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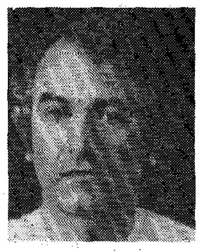

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A High-Power *W*-Band (90–99 GHz) Solid-State Transmitter for High Duty Cycles and Wide Bandwidth

GLENN R. THOREN, MEMBER, IEEE, AND MICHAEL J. VIROSTKO, MEMBER, IEEE

Abstract —**A high average power *W*-band solid-state transmitter using a 2-diode and a 4-diode IMPATT power combiner has achieved over 1.89 W and exceedingly versatile performance over a broad range of pulsewidths and duty cycles with a tunable bandwidth from 90 GHz to 99 GHz.**

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I. Introduction

A NEW GENERATION of millimeter-wave systems will demand high-power solid-state *W*-band transmitters [1]. Millimeter-wave tracking radars and active seekers for precision guided munitions need small, lightweight, reliable solid-state transmitters capable of operating over a broad range of pulsewidths, duty cycles, and

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bandwidths. A transmitter has been developed that delivers state-of-the-art power levels over broad ranges of these parameters. Signal processing techniques that use a variety of pulse codes (digital sequence and chirps) can be readily employed with this transmitter.

Previous implementations of *W*-band transmitters have been limited to pulsewidths less than 300 ns (typically 100 ns) and duty cycles less than 2 percent (typically 0.5 percent) [2], [3]. High average power levels in combination with signal processing are needed for longer detection range and target classification.

In this development effort commercially available silicon IMPATT diodes were combined in a unique modification of a Kurokawa waveguide combiner designed for versatile operation at *W*-band. A key element in achieving such a versatile transmitter was the ability to adjust precisely the circuit impedance that is seen by each IMPATT in the power combiner. This paper will present this power-combiner design and the performance of this new solid-state *W*-band transmitter.

II. IMPATT Power Combiner

Both 2-diode and 4-diode IMPATT power combiners were developed for this transmitter. Fig. 1 graphically shows the achievements for this development, while typical performance for each combiner is summarized in Table I. The combiner design is a modification of the Kurokawa waveguide combiner. Both combiners used identical coaxial tuning modules so that all internal parts are interchangeable, thereby minimizing the design complexity and development cost.

Fig. 2(a) shows several of these combiners assembled and disassembled. The 4-diode combiner is a 6-diode combiner with the two coaxial bias lines near the sliding short blocked off. The unique precision tuning elements, heat sinks, and internal waveguide configuration are also shown. Cooling, with a room-temperature water reservoir, was used to maintain a relatively constant ambient temperature for the 4-diode combiner. Cooling was not necessary, however, and was not used at all for single-diode units or the 2-diode combiner.

The ability to adjust precisely the impedance seen by each IMPATT led to very high combining efficiencies. The IMPATT's performed more efficiently in the combiners than their individual operating data would predict. Combiner circuit losses are difficult to determine at these frequencies but are probably less than 1 dB based on the observed performance. No iris coupling or screw tuning was used to match the reduced-height waveguide of the power combiner to the full-height waveguide of the measurement network. A simple tapered transition built as part of the combiner circuit was used for this interface. The precision tuning elements are shown in Fig. 2(b).

A. IMPATT's

The IMPATT's used are Hughes CW silicon double-drift diodes mounted on type IIA diamond (47106H-0120) and specified at 200 mW per device with thermal coefficients of

