstrip circulators, and the circuit topology. With the exception of the circuit topology, the details of the amplifier components design have been reported elsewhere [2] and will not be repeated here.

The circuit impedance is designed to present the desired load impedance at the fundamental frequency based on the required bandwidth, gain, and output power. In addition, careful consideration also must be given to the circuit impedances presented to the diodes at subharmonic frequencies. High-power IMPATT- or Read-diode amplifiers sometimes exhibit the parametric oscillation (suck-out) effect at high-drive levels due to an improperly designed circuit. This effect is generally characterized by a sharp dip in the gain-frequency response. Examination of the frequency spectrum shows that a strong parametrically induced signal appears at one-half the signal frequency. This spurious signal has the effect of robbing the power from the desired signal frequency and often results in a premature power saturation of the amplifier. The theory of the parametric instabilities has been treated by a number of authors [9]–[12]. It has been shown that a relatively low value of load impedance will have to be presented to the diode at the subharmonic frequencies to eliminate this problem. Generally, two approaches can be taken. The first approach is to use a half-wave open stub placed near the diode. This stub will then present a short circuit to the diode at the subharmonic frequencies and, hence, prevent the parametric oscillation from building up. The second approach is to design a microwave circuit that will have the desired circuit impedances at both the fundamental and subharmonic frequencies by taking into consideration the out-of-band characteristics of the circulator, the dc block, and the matching network. The second approach has been used successfully at Texas Instruments for high-power high-efficiency GaAs Read amplifiers at X and Ku bands.

Fig. 3 shows a microstrip circuit topology that is particularly well suited for the high-power high-efficiency application of a GaAs Schottky–Read diode operated either as a free-running oscillator or as a reflection amplifier. This circuit consists of an edge-coupled line, serving both as a dc block and as a part of the matching network, and three series transformers. An open-circuited shunt stub is used as shown in the figure. The characteristic impedances of the transmission lines and their associated lengths are also indicated. The required even- and odd-mode impedances of the edge-coupled section correspond to a width-to-height (W/h) ratio of 0.2 and a spacing-to-height ratio of 0.1 with alumina as the dielectric substrate ($\epsilon \sim 9.6$). A lumped inductance of 0.2 nH corresponding to the minimum achievable bondwire inductance in the mounting configuration is shown as an integral part of the circuit. Fig. 3(b) shows a Smith-chart plot of the impedance locus of the circuit shown in Fig. 3(a). While the Smith chart indicates a circuit resistance of 2–4 Ω for

