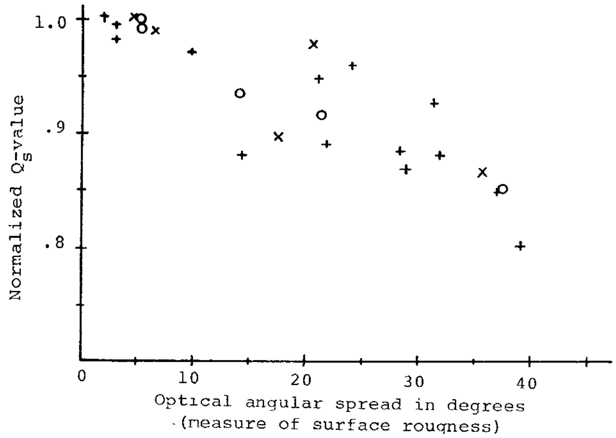

Fig. 4. Normalized Q_s values for the H-guide resonator.

the value of the resistance ratio (1.43 for mechanical polishing) dropped to about 1.3. The errors of the total Q-value measurements including the effects of cavity dismantling were about ±2 percent. The results clearly show the effect of surface roughness. They also indicate that other effects such as work hardening, oxidation, surface defects, and general surface effects also contribute to excess losses and thus contribute to the discrepancy between measured and computed values of the surface resistance.

ACKNOWLEDGMENT

The author wishes to thank Dr. L. Adair, R. Kraft, and M. D. Summerlin for their assistance in the investigation.

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Microwave Amplifier Using Several IMPATT Diodes in Parallel

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***Abstract*—IMPATT diode amplifiers are described that use several packaged diodes in parallel in a coaxial housing. With a pair of GaAs Schottky-barrier diodes, a power output of 8 W (input locking power equals 300 mW) was obtained at 4 GHz without exceeding safe operating temperatures. Similarly, three-diode circuits produced 15 W (locking power equals 3.5 W) at 4 GHz and >10 W (locking power equals 2.7 W) at 6 GHz under safe operating conditions. The maximum power obtained from the pair was 11 W. The maximum power obtained from the 4 GHz three-diode circuit was 21 W. The efficiency of the diodes at the maximum power level was 12–13 percent. The characteristics of the pair are compared with those of the individual diodes and it is concluded that this power-combining scheme is very efficient and should be economically advantageous.**

The scheme permits the total diode area utilized in a single cavity to be increased significantly beyond that which is practical in a single diode package. The use of parallel operation permits efficient heat sinking of each diode package, which is impractical with series operation. The technique employed has been shown to be suitable for extension to three or more diodes for higher power. It is required that each set of diodes be matched for similar I–V characteristics. With this constraint, the close RF coupling of the diodes in conjunction with appropriate stabilizing resistor(s) assures that the diodes operate cooperatively as a unit capable of being powered from a single current-regulated source.

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INTRODUCTION

The need for high-power IMPATT microwave amplifiers imposes the problem of economically combining diodes for maximum power output. Present schemes [1], [2], [5] combine oscillators rather than diodes. They require individual oscillator circuits and separate current-regulated power supplies. One alternative approach is to connect diodes in series in the same resonator circuit [3]. This approach is unrealistic for our projected power levels (>5 W) because of the heat-sinking problem [3]. Parallel connections of two and three diodes are therefore considered in this short paper. The individual diodes are designed as large in area as is practical taking into account thermal, bonding, and RF impedance considerations.

DESIGN CONSIDERATIONS

The purpose of this investigation was primarily to demonstrate the possibility of adding power by paralleling two packaged diodes. Ideally, this requires perfectly matched sets of diodes. This would require matching with respect to their breakdown voltage, susceptance, and negative conductance. These three requirements are not necessarily related.

Preliminary tests showed that a breakdown voltage range ±1 V was practical and acceptable for the experiment, pending further investigation. No special requirements were imposed on the diode impedance. The oscillator circuit, which was a coaxial circuit for low Q, had to satisfy several requirements.

1) *Diode Mounting*: The diodes had to be mounted such that the coaxial transformer could slide into very close proximity of the diodes to permit tuning of large-area (high-capacitance) units.

2) *Bias Circuit*: The bias should be introduced in such a way as to directly complement the impedance seen by the diode and to avoid uncontrollable impedance transformation out of the operating band of the amplifier.

