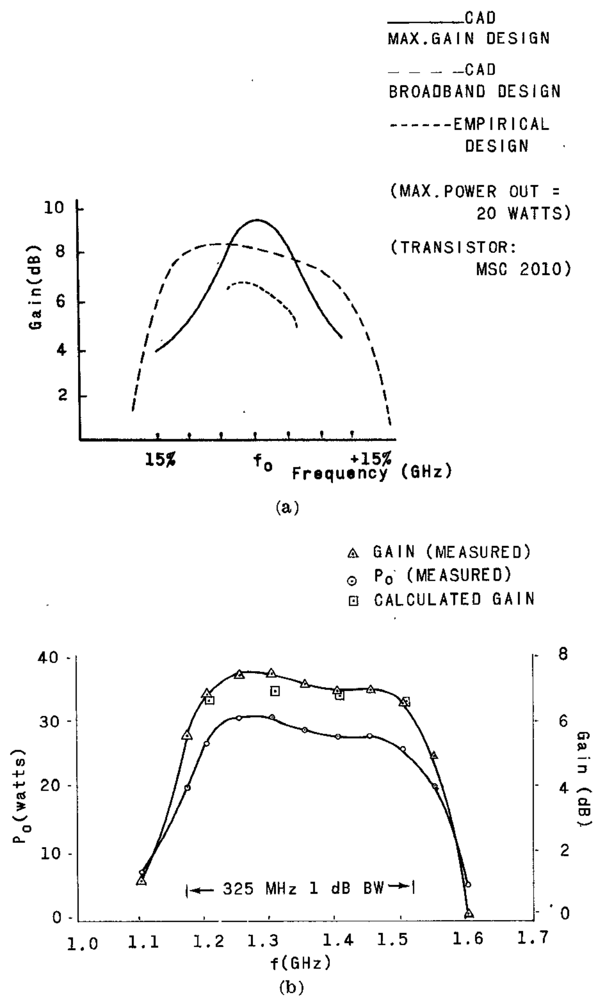

Fig. 3. (a) MSC 2010 CAD amplifier. (b) PH1520A CAD amplifier.

mismatch was rather modest (VSWR less than 1.4 with respect to maximum power operation). The total time required for the design, fabrication, and test of these amplifiers was less than one week each, and they required no experimental adjustments to meet the design criteria.

Subsequent effort will be applied to achieving the same degree of precision in the generation of matching networks for individual cells of multicell transistors. Methods will be sought for the generation of high-precision electrically reproducible networks for multicell matching (not necessarily lumped circuits), to minimize unit-to-unit variations in performance. Also, the intrinsic bandwidth limitations of various manufacturers' unit cells will be investigated to establish the degree of network complexity required to fully utilize the transistor's capability.

ACKNOWLEDGMENT

The authors wish to thank H. Heddings for his excellent measurement and fabrication support.

REFERENCES

[1] B. P. Hand, "Developing accuracy specifications for automatic network analyzer systems," *Hewlett-Packard J.*, vol. 21, p. 16, 1970.
[2] G. T. O'Reilly and R. E. Neidert, "Computer program for increasing the accuracy of impedance measurements performed with a Hewlett-Packard manual network analyzer," Naval Res. Lab., Washington, D. C., NRL Memo. Rep. 2676, Nov. 1973.
[3] R. E. Neidert and G. T. O'Reilly, "Very large impedance steps in microstrip," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-22, pp. 808–810, Aug. 1974.
[4] G. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures.* New York: McGraw-Hill, 1964.

X-Band TRAPATT Amplifier

N. W. COX, MEMBER, IEEE, C. T. RUCKER, MEMBER, IEEE, G. N. HILL, AND K. E. GSTEIGER, SENIOR MEMBER, IEEE

***Abstract*—The design and performance of broad-band TRAPATT amplifiers in *X* band are described along with a discussion of critical circuit parameters. Bandwidths of 10 percent and peak powers up to 38 W have been achieved using coaxial circuits with single and multichip diodes.**

INTRODUCTION

Wide-band TRAPATT amplifiers have been reported at frequencies between 1 and 5 GHz with bandwidths up to 15 percent [1]–[4]. At higher frequencies TRAPATT amplification has been achieved using an injection-locked oscillator [5], but no wide-band stable amplifier operation has been reported. This short paper describes an *X*-band pulsed TRAPATT amplifier which has demonstrated bandwidths of 10 percent with 5-dB gain. The design of the coaxial amplifier is described along with performance data on five units. Data are included for amplifiers utilizing stacked mesa diodes (higher peak power) and for ring diodes on diamond heat spreaders (improved thermal characteristics).