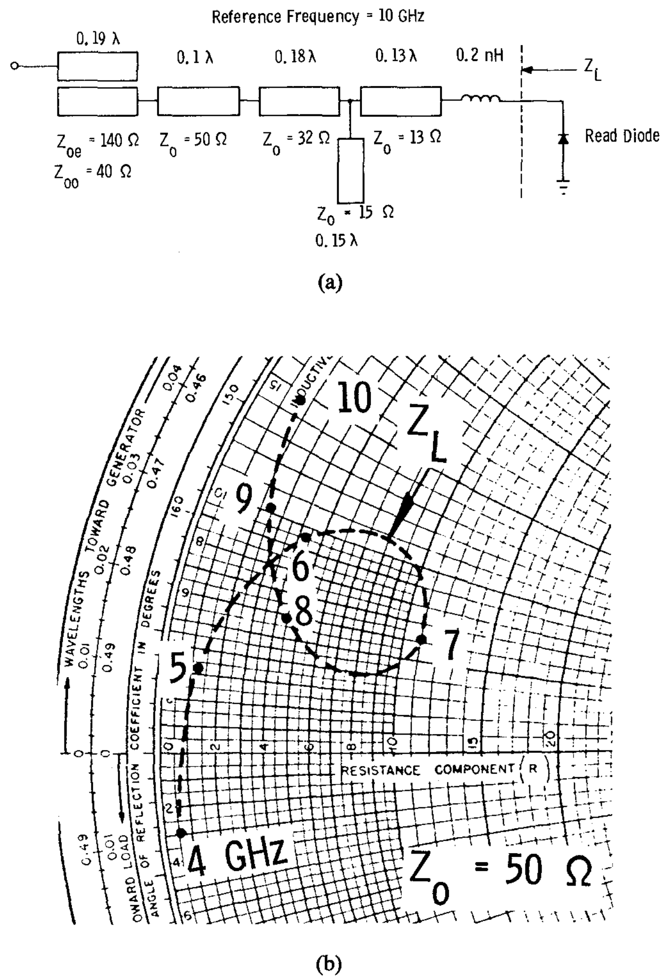

Fig. 3. Microstrip circuit for Schottky–Read oscillator or amplifier operation. (a) Circuit topology. (b) Impedance locus.

frequencies between 8 and 10 GHz, even lower impedance (~1 Ω or less) can be achieved by changing the characteristic impedances shown. For this purpose, an array of 10-mil by 10-mil tuning pads adjacent to the transformer sections has been provided on the microstrip circuit. By selective bonding of these pads with gold straps, a very wide range of circuit impedances with the desired reactance slope parameters can easily be obtained. This makes it possible to use the basic circuit topology shown in Fig. 3(a) for both oscillator and amplifier operation. A significant feature of the circuit shown in Fig. 3 is that it provides a very low impedance at the subharmonic frequencies (4–5 GHz). This is responsible for the immunity of this circuit to the large-signal parametric instabilities or the "suck-out" effect commonly observed in high-power IMPATT/Read-diode amplifiers. It should be noted that the impedance locus shown in Fig. 3(b) was obtained with a 50-Ω load impedance at all frequencies. Subsequent microwave impedance measurement of the MIC circulator-circuit combination shows a circuit impedance locus similar to that shown in Fig. 3(b), indicating that, for the MIC circulator used, deviation of the circulator input impedance from 50 Ω is not severe at the subharmonic frequencies.

One of the major problems to be overcome for the Read amplifier is the large change in diode negative resistance that accompanies an increase in the input drive level. It has been observed that the high-power high-efficiency mode of operation can be achieved only with a substantial RF voltage swing across the diode accompanied by a large dc current modulation. This is due to the fact that depletion width modulation plays an important role in high-efficiency operation [13]. The circuit impedance required to maximize the power-added efficiency at large-signal drive conditions and to produce a gain of 6 dB will result in a small-signal gain in excess of 20 dB. Because of large-signal rectification effects, the dc bias load line will determine the ultimate operating point of the diode with a given quiescent bias point. Use of a low value of bias resistance to reach the optimum large-signal bias point is desirable because the gain at small-signal levels is much lower because of lower current. Such a scheme has been used successfully in a *Ku*-band high-power Schottky–Read amplifier for minimizing the small-signal amplifier gain [3].

A bias load line as low as 10 Ω has been used for the *X*-band amplifiers reported here. The use of low resistance in the bias circuit not only reduces the small-signal gain of the amplifier but also keeps the bias circuit losses to a minimum. Although, theoretically, the low value of bias resistance used may not be compatible with the requirement to minimize the bias line oscillations caused by RF signal-induced low-frequency negative resistance, no such undesirable oscillations have been observed experimentally [14]. This could result from a fortuitous loading of the diode at the fundamental and harmonic frequencies which may have the effect of reducing the low-frequency RF induced negative resistance. In some cases, however, the use of ferrite beads on the bias leads was necessary to eliminate the bias line oscillation at MHz frequencies.