3) *Amplifier Mounting*: The coaxial housing was to be mounted in the plane of the suspended stripline to permit ready integration into the stripline housing and eventual replacement of the hybrid coaxial-stripline configuration by an all-stripline design. This design would take advantage of the whole amplifier housing as a heat sink.

COAXIAL HOUSING

The coaxial part of the amplifier is shown in Fig. 1. The diodes were arranged in V shape rather than parallel to minimize the series inductance of the circuit and to facilitate a simple connection between the center contact of the diodes and the coaxial center conductor. Bias was introduced in the stripline portion of the amplifier, external to the coaxial housing.

Initial tests of the diode pair were made without the stabilizing chip resistor. This resulted in a nonsymmetrical mode of oscillation

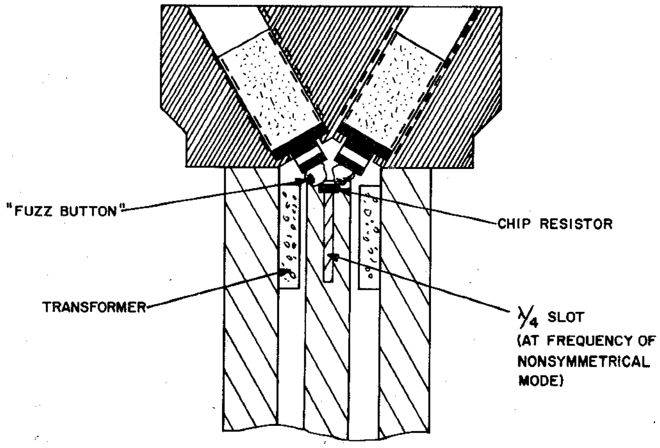

Fig. 1. A 7-mm coaxial IMPATT oscillator using IMPATT pair.

between the two diodes at about 5.1 GHz. This nonsymmetrical mode coupled only weakly to the load and was suppressed by a small low-power chip resistor soldered across a slot in the coaxial line [4], [5]. Its value was chosen to exceed the combined negative resistance of two series-connected diodes. The slot was dimensioned to be $\lambda/4$ at the frequency of the nonsymmetrical mode. The "fuzz buttons," which are compressed balls of very thin wires, assured a good pressure contact in the experiment.

The three-diode housing was identical to the one shown in Fig. 1, except the diodes were mounted on 120° centers, maintaining rotational symmetry. The center conductor had a three-way $\lambda/4$ slot and the mode-suppression circuit was composed of three resistors delta connected across the top of the center conductor.

EXPERIMENTAL RESULTS

The experiments were done with noncommercial GaAs Schottky-barrier IMPATT diodes. Data for the 4-GHz pair are listed in Table I. For the 4-GHz three-diode experiments an additional diode, similar to those listed in Table I, was used. Power versus current curves for each diode of the pair, measured for different values of the characteristic impedance of the coaxial transformer, are presented in Fig. 2.

To find the transformer for optimum power output of the diodes a set of power versus current curves was generated. The two-diode circuit was least susceptible to parametric oscillations [6] when the 10.6-Ω transformer was used. With this transformer, 11.1 W of output power was obtained from the diode pair (Fig. 3). This corresponds to an overall dc-to-RF efficiency of 12.3 percent. The diodes have an approximate thermal resistance of 5°C/W. This implies a junction temperature of 225°C at 25°C ambient for 5.5 W per diode. A practical junction temperature of 190°C at 25°C ambient permits about 4.3 W per diode assuming 12-percent efficiency.

It is very difficult to compare the data from the single diodes with the measurements done on the pair. The ultimate proof that 100-percent power addition from the two diodes is obtained would require their operation at the point of optimum power-capability for both diodes. This is not feasible with the present circuit configuration because of instabilities at the very high power levels for some transformers. An indication of the excellence of combining is given by the efficiency (including resistor loss) of the pair (12.3 percent) which is close to the observed maximum efficiency of the individual diodes (13.3 percent). Taking into account that only transformers variable in steps of 20 percent were available the close agreement is excellent.

Noise measurements as described by Tatsuguchi *et al.* [7] were made on the individual diodes. These can be compared with the power versus noise curves for the diode pair with an input locking power of 300 mW as exhibited in Fig. 4 where the curves for one of the individual diodes with 150-mW input are shown for the purpose of comparison. The noise figure at higher power levels is very sensitive to small changes in transformer impedance, but even with this restriction, at the same noise figure, points of 3-dB power addition (doubling of power) can be found at the high power levels for the pair as compared to the individual diode.