CIRCUIT DESCRIPTION

The coaxial amplifier circuit consists of the diode package and mount, a length of transmission line, a low-pass filter, and three tuning slugs. A cross-sectional drawing of the amplifier structure, which is similar to the *S*-band amplifier of [1], is shown in Fig. 1.

A five-section Chebyshev low-pass filter with a cutoff frequency of approximately 12 GHz was designed for the 0.162-in-diameter coaxial line. The filter, which consists of a series of alternating low- and high-impedance sections of transmission line machined on the center conductor, was fitted with a Teflon sleeve for support in the coaxial line. To adjust the phase of the harmonics reflected from the filter, the amplifier was constructed initially with spring fingers on the center conductor so that location of the filter relative to the diode could be optimized experimentally. The type of low-pass filter characteristic utilized in the amplifier does not appear critical, provided that adjustment of the filter spacing with respect to the diode is available.

Three 16.5-Ω slugs of varying lengths were positioned on the output side of the low-pass filter and were used to tune the amplifier response by adjustment of the load impedance at the fundamental frequency. These slugs had little effect on the loading at harmonic frequencies because of the low-pass filter. The principal effect of the three slugs was to smooth the amplifier passband; very little effect on the frequency of operation or bandwidth was observed.

The amplifier center frequency was adjusted by varying the corner inductance of the diode mount. This adjustment was accomplished with a series of tuning rings having various inner diameters as shown in Fig. 1.

In order to suppress oscillations in the amplifier, adjustment of the diode package parasitics was found necessary. Time domain computer simulations of the type reported by Carroll and Crede [6] for TRAPATT oscillators were performed to study the effect of variations in these parasitics for amplifiers. In these simulations the diode was represented by a current pulse generator in shunt with the diode depletion layer capacitance. The pulse generator represents the large, short duration current pulse induced by the charge carriers generated by the avalanche multiplication. This diode equivalent circuit was used in conjunction with a circuit model to compute in the time domain the diode voltage. The diode voltage was then analyzed for compatibility with the TRAPATT mode.

To establish confidence in the usefulness of this type of simulation, the load impedance of a TRAPATT oscillator was carefully measured using an automatic network analyzer and was used in the simulation

Manuscript received May 31, 1974; revised August 30, 1974. This work was supported by the Naval Electronic Systems Command under Contract N00039-72-C-0207.
N. W. Cox, C. T. Rucker, and G. N. Hill are with the Engineering Experiment Station, the Georgia Institute of Technology, Atlanta, Ga. 30332.
K. E. Gsteiger is with Harris Semiconductor, Melbourne, Fla.

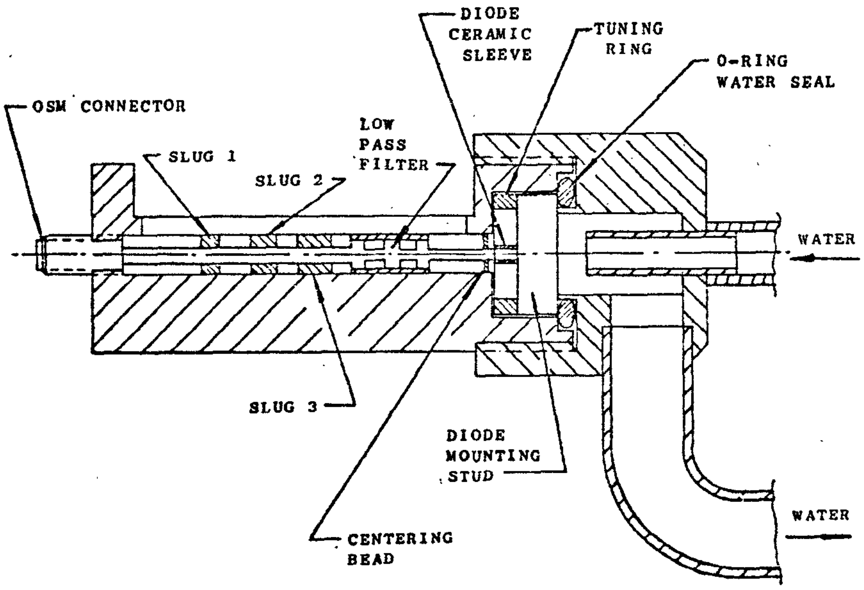

Fig. 1. *X*-band TRAPATT amplifier.