IV. Module Integration and Performance

Having perfected a microstrip circuit design for the Read diode, it can be easily combined with an MIC circulator to obtain the completely integrated single-stage amplifier module as shown in Fig. 4. Its dimensions are 1.3×0.8×0.6 in. Two separate substrates, one each for the circulator (0.4×0.6×0.020 in) and the amplifier circuit (0.6×0.6×0.01 in) are used. Because of the difference in the thickness of the ferrite and the alumina substrates, a 10-mil step is provided on the amplifier housing. A silver-based conductive epoxy is used to mount the substrates on the aluminum housing. A SmCo permanent magnet (0.250 in in diameter and 0.125 in in thickness) located beneath the circulator disk provides the necessary magnetic bias. The optimum field strength is achieved with a 0.020-in thick shim. A quarter-wave high-low impedance section provides the necessary bias choke. Input/output SMA connectors and a bias pin are also

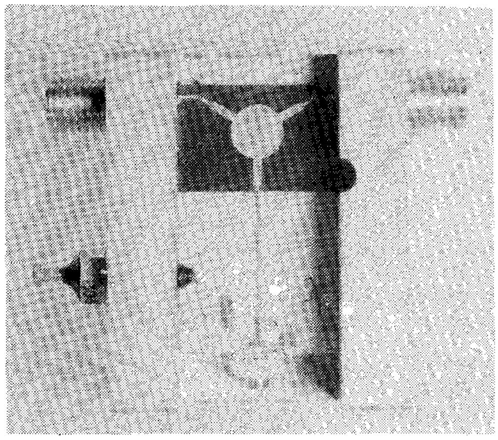

Fig. 4. Schottky–Read-diode amplifier module.

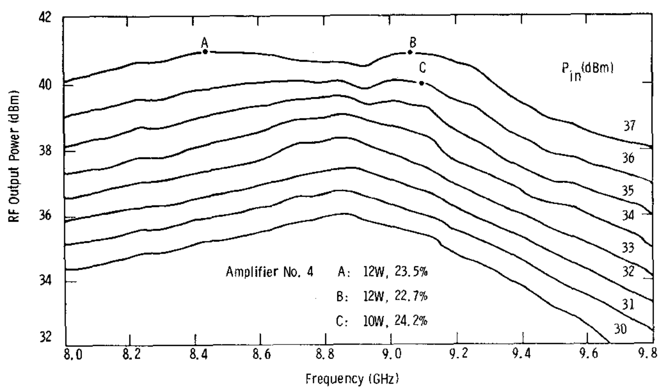

Fig. 5. Output power-frequency response of amplifier module number 4.

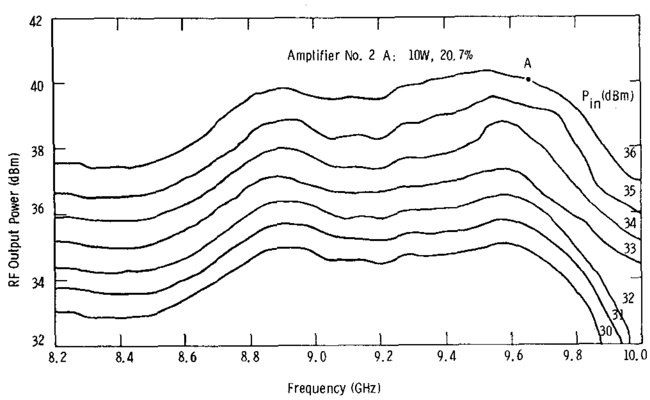

Fig. 6. Output power-frequency response of amplifier module number 2.

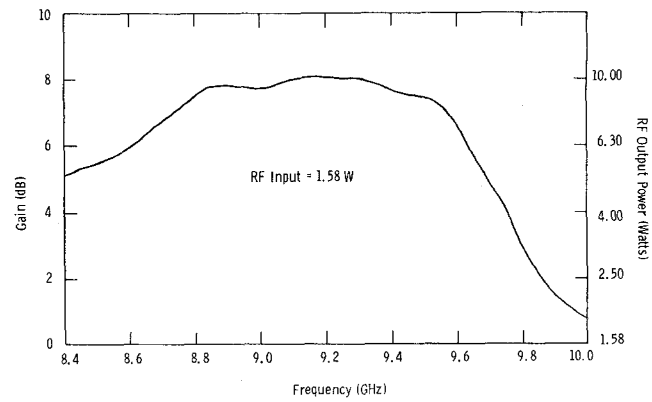

Fig. 7. Gain-frequency response of a two-stage 10-W Schottky–Read amplifier.

shown in Fig. 4. The inner surface of the module cover is coated with a thin layer of lossy material (ECCOSORB) to prevent "box" resonance or any other higher order propagation modes associated with the amplifier dimension.