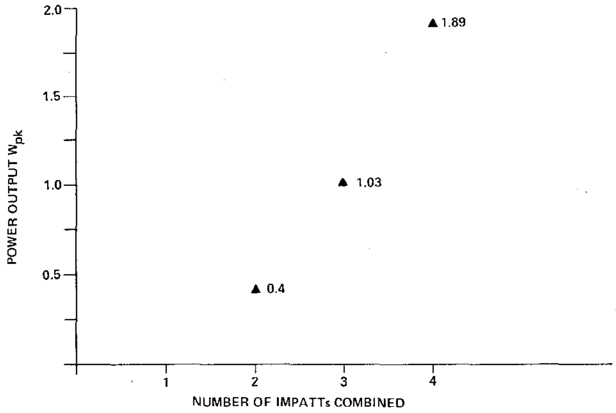
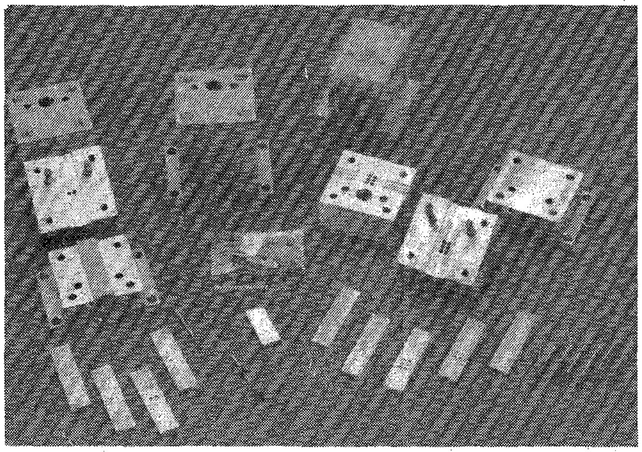
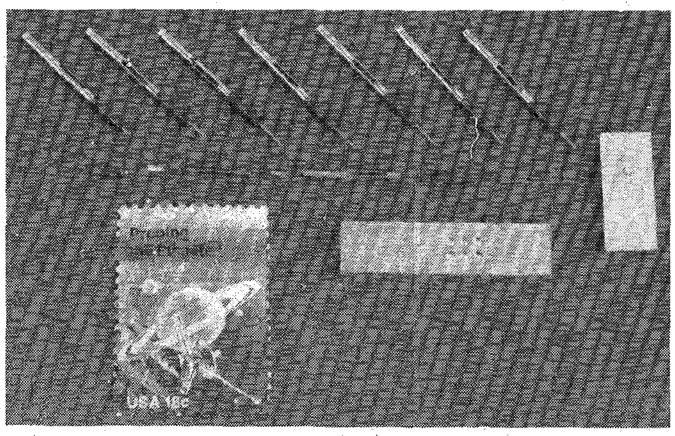


Fig. 1. *W*-band IMPATT power-combiner performance.



(a)



(b)

Fig. 2. (a) Power combiners with internal structure and parts displayed. (b) Precision tuning assembly details.

TABLE I
MILLIMETER-WAVE IMPATT POWER-COMBINER PERFORMANCE

Item	Performance Achievements	
	2 Diode Combiner	4 Diode Combiner
Frequency*	92 - 104 GHz	90 - 99 GHz
Power	300+ mW Freerunning 400+ mW Injection Locked at 10-13 dB Gain	1.89 W Free Running and Injection Locked at 13 dB Gain
Pulsewidths	100 nsec to 4 μsec (cw-like operation)	
Duty Cycles	1 - 35%	5 35%
Injection Locking Bandwidth	>900 MHz at 10-13 dB gain	>900 MHz at 10-13 dB gain

*Mechanically tuned bandwidth

$\theta_t = 30°C/W$. These IMPATT's were first tested for power versus frequency with a variety of single-diode "fixed-tuned" oscillators circuits including a sliding backshort.

Preselection data (power versus frequency) for diodes 121 and 122 are shown in Fig. 3. IMPATT's with similar characteristics were mounted as sets on the heat sink for operation in both the 2-diode and 4-diode combiner. In the combiners, the IMPATT's were biased and the position of the precision tuning elements were adjusted for maximum output power and single-frequency operation.

A comparison of the individual diode operating characteristics with the 4-diode combiner performance is shown in Table II. This comparison points out the higher efficiency and improved performance achieved in the precision tuned 4-diode combiner as compared with a single-diode "fixed-tuned" circuit.

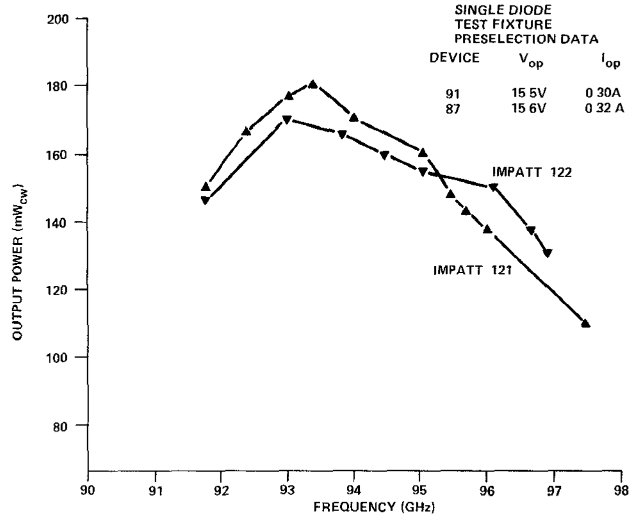


Fig. 3. Preselection data for IMPATT's 121 and 122.