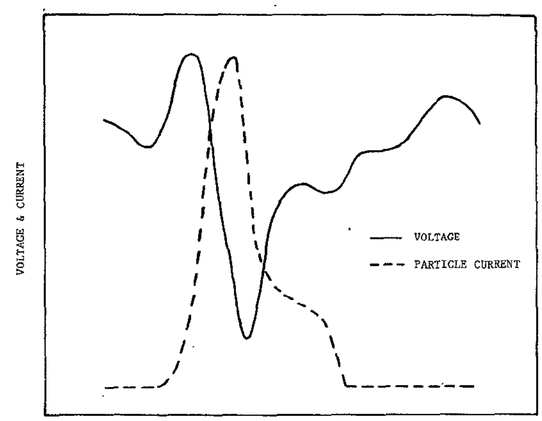

Fig. 2. TRAPATT voltage and current for computer simulation using measured load impedance.

in lieu of a modeled load. An *S*-band oscillator was utilized so as to allow measurement of at least five harmonic frequency impedances. The assumed impulsive current waveshape is shown in Fig. 2 along with the computed voltage response. This voltage waveshape displays the classical TRAPATT behavior as expected and correlates well with reported sampling scope measurements of voltage waveshapes of *L*-band oscillators.

To further assess the simulation, the effect of changing the diode package lead inductance for a TRAPATT oscillator was evaluated theoretically at *S* and *X* bands and was determined to agree well with experimental results. Values of lead inductance outside the optimum range identified resulted in lower triggering voltages as well as reduced dV/dt in the computer simulations; experimentally the effect was reduced efficiency.

The success of the simulation procedure for evaluation of TRAPATT oscillator circuits prompted its use with TRAPATT amplifiers. For amplifiers the peak overvoltage must be suppressed to prevent oscillations. Computer simulations revealed that with the type of amplifier circuit utilized the overvoltage was very sensitive to the diode package lead inductance. In order to suppress the trigger voltage, simulations, along with experiments, revealed that the inductance of a single 1-mil-diameter gold wire (0.94 nH) in the conventional short pill package was sufficient and the amplifier was stable. In most cases at *X* band the inductance of a pair of gold wires in the short pill package was insufficient to suppress oscillations and stable amplification could not be obtained. TRAPATT *oscillators* generally require much lower lead inductance (two–four wires or a wire mesh) thus making amplifier and oscillator package requirements incompatible for the type of circuits utilized in this investigation.

Adjustment of the package parasitics was also required for broad bandwidth operation. Small variations in the package parasitics resulted in large variations in amplifier bandwidth. Control of the package parasitics was achieved by varying the number and length of contact wires between chip and package as well as by varying the height of the chip with respect to the cap on the package. Package capacitance and inductance were both optimized experimentally for the amplifier.

These experiments on TRAPATT amplifiers indicate that package parasitics are the most critical circuit parameters in amplifier design. In some instances tuning of the circuit via adjustment of the package parasitics resulted in increases in amplifier bandwidth by a factor of two or more. Adjustment of other circuit parameters had little effect other than shifting center frequency and suppressing holes in the passband.

DIODES

Diodes utilized in the amplifier were of the p^+n-n^+ type. The n-type layer of 8×10^{15} donors/cm^3 was grown by vapor epitaxy on an arsenic doped substrate with a resistivity of 0.001 Ω-cm. Gas flow and growth parameters during the epitaxial process were adjusted to ensure an abrupt n-n^+ interface. The p^+-n junction was formed by diffusion of boron to a junction depth of 1.5 μm. The thickness of the n layer was adjusted so that the drift width ranged between 0.8 and 1.3 μm. Prior to metallization on the p^+ and n^+ faces the slices were thinned to a total thickness of 20 μm to reduce series resistance.

PERFORMANCE

Typical photographs of amplifier detected RF output pulse and spectrum are shown in Figs. 3 and 4, respectively. These photographs correspond to the amplifier center frequency of 8.25 GHz. Gain for this particular amplifier was approximately 5 dB. Rise and fall times for the applied RF pulse were approximately 20 ns and little or no deterioration of pulse rise time was observed due to the amplifier. The ripple shown on the RF output pulse was due to the input signal. A thirty-percent voltage drop and twenty-five-percent current rise were observed at the amplifier center frequency. At the 3-dB band edges the changes in current and voltage were normally somewhat less.

