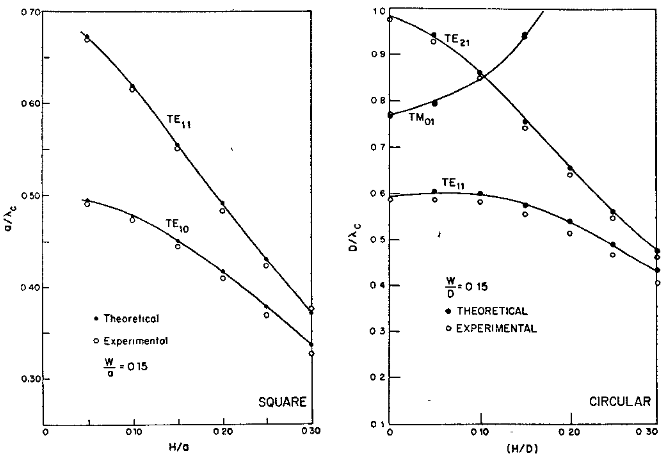

Fig. 8. Experimental versus computed modal cutoff frequencies for quadruple-ridged circular and square waveguide.

only excites the TE_{10} mode in a square waveguide and the TE_{11} mode in a circular waveguide, because all of the other modes shown have a null field at the center. When the coupling hole is moved to a corner, all the modes are excited. Typical outputs of a transmission sweep measurement for quadruple-ridged square and circular waveguide with center-hole and off-center-hole excitation are given in Fig. 7. The cavity length is such that there exist two fundamental-mode resonances in the frequency range of 2.5–4.0 GHz.

The relative amplitudes of the mode resonances depend upon the location of the coupling hole. The asymmetrical modes are difficult to excite because their coupling coefficients are small compared to those of the symmetrical modes. The photographs for off-center-hole excitation show that the asymmetric mode amplitude is considerably smaller than that of the symmetrical mode. Therefore, it becomes easy to overlook some modes in an experimental study without *a priori* theoretical knowledge of their characteristics. We suspect that this is the reason why some of the published literature on the subject does not contain an accurate description of the modal spectrum. A recent paper [8] states that experimental results obtained by Clark [9] in 1971 agree with our results. However, the figure presented in support of this statement shows increasingly larger disagreement in the TE_{21L} cutoff for H/D values greater than about 0.15 to the effect that a 2:1 bandwidth is eventually reached. Our results show this limiting bandwidth to be almost zero. The error in Clark's work could be due to confusing the TE_{21L} mode with the TE_{01} mode (see Fig. 4 above), especially if the ridge width was large.

The theoretical and measured cutoff frequencies for the TE_{10} and TE_{11} modes for quadruple-ridged square waveguide, and for the TE_{11}, TM_{01}, and TE_{21} modes for quadruple-ridged circular waveguide are plotted in Fig. 8. The small circles, representing measured values, and the solid lines, representing computed values, indicate excellent agreement between theory and experiment.

VI. CONCLUSION

It is concluded from this study that quadruple-ridge loading does not broaden the bandwidth of square waveguides and only moderately broadens the bandwidth of circular waveguides because the higher order modes are heavily affected by the ridge loading.

However, the fundamental mode is a symmetrical mode, and the next higher order mode is an asymmetrical mode. The asymmetrical mode may not be excited for some applications, for example, when the waveguide is used as a feed in a reflector antenna system. Then, TM_{01}-limited octave bandwidths may be obtained, as in fact was shown to be the case [4]. But in phased array antenna applications asymmetrical modes may be excited when the beam scans off-boresight and care should be taken to guard against possible mode resonance coupling phenomena such as blind spots.

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Experimental Study of Series Connected TRAPATT Diodes

K. REED GLEASON, MEMBER, IEEE, C. T. RUCKER, MEMBER, IEEE, N. W. COX, MEMBER, IEEE, A. C. MACPHERSON, SENIOR MEMBER, IEEE, AND ELIOT D. COHEN, MEMBER, IEEE

***Abstract*—The results of experiments using TRAPATT diodes connected in series at 0.5, 2, and 8 GHz are described. These experiments demonstrate that successful series operation of TRAPATT's at frequencies up to at least 2 GHz can be achieved in a configuration suitable for long pulsewidth or CW operation. An 8-GHz operation of series stacked TRAPATT's yielded high power outputs at the same efficiency achieved with single devices but no well heat sunk configuration was found that yielded good efficiency.**

INTRODUCTION

The series connection of TRAPATT diodes is a desirable way to obtain increased power output over that afforded by a single device, particularly because this connection results in an increased impedance level. In the past, TRAPATT diodes have been operated in series-stack configurations at *D* and *E* bands to generate high peak power outputs with good efficiency [1], [2]. Stacking is attractive because parasitic elements which interfere with TRAPATT operation are minimized. Unfortunately, long pulsewidth and/or CW operation are difficult to achieve with this arrangement because of problems associated with heat sinking of the upper diodes in the stack. In the experiments described here other configurations were used to demonstrate that successful series operation of TRAPATT's can be achieved even with substantial parasitic capacitance and/or inductance present.