TABLE II
COMPARISON OF IMPATT PERFORMANCE BETWEEN THE FIXED-TUNED SINGLE-DIODE CIRCUIT AND THE 4-DIODE POWER COMBINER

Device	Data	V_{BK} V	C_O pF	V_{OP} Ave. V	Peak V	I_{OP} mA	P_{IN} W	RF CW mW	P_{OUT} Pulsed mW	f_o GHz	* η %	θ_t °C/W	T_j °C
241	Single Diode	15.1	.93	18.3	---	268	4.90	240	---	93.2	4.89	30.0	169
	α 4-Diode Combiner	N/A	N/A	16.7	17.5	440	7.35	---	420*	90.0	5.72	30.0	<253
242	Single Diode	15.1	.97	18.7	---	289	5.40	250	---	93.6	4.63	30.0	184
	α 4-Diode Combiner	N/A	N/A	16.5	17.5	310	5.11	---	296*	90.0	579	30.0	<184
243	Single Diode	15.0	.95	18.6	---	272	5.06	250	---	93.6	4.94	30.0	174
	α 4-Diode Combiner	N/A	N/A	16.7	17.5	500	8.35	---	477*	90.0	5.71	30.0	<285
244	Single Diode	15.1	.97	18.4	---	280	5.15	250	---	93.3	4.85	30.0	176
	α 4-Diode Combiner	N/A	N/A	16.7	17.5	480	8.02	---	457*	90.0	5.70	30.0	<274

α 0.1 to 4.0 μsec pulsewidth
* estimated in proportion to current (I_{OP})

B. Modulators

The breadboard modulators were designed for versatile performance. The modulator input was a TTL voltage pulse exceeding 100 ns with duty cycles ranging from 1–50 percent. The modulator transformed this voltage pulse into current pulses which could be continuously varied from 1–500 mA. A maximum of eight current pulses, all independent of each other, were provided. A logic protection circuit was included to shut down the transmitter in the event of an IMPATT failure.

The power transistors of this circuit were approaching their safe operating limits during high duty cycle. Occasional transistor failures occurred with no loss of IMPATT's. The modulator can be designed to use hybrids that have demonstrated better reliability in other Raytheon development efforts.

C. Precision Tuning

As a free-running oscillator, it is possible to induce a "frequency jump" during the RF pulse. This undesirable condition is the result of the motion of the characteristic impedance of the IMPATT as it heats up in combination with a loop in the circuit impedance of the waveguide. By noting the extent of the frequency jump it is possible to adjust the position of the Eccosorb terminations and the sliding waveguide short to avoid such loop in the circuit impedance and to achieve stable operation during both short and long pulses.

The Eccosorb termination used in the precision tuning of the power combiner can be "shaped" to vary the value of its impedance. This is an additional complexity in the matching technique, but a highly desirable feature when properly understood. A long taper results in a greater attenuation of unwanted frequencies as well as any RF signal at the desired frequency that is not coupled to the cavity. By decreasing the length of the taper (in the limit a flat Eccosorb face will result), more energy is reflected back toward the cavity. The proper positioning of a flat-faced Eccosorb load will reflect the RF energy at the desired frequency back into the cavity and thereby improve the efficiency of the combiner circuit. The Eccosorb load is a complex impedance that will alter the circuit load impedance at all frequencies as the Eccosorb is moved in the coaxial line. The accurate positioning of precision tuning element (see Fig. 2(b)) was vital to appropriately match each individual IMPATT in the power combiner to achieve high-power broad-band efficient operation.

An example of an improperly tuned circuit is seen in Fig. 4 where many distinct and different frequencies are present during each RF pulse. Such operation is eliminated by adjusting the precision tuning assemblies to obtain the proper circuit impedance and a coherent single frequency signal from the IMPATT. When the IMPATT combiner is operated as a free-running oscillator there may be both a frequency chirp and amplitude chirp as the junction of the diode changes temperature. The amplitude chirp can be minimized by a more accurate matching of the IMPATT impedance. The frequency chirp can be substantially mitigated by this tuning technique or eliminated when injection locking is used.