Performance data for 5 amplifiers are shown in Table I, where 2 sets of data are given. The diode performance includes only the one-port amplifier circuit whereas the module performance includes losses of the circulator, bias T, and omni spectra miniature (OSM) adapter, each of which is a separate component. Loss of these three components is approximately 0.6 dB per pass, yielding a total reduction in amplifier gain of 1.2 dB. Integration of these components into the amplifier structure should reduce the loss to less than 0.4 dB per pass which would result in a significant improvement in module performance.

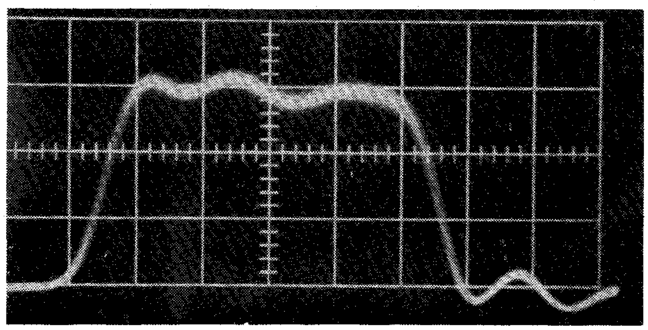

Fig. 3. Detected RF output pulse of amplifier (horizontal scale = 20 ns/cm).

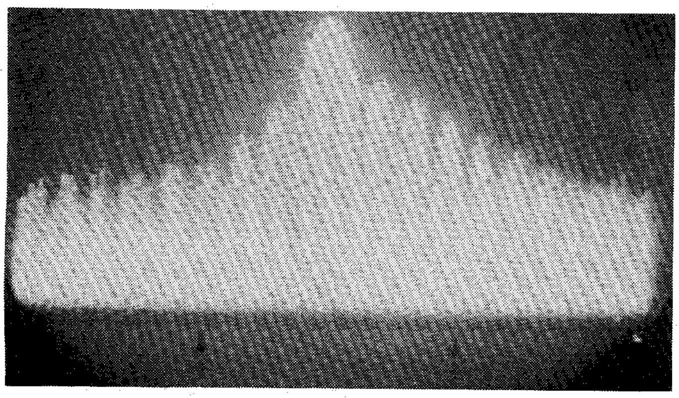

Fig. 4. Spectrum of amplifier RF output (log display).

TABLE I
PERFORMANCE DATA FOR TRAPATT AMPLIFIERS

UNIT #	DIODE DESCRIPTION	CENTER FREQUENCY (GHz)	BANDWIDTH 3 dB MHz	BANDWIDTH 1 dB MHz	DIODE Po (Watts)	DIODE Gain (dB)	DIODE Eff. (%)	MODULE* Po (Watts)	MODULE* Gain (dB)	MODULE* Eff. (%)
1	Circular Mesa	8.325	390	175	9.8	6.3	16.1	8.5	5.1	12.7
2	Stacked Pair of Circular Mesas	8.350	745	390	33.9	4.9	13.1	29.5	3.7	9.7
3	Ring on Diamond	8.290	855	525	8.3	5.0	12.0	7.2	3.8	8.9
4	Circular Mesa	8.140	730	330	8.2	5.35	15.4	7.2	4.15	11.7
5	Ring on Diamond	8.495	735	310	7.7	4.7	13.3	6.7	3.5	9.6

Note: Module performance includes losses of circulator, bias T, and OSM adapter.

The frequency resonse of amplifier module 4 is shown in Fig. 5. As seen from the curve, the gain is well behaved and smooth over the passband provided the amplifier circuit is carefully adjusted to eliminate spurious signals and holes in the passband. With a group of diodes closely matched in capacitance and fabricated from the same slice, the general amplifier response was found to be reproducible although fine tuning at the fundamental frequency was sometimes required to eliminate narrow-band holes in the passband and to achieve the maximum bandwidth.

Gain of the amplifiers varied between 4.7 and 6.3 dB with the higher values normally associated with narrower bandwidths. The maximum gain observed for this type amplifier was approximately 7 dB.