SERIES CONNECTION AT 0.5 GHZ

Two- and three-diode series connections of Fairchild FD-300 diodes were operated in the TRAPATT mode at approximately 500 MHz. These diodes are mounted in glass packages with pigtail leads. In the experiments, the series connection was made by simply soldering the leads together. The resulting interconnecting leads were approximately 165 mils long and 40 mils in diameter. The diodes were mounted in a modified GR 874-X insertion unit at one end of a conventional 14-mm diameter three-slug tuner.

Best results are summarized in Table I. In general, the series connected diodes gave better performance at higher currents than the single diodes. Note that at 1.8 A the 1,6 pair performed better than would be expected from scaling considerations; the efficiency doubled and the power increased by a factor of almost 6. The 9, 11, 12 triplet yielded 50 percent more than the sum of the powers at slightly re-

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K. R. Gleason, A. C. Macpherson, and E. D. Cohen are with the Naval Research Laboratory, Washington, D. C. 20375.
C. T. Rucker and N. W. Cox were with Sperry Microwave Components, Gainesville, Fla. 32601. They are now with the Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Ga. 30332.

TABLE I
RESULTS OF 500-MHz SERIES COMBINING EXPERIMENTS

Diode Number	D.C. Power Input (Watts)	Power Output (Watts)	Efficiency (%)	Operating Voltage (Volts)	Operating Current (Amps)
1	159	32	20	159	1
6	133	33	24	148	.9
9	133	33	24	148	.9
11	119	33	24	149	.8
12	132	39	29	132	1
1 & 6	459	177	39	255	1.8
1 & 6	408	147	36	255	1.6
1 & 6	344	67	19	255	1.35
9 & 11	414	71	17	276	1.5
9, 11 & 12	774	151	20	430	1.8

duced efficiency and again the current could be nearly doubled. The output of the 9, 11 pair approached the power sum, again with increased current.

These experiments are particularly interesting because prior attempts to operate FD-300 diodes in series were unsuccessful [3]. It is concluded that series connection of up to three TRAPATT diodes at 0.5 GHz works better than can be predicted by simple scaling.

SERIES CONNECTION AT 2 GHZ

Table II gives the best results obtained from series connection of complementary structure (n^+pp^+) TRAPATT diodes fabricated at the Naval Research Laboratory. In this case, it was not practical to measure the power output of diodes A and B, connect them in series, and measure the output of the pair. Instead, the pertinent RF parameters (power output, efficiency, etc.) of a group of single diodes from the same wafer were measured and shown to be nearly identical. Then a series pair was formed from diodes of the same slice. Fig. 1 indicates the arrangement used.

As in the 0.5-GHz experiments, the optimum current and power output were anomalously high. Note also that the optimum frequency of operation dropped slightly for the series connected diodes. In these experiments as well as for the pairs tested in the 0.5-GHz experiments, the series connected devices tuned easily. Similar results were also obtained for complementary-inverted structure (p^+pn^+) devices fabricated at the Naval Research Laboratory.

In another experiment, a complementary structure TRAPATT diode was connected in series with a complementary-inverted structure TRAPATT diode on the same heat sink. Even though the characteristics of the two devices were quite different, the series combination yielded 51-W peak power output with 29-percent efficiency at 1.8 GHz. Again, this was more than double the power output achieved with devices of either type operated singly with the same efficiency.