With the module described above, several single-stage Schottky–Read amplifiers were developed. Depending on the number of mesas used, these amplifiers are capable of delivering output powers of 5–12 W at X band with 3–5-dB gain and 17–25-percent power-added efficiency. Figs. 5 and 6 show the output power-frequency response of two of these amplifiers. RF input powers from 1 W (30 dBm) up to 5 W (37 dBm) are also indicated in each figure. 10–12 W of output power with more than 20-percent efficiency at 4-dB gain can be achieved. Selected operating points are indicated along the response curves of the amplifiers to show the corresponding output power and efficiency. The highest power-efficiency-gain combination is obtained with module number 4, which shows an output power at 4-dB gain of 12 W with 23.5 percent at 8.4 GHz. The highest efficiency of 24.2 percent also is obtained with this same amplifier at 9.1 GHz with 10-W output and 4-dB gain. These amplifiers generally operate with a 1-dB bandwidth in excess of 1 GHz. The operating voltage is on the order of 45–50 V with a dc current at the highest RF output power of between 500 and 800 mA.

With an input RF drive of from 30 to 33 dBm, the gain generally increases to 5–7 dB with a reduction in power-added efficiency. With the constant voltage power supply adjusted for a value corresponding to that required for the optimum operating point of the amplifier and with a 10-Ω resistor as the bias load line, the output power-frequency response curves shown in Figs. 5 and 6 were obtained for different RF input levels. Because of the large-signal rectification effects, neither diode voltage or diode current is kept constant in these curves. However, with a constant supply voltage applied, the diode current increases with a corresponding drop in operating voltage along the 10-Ω load line as the RF signal level is increased. In most of these amplifiers, a spurious oscillation with an output level of 20–25 dBm generally exists when the input RF drive is removed completely. This is due to the high small-signal gain of the amplifiers discussed earlier. Although this spurious oscillation can be eliminated by reducing the bias voltage, subsequent operation of the amplifier with the same input RF drive will result in a smaller gain at reduced output power. To ensure unconditionally stable operation of the amplifier, an active bias network can be designed that will enable the amplifier to be biased at a reduced current level under small-signal conditions. A Schottky-barrier diode detector and an MIC directional coupler can be located conveniently at the input of the amplifier to detect the incoming RF signal and provide a video signal to the voltage regulator for tailoring the supply voltage to the amplifier as a function of RF input levels.

The above discussion shows that a single-stage four-mesa Schottky–Read amplifier generally has a gain of ~4 dB with an output power of 10 W. To increase the gain, several amplifiers must be cascaded. Fig. 7 shows the gain-frequency-response curve of a two-stage Schottky–Read amplifier. An output power of 10 W at 8-dB gain can be obtained at a center frequency of 9.1 GHz. The 1-dB bandwidth is 800 MHz (8.7–9.5 GHz). The overall efficiency is 18 percent. This lower efficiency value is due to the use of a lower efficiency amplifier in the first stage.

V. Conclusions

Stable amplifiers using GaAs Read diodes have been built that can deliver 10–12 W of CW power at *X* band at 4-dB gain and greater than 20-percent power-added efficiency. These single-stage amplifier modules (1.3×0.8 ×0.6 in) incorporate four-mesa Read diodes with power combining at the chip level. Small size, light weight, high power, and high efficiency are characteristic of these modules. Higher gain has been achieved with a two stage amplifier, and higher output power can be obtained with circuit level power combining. The results indicate that these solid-state power amplifiers have potential applications for TWT replacement in communication satellites and phased-array radar systems.

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