The saturation curve for amplifier module 1 is shown in Fig. 6. At power levels below the lowest value plotted, the diode dropped out of the TRAPATT mode. The dynamic range varies considerably from unit to unit, depending on tuning, but 6 dB below the maximum power point seems typical for the drop mode point. Above the maximum power point the gain falls off rather rapidly with increasing input power. At other frequencies within the passband the saturation characteristics vary somewhat and must be examined carefully while tuning.

Amplifier unit 2 contained a stacked pair of circular mesas connected in series for achieving higher peak powers [7]. Power output for the unit was 33.9 W with 4.9-dB gain and 13.1-percent efficiency over a 3-dB bandwidth of 8.9 percent. Another such unit demonstrated 16.2-percent efficiency with 38-W output and bandwidth in excess of 6 percent. Due to poor heat sinking of the upper mesa in the diode stack, the maximum pulse length for these oscillators was limited to approximately 1 μs at a 1-kHz repetition rate.

Two of the five amplifier modules contained ring-type diodes mounted on diamond heat spreaders [5], [8]. Efficiencies of the amplifiers utilizing rings on diamond were found to be consistently lower than for conventional circular mesas. This decreased efficiency of the rings was determined to result from a higher operating voltage (i.e., less voltage drop in the TRAPATT mode) and was present in both amplifiers and oscillators. The cause of the higher operating voltage appears to be related to the distributed nature of the ring diode whose circumference is an appreciable portion of a wavelength at higher harmonics. Multiple contact wires spaced around the ring affected performance considerably but did not result in any appreciable reduction in the operating voltage.

A comparison of amplifier efficiency with that of oscillators at the same frequency using similar diodes reveals a rather large reduction in efficiency for the amplifier. An exact comparison using the same diode for both oscillator and amplifier is not feasible due to conflicting package requirements for the two cases, but a reduction of 30 percent in efficiency is indicated for the amplifier. A similar reduction in efficiency has been observed with E-band amplifiers. An explanation for the reduction in efficiency is probably related to nonoptimum device loading. The circuit has been designed for low reactance slopes and consequently, the diode may not be properly matched at the fundamental and harmonic frequencies over the bandwidth of the amplifier. With the conventional five-slug oscillator structure extremely sharp reactance slopes are present and the load impedance can be properly matched to the diode at the single frequency of oscillation and its harmonics, thus yielding device voltage and current waveshapes compatible with higher efficiency.

CONCLUSIONS

Wide-band TRAPATT amplifiers have been demonstrated at X band for pulsed applications. For high peak power short-pulse requirements, stacked mesas resulted in significant increases in amplifier peak power. The tuning of TRAPATT amplifiers has been found to be critically dependent on diode package parasitics which must be

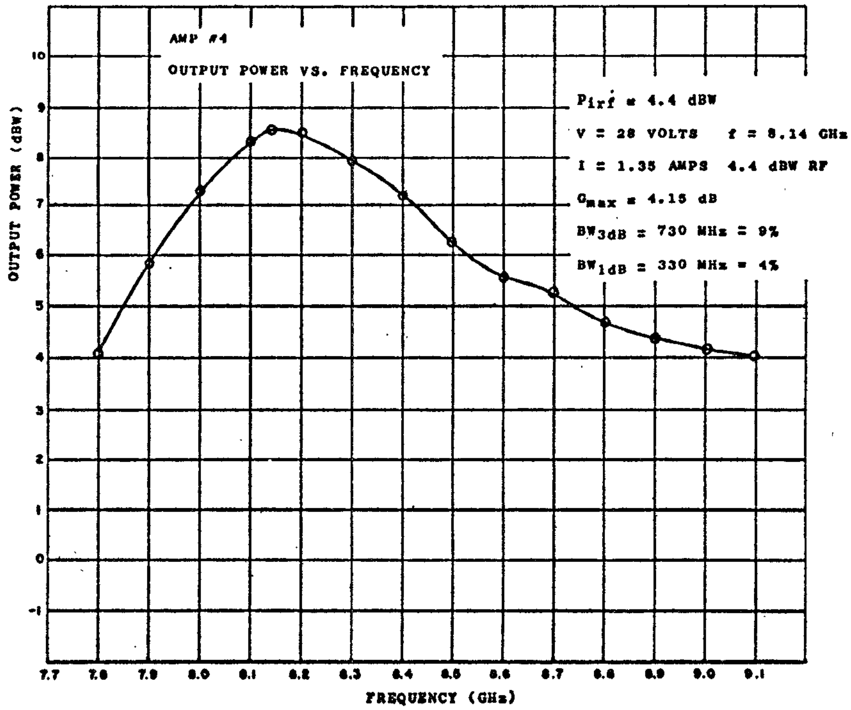

Fig. 5. Amplifier output power versus frequency.