The results of accurately tuning the IMPATT's is seen in

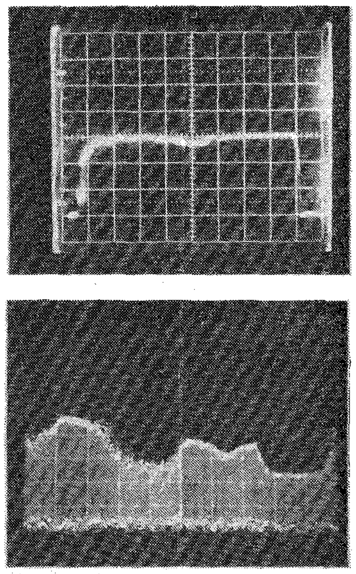


Fig. 4. Improperly tuned multifrequency 2-diode combiner.

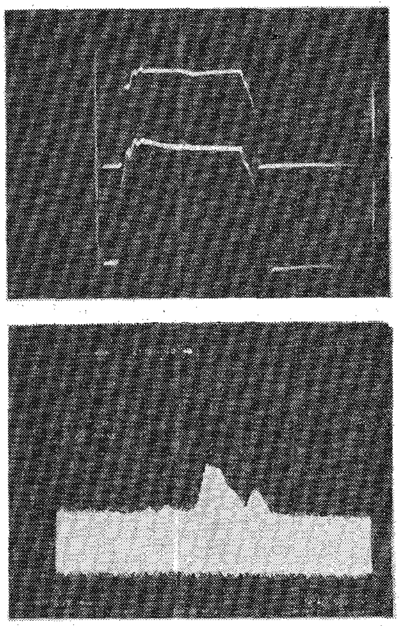


Fig. 5. Free-running operation of 2-diode power combiner.

Fig. 5. This spectrum indicates coherent operation in the power combiner. Additional tuning is provided by a sliding short within the reduced height waveguide. No ramping or variation in the biasing current pulse amplitude was necessary since both the undesirable frequency jumps and any power amplitude variation across the RF pulse could be eliminated by proper tuning.

III. 2-Diode Combiner

The 2-diode combiner achieved more than 300 mW as a free-running oscillator. More than 400 mW was achieved when this unit was injection-locked at gains between 7 and 15 dB. More than 300 mW was achieved for duty cycles between 1 and 35 percent and pulsewidths ranging from 100 ns to more than 4 μs. No tuning of the combiner was needed to accommodate these broad variations. By slightly adjusting the precision tuning elements and the position of the sliding short, this performance was obtainable over a frequency range from 92 GHz to 104 GHz. Such versatility is a significant state-of-the art accomplishment. At a 10-dB locking gain about 1-percent instantaneous bandwidth was achieved. No effort was made to optimize this instantaneous bandwidth beyond 1 GHz. Duty cycles in excess of 35 percent were not tested due to a decrease in the current amplitude supplied by the breadboard modulator circuits. It is expected that such performance will be maintained at duty cycle well in excess of 50 percent.

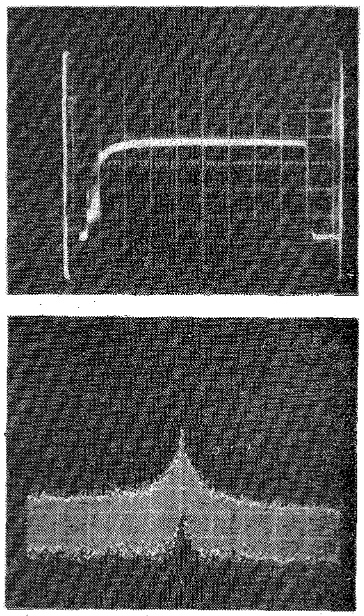


Fig. 6. Injection locked 2-diode combiner.

An example of the performance of the 2-diode combiner is shown in Figs. 4 and 6. The combiner is operating as a free-running oscillator in Fig. 4. The detected RF envelope closely resembles the current pulse, reproducing even the ripples on the leading and trailing edges of the pulse. The rise time of the RF envelope is less than the driving current pulse because the IMPATT requires between 100 mA and 200 mA of current before it will begin to oscillate.

The RF spectrum is detected from the harmonic mixer using a synthesized local oscillator at about 6 GHz. Fig. 4(b) shows a typical free-running spectrum. When the combiner is injection locked by a single IMPATT the output is as seen in Fig. 6. Unstable operation is observed during the rise time of the RF envelope due to the large change in temperature of the IMPATT that causes a rapid change of the IMPATT characteristics during the first 30 to 50 ns of oscillation. The injection-locked pulse is stable at a single frequency for the rest of the 4 μs in this example. Higher locking power with a more optimum matching to the IMPATT will minimize this region of instability.

