Millimeter-Wave Silicon IMPATT Sources and Combiners for the 110–260-GHz Range

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Abstract—This paper reports recent progress in CW and pulsed silicon IMPATT sources in the 110–260-GHz frequency range. Pulsed output power levels of 3, 1.3, and 0.7 W, and CW output power levels of 110, 60, and 25 mW have been consistently achieved from single-drift IMPATT diodes at 140, 170, and 217 GHz, respectively. A Read-type IMPATT diode that generated good output power over a wide frequency range was fabricated. A bridged double-quartz standoff package was developed and successfully used for the entire frequency range. Power combiners at center frequencies of 140 and 217 GHz were developed with peak output power of 9.2 and 1 W, respectively.

I. Introduction

SIGNIFICANT progress in output power has recently been achieved with silicon IMPATT oscillators in both CW and pulsed modes of operation at frequencies above 100 GHz [1]–[6]. Most results were achieved with double-drift diodes in direct contact packages or in single-quartz standoff packages. Both package types use a gold ball as a contacting pad and this can be easily knocked off, causing irreparable damage to the diode.

This paper describes single-drift diodes (p^+-n-n^+) which deliver comparable or higher output power levels than those previously reported. Pulsed output power levels of 3, 1.3, and 0.7 W and CW output power levels of 110, 60, and 25 mW have been consistently achieved at 140, 170, and 217 GHz, respectively. The pulsed diodes were operated at 100-ns pulsewidth and 25-kHz pulsed repetition rate. A bridged double-quartz standoff package was developed and used successfully for the entire frequency range of 110–260 GHz. This package is much more reliable and rugged than the direct contact package or the single-quartz standoff package.

A Read IMPATT diode (p^+-n^+-n-n^+) was also fabricated and found to operate over a wide-frequency range. For the same diode lot, peak output power levels of 2.5 and 0.22 W have been observed at 138 and 208 GHz. CW output power levels of 20 and 5 mW have also been achieved at 125 and 177 GHz, respectively.

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To increase output power, power combining techniques developed at lower frequencies [7], [8] were extended to 140 and 217 GHz. Ngan [9] has reported the achievement of 3-W peak output power near 145 GHz by combining two IMPATT diodes. This paper reports a peak output power of 5.2 W achieved for a two-diode combiner and 9.2 W for a four-diode combiner at 140 GHz. A two-diode combiner was also developed at 216 GHz with a peak output power of 1.05 W.

II. Single-Drift IMPATT Diode Development

Theoretically, the double-drift diode can provide higher power and efficiency than the single-drift diode as well as higher device impedance for easier circuit matching. However, the double-drift diode requires a more complicated doping profile. Multilayer structures must be fabricated using multiple epitaxy or ion implantation techniques, with precision control on thickness and doping density. Either technique results in a graded profile around the p-n junction. For low frequency diodes, the grading due to straggling is not significant since the grading portion is small compared with the total epithickness. But for high-frequency diodes, the epithickness is on the order of only a few tenths of a micron and the straggling-induced profile grading at the p-n junction causes performance degradation. This does not occur in higher frequency single-drift diodes with shallow p^+ diffusion, which also offer the attractive feature of fabrication simplicity.

At frequencies beyond 100 GHz, diode fabrication requires a considerable amount of care because of the extremely small dimensions involved. Due to these small dimensions, the performance of the IMPATT diode depends critically on how well the diode parameters are controlled. The problem is further complicated by the fact that an accurate description of the high frequency IMPATT is virtually impossible without a full understanding of the large-signal interaction between the diode and circuit. For our design, an analytical approach backed by empirical data was employed. As shown in Fig. 1, the theoretical values for the diode parameters, such as doping densities and epithickness, were first obtained by a small-signal computer calculation. IMPATT diode wafers were then fabricated using these diode design parameters, with some intentional variations in the doping profile for optimization purposes. After fabrication, the profile was characterized by $C-V$ measurement and secondary ion mass spectroscopy (SIMS) analysis. RF testing yielded informa-