TABLE I
4-GHz DIODES

	Diode 1	Diode 2
Breakdown voltage V		
at -10 μA:	115 V	115 V
-1 mA:	118 V	116 V
-10 mA:	120 V	120 V
Zero bias capacitance C_0:	18.8 pF	19.2 pF
Breakdown capacitance C_B:	1.5 pF	1.6 pF

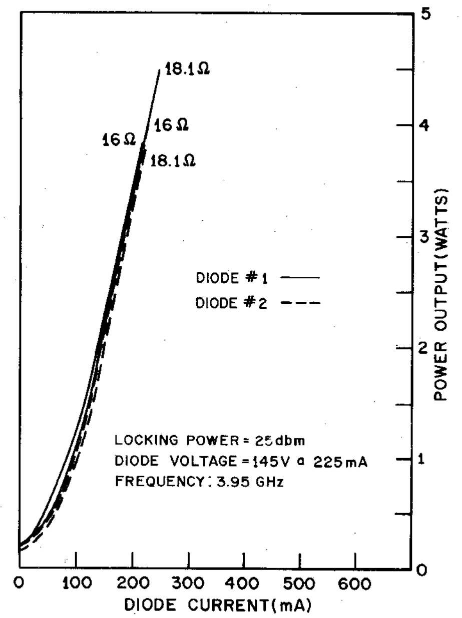

Fig. 2. Diode power output versus current.

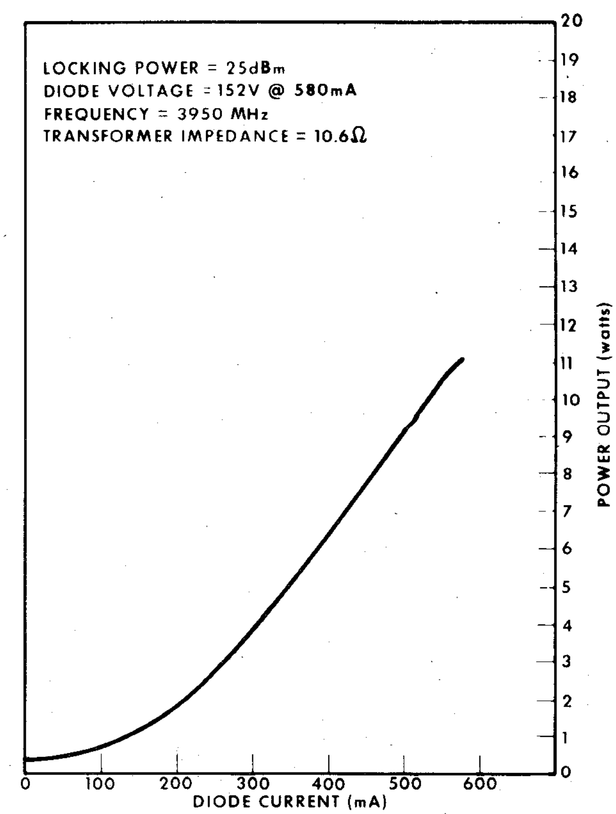

Fig. 3. Diode-pair power output versus current. Diodes 1 and 2.