TABLE II
RESULTS OF E-BAND SERIES COMBINING EXPERIMENTS

	Power Output (Watts)	Efficiency (%)	Operating Voltage (Volts)	Operating Current (Amps)	Frequency (GHz)
Single	23.5	30	72	1.1	2
Pair	65	33	120	1.65	1.86
Pair	75	32	130	1.8	1.75

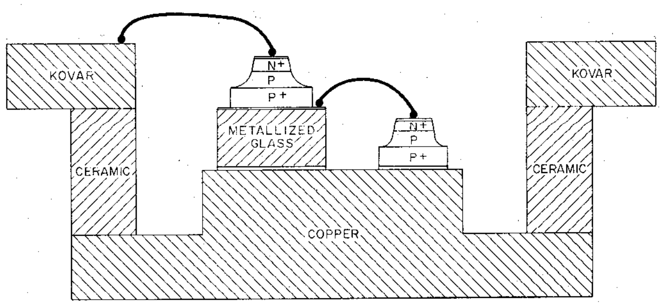

Fig. 1. 2-GHz series combining, identical-diodes, parallel heat sinking.

SERIES CONNECTION AT 8 GHZ

Various attempts at series electrical connection and parallel heat sinking on diamond were unsuccessful at I band; on the other hand, stacked diode configurations were successful. Experiments with both types of assemblies using diodes fabricated at Sperry Microwave Components are described below.

Stacking of mesa diodes was accomplished by soldering the diodes together in a conventional pill package normally used for evaluation of single mesa configurations. Performance data for the TRAPATT oscillators using stacked diodes are given in Table III. Typical single mesas of approximately 0.55-pF capacitance at -10 V exhibited efficiencies of 15–20 percent using the same material as the stacked diodes. Thus no efficiency degradation was observed with the stacked devices. Note that diode 21 used the smallest area devices ($\sim$1.12 pF/chip) and had the highest efficiency. Diodes 42, 20, and 26 had approximately equal areas for the individual chips ($\sim$1.50 pF/chip, $\sim$ 1.72 pF/chip, and $\sim$1.53 pF/chip, respectively) and exhibited similar efficiencies. The reduced efficiencies of the larger diodes are probably a result of the lower impedance level which emphasizes the significance of circuit losses. With conventional single mesa configurations, using the same material, the efficiency is less than 10 percent with diodes larger than 1.1 pF. Obviously, the higher impedance level of the series connected diodes is extremely beneficial to the generation of higher powers since larger area diodes can be utilized.

Numerous tests of series connected I-band devices, mounted thermally in parallel, were also performed. Since high efficiency oscillators had been achieved by placing a single diode on diamond in the center of an 80-mil ceramic sleeve, series connected diodes were mounted in this package as shown in Fig. 2. The best result obtained using this configuration was 6.74 W and 8-percent efficiency at 8.16 GHz. Although most of the configurations tested could be adjusted for TRAPATT operation, oscillations with greater than 10-percent efficiency could not be obtained. Some possible reasons for the low efficiency were: excessive dielectric loss in the diamond [4]; the small shunting capacitance ($C < 0.02$ pF) resulting from the metallization under the second or insulated diode or the inductance ($L < 0.1$ nH) introduced by the interconnecting gold wire.

Experiments were performed to investigate these potential problem areas. The tests included substitution of quartz in place of diamond to reduce loss and etching away of part of the metallization to reduce the shunt capacitance (Fig. 3). Neither of these changes resulted in improved efficiency.

Since large changes in both dielectric losses and shunting capacitance did not result in appreciably better (or worse) efficiency, it was tentatively concluded that the interconnecting wire inductance was at fault. To test this hypothesis the configuration of Fig. 4 was assembled so that a small inductor was inserted between the two diodes of the stacked pair arrangement previously used to obtain high efficiency TRAPATT. After much tuning, this assembly could be made to oscillate at 6.4-GHz 6-W peak output and 6.4-percent efficiency. Other suspended assemblies either did not oscillate at all or provided even lower efficiency. This experiment appeared to support the conclusion that low efficiency is caused by the small inductance between diodes. Nevertheless, one further experiment was performed using the previous configuration of Fig. 2. For this case, two mesa diodes were mounted as in Fig. 2, but each diode was tested separately before interconnection. Results were as follows.

	Power (W)	Frequency (GHz)	Efficiency (percent)
Diode 1	6.3	8.2	23.8
Diode 2	5.0	8.6	16.5

When the above diodes were connected in series, the results were as follows.

	Power (W)	Frequency (GHz)	Efficiency (percent)
Diodes (1,2)	8.0	6.5	6.1

This experiment eliminated the possibility that either diode used in the many series mesa pairs was faulty.