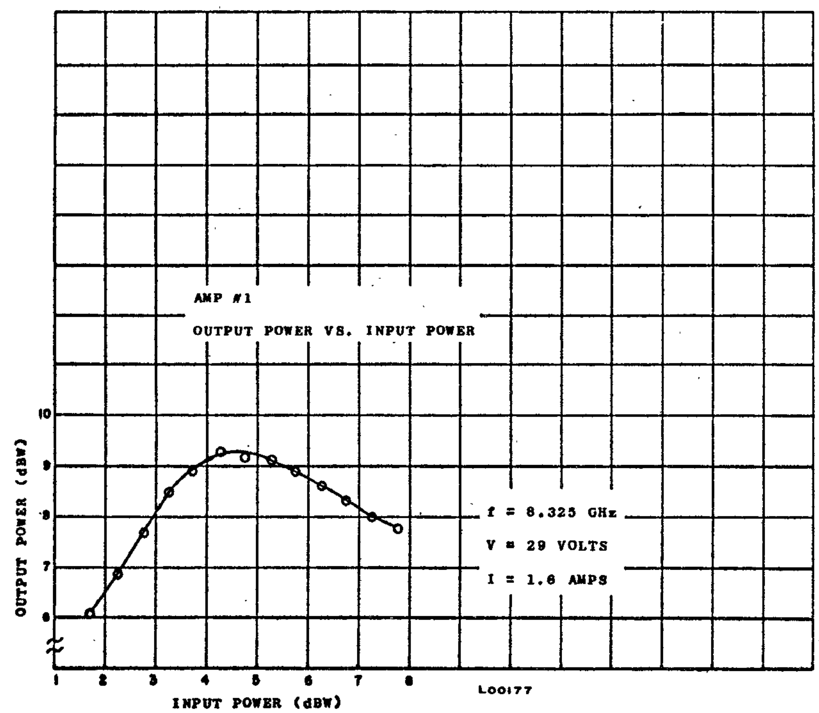

Fig. 6. Amplifier output power versus input power.

optimized experimentally for stable operation and maximum bandwidth.

ACKNOWLEDGMENT

The authors wish to thank M. Grace for his assistance in the computer simulations as well as for many helpful discussions.

REFERENCES

[1] M. I. Grace, "Broadband high-efficiency-mode amplifiers at S-band," in *Proc. 1971 European Microwave Conf.* (Stockholm, Sweden), pp. A8/1.1–A8/1.4.
[2] A. S. Clorfeine *et al.*, "Wideband high-power TRAPATT circuits," in *1974 IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers*, pp. 96–97.
[3] A. Rosen, J. F. Reynolds, and J. M. Assour, "Broadband high-power TRAPATT diode amplifier at S-band," *Electron. Lett.*, vol. 7, Dec. 30, 1971.
[4] A. Rosen, J. F. Reynolds, S. G. Liu, and G. E. Theriault, "Wideband class-C TRAPATT amplifiers," *RCA Rev.*, vol. 33, p. 729, Dec. 1972.
[5] N. W. Cox, K. E. Gsteiger, G. N. Hill, and C. T. Rucker, "X band CW TRAPATT oscillators using ring diodes on diamond heat spreaders," *Electron. Lett.*, vol. 9, pp. 269–270, June 14, 1973.
[6] J. E. Carroll and R. H. Crede, "A computer simulation of TRAPATT circuits," *Int. J. Electron.*, vol. 32, pp. 273–296, 1972.
[7] K. R. Gleason, C. T. Rucker, N. W. Cox, A. C. Macpherson, and E. D. Cohen, "Experimental study of series connected TRAPATT diodes," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-22, pp. 804–806, Aug. 1974.
[8] K. E. Gsteiger, N. W. Cox, G. N. Hill, and C. T. Rucker, "Ring diodes on diamond heat spreaders for X-band CW TRAPATT" (Late Paper), presented at the 1972 Electron Devices Conf.