Many pairs of IMPATT's were run in the 2-diode combiner. Diodes 121 and 122 were the first tested and generated over 300 mW with only minimum tuning and no modification of the original circuit design.

IV. 4-Diode Combiner

The 4-diode power combiner achieved a state-of-the-art power in excess of 1.89 W of peak output power at 90 GHz with duty cycles between 10 and 25 percent and pulse-

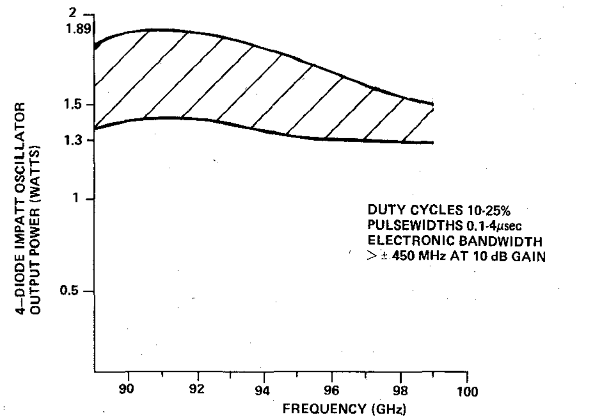


Fig. 7. Peak power performance for mechanically-tuned range of 4-diode IMPATT oscillator.

widths from 0.1 to 4 μs. For duty cycles from 5 to 35 percent this unit generates over 1.3 W of peak power over the mechanical tuning range of 90 to 99 GHz. Mechanical tuning of 35 MHz/mil is easily obtained with just the sliding short between 89.5 and 90.5 GHz with less than 0.9-dB variation in output power. Frequencies lower than 89.5 GHz were not tested for injection-locking bandwidth since no locking source was available. The injection-locked bandwidths were about 1 percent for 10 to 13-dB gain. Fig. 7 shows the operating range of this power combiner.

A comparison of the operating data observed in the 4-diode combiner and the data received for CW operation of the individual IMPATT's indicates that the typical maximum junction temperature of each diode is slightly higher in the 4-diode combiner at maximum drive levels (see Table II). This estimate of the peak junction temperature is the maximum expected temperature at the end of the RF pulse. The diode junction (principally the avalanche region of the IMPATT) will heat up during the pulse and cool off between pulses. The expected MTBF for constant junction temperature less than 200°C is greater than 100 000 h. Since the estimated peak junction temperature exceeds 250°C for only brief periods, the reliability for a defect-free IMPATT should approach the expected MTBF. Even though the IMPATT's are operating at higher junction temperatures in the 4-diode combiner, the estimated efficiency of each IMPATT is greater than the efficiency seen in the single-diode test circuit.

Typical waveforms for the free-running 4-diode combiner output stage of the transmitter are shown in Fig. 8. The RF envelope is flat since the amplitude chirp has been eliminated by the precision tuning. The diodes are operating coherently at a single frequency. This was confirmed experimentally in the measurement network by adjusting the cavity frequency meter through the RF envelope and observing a uniform drop in the amplitude of the envelope when this combiner was injection-locked. Slight instabilities can be seen in the first 40 ns of the RF envelope due to the initial heating of the IMPATT. The duration of these instabilities is decreased to less than 20 ns with injection-locking.

A typical voltage pulse for this combiner is also shown. The voltage increases during this one μs pulse from 15.8 V to 17.5 V as the IMPATT heats up. The coherent output power of the 4-diode combiner was obtained from 90 GHz to 99 GHz by slightly adjusting the position of the Eccosorb terminations and the waveguide sliding short.

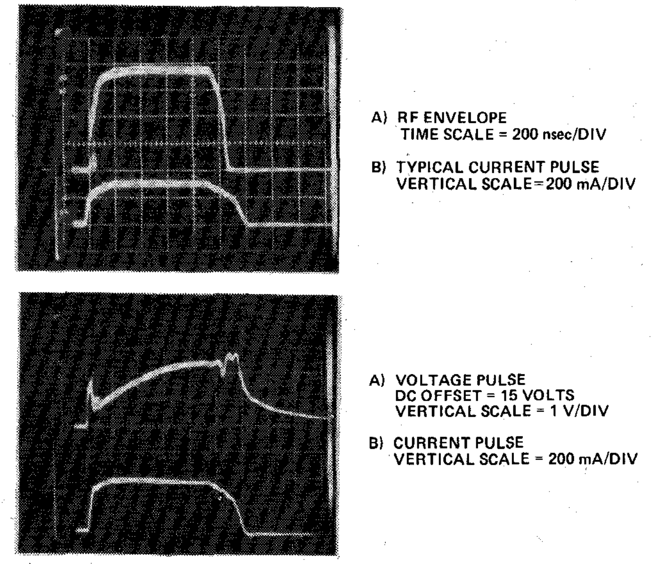


Fig. 8. Typical waveforms in W-band 4-diode power combiner at 1.89 W.