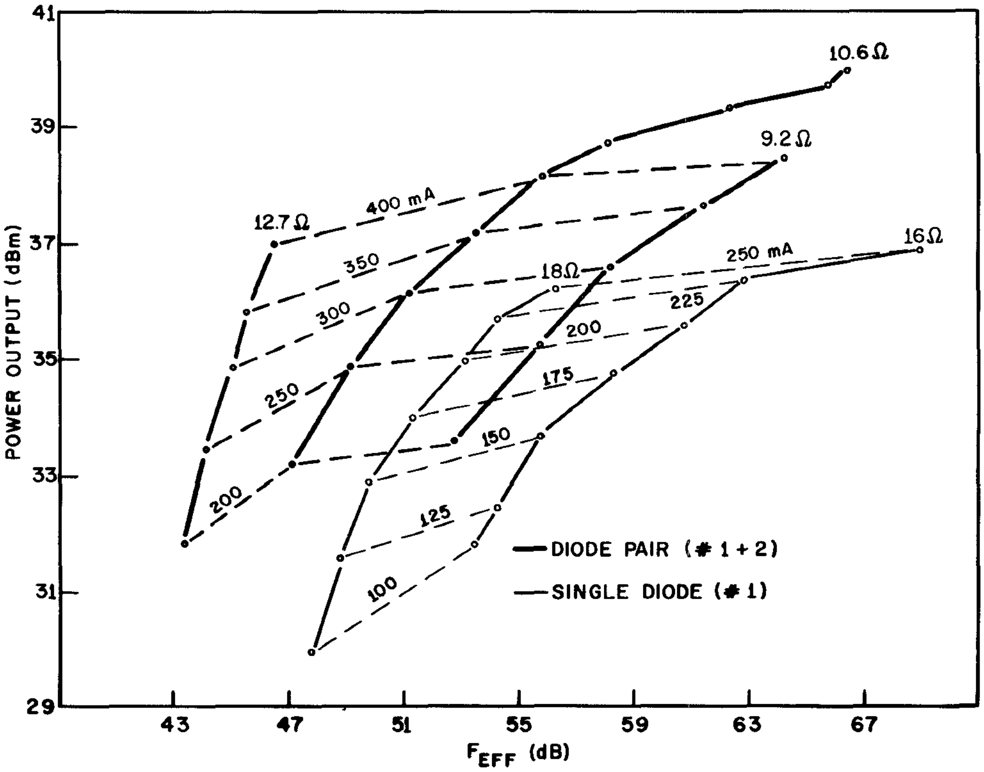

Fig. 4. Power versus noise for diode pair as compared to single diode.

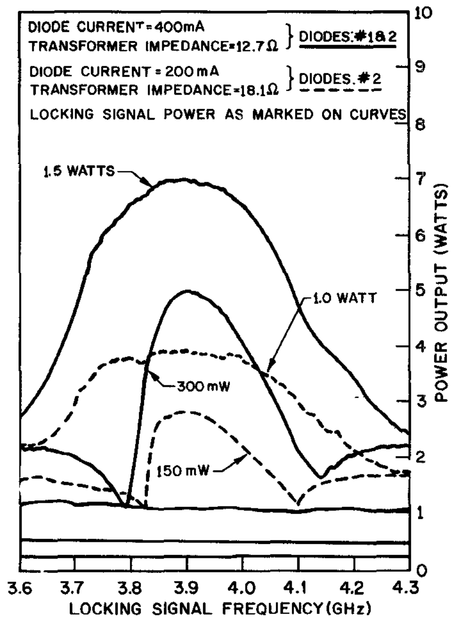

Fig. 5. Oscillator locking range for diode pair as compared to single diode.

For most applications it is important to know the locking range of the oscillator. The locking range increases with input power level and transformer value. An 18-Ω transformer was found to give acceptable noise-figure values for a possible application. The locking curves for the diode pair (Fig. 5) at the same input power level per diode and with a 12.7-Ω transformer show essentially the same locking bandwidth. It is noted that the 12.7-Ω transformer is approximately $1/\sqrt{2}$ times the 18-Ω transformer to assure similar per diode impedances in each case.

To demonstrate the feasibility of using more than two diodes in the parallel configuration, three-diode circuits were assembled for testing at 4 and 6 GHz. Power versus current curves were generated at each frequency (Figs. 6 and 7) using 9-Ω transformers. At 4 GHz, power output exceeding 20 W was obtained with a locking power of 3.5 W and an efficiency of 13.5 percent. However, with the diode junction temperature restricted to a safe level, the power output was 15 W. The 6-GHz circuit provided over 10-W output (input locking power equals 2.7 W) while restricted to safe operating conditions.

SUMMARY AND CONCLUSION

It has been shown that direct paralleling of diodes is possible in a very simple configuration. The transformer impedance levels are such that a translation of the scheme from coaxial to stripline seems feasible. There are two features of this scheme that should provide