An interdigital metallization scheme for the series interconnection resulted in the best performance of diodes mounted thermally in

TABLE III
RESULTS OF *I*-BAND SERIES COMBINING EXPERIMENTS WITH STACKED DEVICES

Diode	No. of Mesas	Net Cj (pF)	Breakdown Voltage (Volts)	Output Power (Watts)	Frequency (GHz)	Efficiency (%)	Pulse Width (usec)
42	2	0.75 @ −20v	57	22.4	7.74	17.9	0.5
21	2	0.56 @ −20v	58	20	8.21	24	1.5
20	2	0.86 @ −20v	48	14.3	8.36	16.5	0.2
26	3	0.51 @ −30v	74	30	8.05	16	0.2

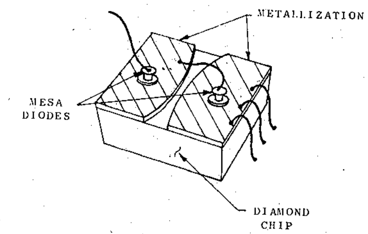

Fig. 2. Initial diamond heat sunk series pair.

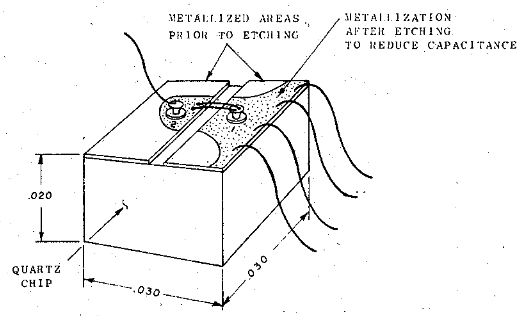

Fig. 3. Diode configuration for reduced capacitance and dielectric loss.

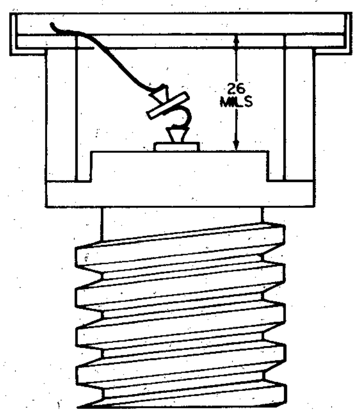

Fig. 4. *I*-band suspended series combining.

parallel. This approach was utilized in an effort to minimize the parasitic interconnect inductance. The top of the diamond was first etched with a "finger" protruding from one half of the metallization into the other half. The diode which was to be connected to ground was then mounted on the "finger" and a wide, low inductance gold strap (mesh or ribbon) was used between points *A*–*A* to contact the diode from both sides (Fig. 5). Numerous diode pairs were assembled in this configuration; none showed efficiency better than 12 percent. Geometric and heat-sinking restrictions did not allow further reduction in diode spacing.

As a final test of the techniques being used to fabricate the various test diodes discussed, series interdigital IMPATT diodes were fabricated. These diodes performed well, as expected from Josenhans' work [5].

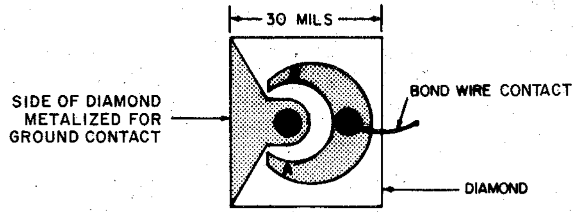

Fig. 5. Interdigital series pair. A wire mesh connecting points *A* to the top of the left diode is not shown.

CONCLUSIONS

The series connection of TRAPATT diodes for high efficiency operation has been shown to be feasible from approximately 0.5 to 8 GHz. In the lower frequency experiments, higher power outputs than would be expected from scaling considerations were often observed, accompanied by higher operating currents. This is probably due to the increased impedance associated with the series connection and is in agreement with the common experience that, all other things being equal, diode efficiency decreases with increasing area (decreasing impedance). At the lower frequencies, successful operation can be obtained with realistic parallel heat sunk structures suitable for long pulse or CW operation. This capability is yet to be demonstrated at *I* band.

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Characterization of Microwave Oscillator and Amplifier Circuits Using an IMPATT Diode Biased Below Breakdown

R. C. TOZER, R. CHARLTON, AND G. S. HOBSON

***Abstract*—A convenient laboratory technique is described to measure the internal circuit loss, the load conductance, and equivalent circuit susceptances of microwave diode oscillators and amplifiers using an IMPATT diode biased just below its breakdown voltage.**

In the characterization of the admittance of IMPATT diodes at *X*-band frequencies or above, two difficulties are commonly encountered. Transformation of measurable admittances through the

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The authors are with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, England.