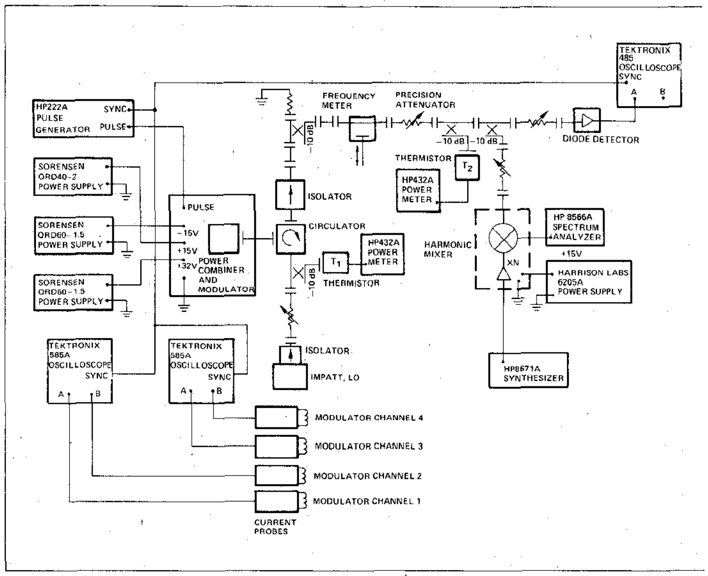


Fig. 9. Waveguide measurement network.

A second 4-diode combiner achieved an output peak power level of 1.03 W at 96.4 GHz with duty cycles between 10 and 30 percent and pulse widths between 0.1 to 4 μs. The same versatility in tuning was also seen in this combiner. One IMPATT had a biasing current much less than the oscillation threshold current. It is believed that this device acted like a tuning element.

V. Measurement Network

The waveguide measurement network is shown in Fig. 9. The insertion loss in each component of the network was calibrated from 90 to 104 GHz. The insertion loss of assembled network was correlated with the sum of the losses in the components. A precision variable attenuator

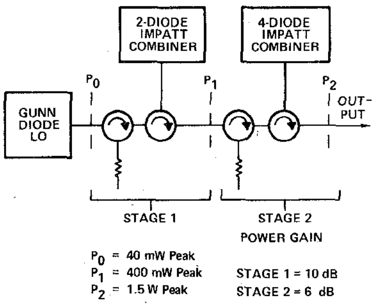


Fig. 10. Block diagram of transmitter with stage gain indicated.

was adjusted to set the network loss at 30 dB for each measurement. The final three-stage transmitter will generate a locked, stable output between 90 GHz and 99 GHz. The estimated gain per stage is indicated in the block diagram in Fig. 10.

VI. Conclusions

A three-stage *W*-Band solid-state transmitter has been assembled using state-of-the-art IMPATT power combiners. More than 1.89 W of peak output power was delivered from the final stage 4-diode combiner. Extremely versatile performance was achieved with coherent operation at pulsewidths from 0.1 to 4 μs and duty cycles from 5 to 35 percent. The mechanical tuning bandwidth ranged from 90 to 99 GHz with up to 1-GHz injection gain within the operating frequency range.

A variety of pulse coded millimeter-wave radar applications can now be addressed where digital or chirp coding, and high-average power is required for long-detection ranges and target classification.

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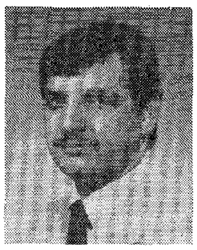
Dr. Thoren has received patents for cylindrical-cavity IMPATT power combiners, coaxial line IMPATT oscillators, pulsed IMPATT transmitters, and multicavity power combiners. He has also authored many papers and presentations on millimeter-wave components, power combining technology, and DSA-mode theory. He is the Chairman of the Boston Chapter to MTT-S, Co-Chairman of the 1983 MTT-S Symposium Publications Committee, Past Chairman of Membership Development for MTT-S, Chairman of Division IV Membership Development, and a Member of the MTT-S Nominating Committee. He is also a member of Eta Kappa Nu and the Electron Devices Society of IEEE.



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