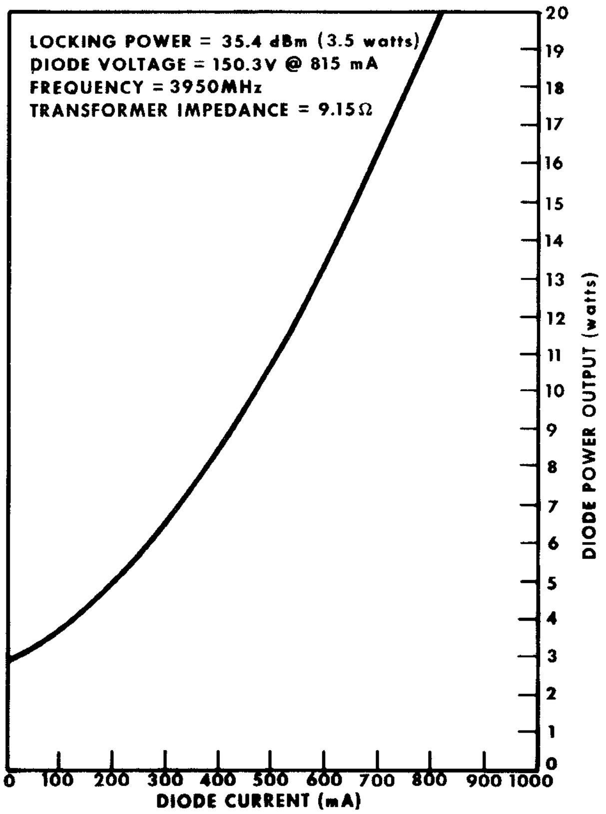

Fig. 6. Diode-triplet power output versus current. A 4-GHz amplifier.

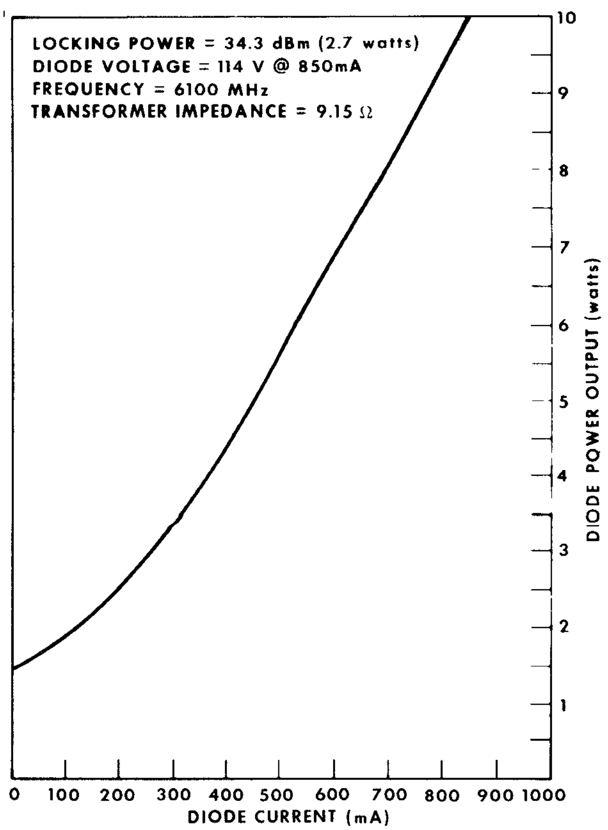

Fig. 7. Diode-triplet power output versus current. 6-GHz amplifier.

significant cost advantages: 1) use of a single tuned cavity with a single transformer, single dc supply circuit, and single set of harmonic filters for two or more IMPATT diodes, and 2) requirement of a single current-regulated source in place of two or more individually controlled current sources. Since the experiments were done with a very well matched pair and triplets of diodes, further studies concerning the necessary characteristics of the individual diodes to be grouped are required. Minor imbalances can be accepted if the amplifier performance is derated correspondingly. It has been shown to be feasible to extend this combining scheme to three or more diodes at both 4 and 6 GHz.

A possible disadvantage would be the unequal division of current for nonideally matched diodes which could necessitate some derating of the maximum dc power to assure acceptable reliability.

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A New Method for Measuring Properties of Dielectric Materials Using a Microstrip Cavity

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***Abstract*—A new nondestructive method has been developed for measuring the dielectric constant and the loss factor of a slab-type material using a microstrip cavity. The method, which uses a simple and rapid substitution procedure, yields accurate results and has a number of advantages over currently available techniques. Experimental details and the theoretical basis are explained and experimental data are presented.**

I. INTRODUCTION

A number of methods are currently available for measuring the dielectric constant ϵ_r and the loss factor tan δ of a material at microwave frequencies. One typical example is the method based on the measurement of the electromagnetic scattering from the dielectric sphere placed in free space [1],[2]. Another common technique is the use of waveguides or waveguide cavities, which are either partially or completely filled with the dielectric materials to be measured. The ridge waveguide method [3] falls into this category.

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