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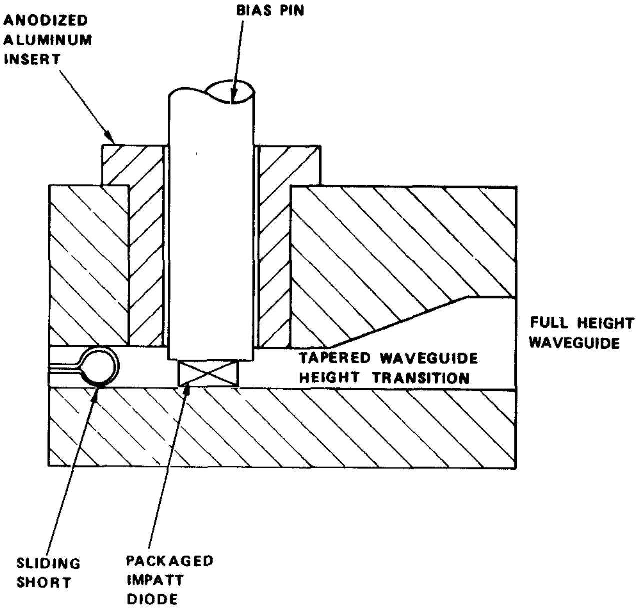

Fig. 4. Single-diode test circuit configuration.

A bridged double-quartz standoff package was developed that has been successfully used for frequencies up to 255 GHz. In the past, the 140-GHz diode was packaged in a gold ball type double-quartz standoff or single-quartz standoff package [1]–[4], and the 217-GHz diode in a direct contact package [5], [6]. These structures have inherent mechanical problems. Gold balls can be easily knocked off, causing irreparable damage to the diode. To overcome these problems, a bridged double-quartz standoff package was developed. In this package, a flat gold ribbon was utilized to replace the gold balls, which serve as a contacting pad for the bias pin, as shown in Fig. 3. The package can be mounted on top of a copper or diamond heatsink. The diamond heatsink is useful for reducing the thermal resistance in CW operation. This package is much more reliable and rugged than the direct contact or single-quartz standoff package. Although the double-quartz standoff package has higher package parasitics than the single-quartz standoff or the direct contact package, these effects can be compensated by better diode designs. In fact, the package parasitics can be used to transform the low diode impedance to high circuit impedance.

III. Diode Evaluation

The diodes were tested in a reduced-height waveguide circuit, as illustrated in Fig. 4. In this circuit, a tapered transition was designed for impedance matching and an adjustable short was employed for power and frequency optimization. Three different types of circuit dimensions were used in the performance testing: 0.065×0.010 in for D-band (110 to 170 GHz), 0.051×0.010 in for G-band (140 to 220 GHz), and 0.043×0.010 in for Y-band (170 to 260 GHz). Bias p-i-n's of different diameters (0.035, 0.031, 0.027, 0.021, and 0.015 in) were used to optimize the power and frequency output. In most cases it was found that the best output power was achieved with a p-i-n diameter of 0.035 in for 140 GHz operation, 0.027 in for 170 GHz operation, and 0.021 in (sometimes 0.015 in) for 217 GHz operation.

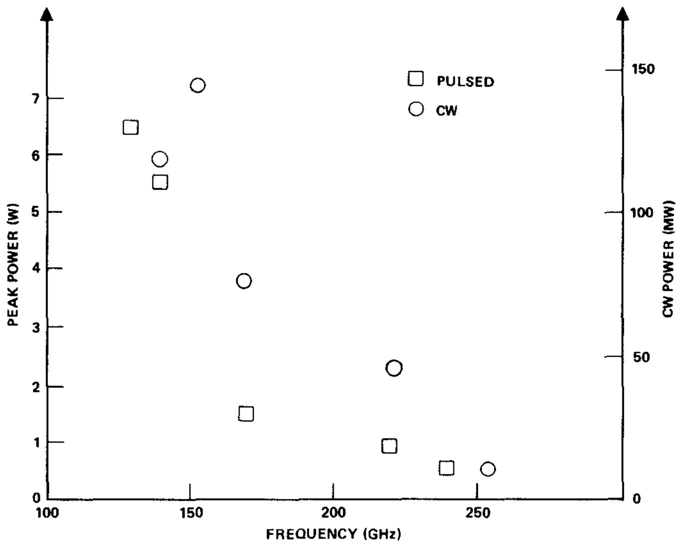

Fig. 5. Summary of diode performance.

Diode performance is summarized in Fig. 5. For pulsed operation, peak output power levels of 3, 1.3, and 0.7 W with efficiencies of 6, 2.5, and 2 percent have been consistently achieved at 140, 170, and 217 GHz, respectively. The highest peak output power observed was 5.6 W at a center frequency of 140 GHz, 6.5 W at 130 GHz, 1 W at 217 GHz, and 620 mW at 240 GHz. The diodes were operated with 100-ns pulsewidth at a 25-kHz repetition rate. For CW operation, typical output powers of 110, 60, and 25 mW, with efficiencies of 2, 1, and 0.7 percent, were achieved at 140, 170, and 217 GHz, respectively. For selected diodes, output power levels of 130 mW at 140

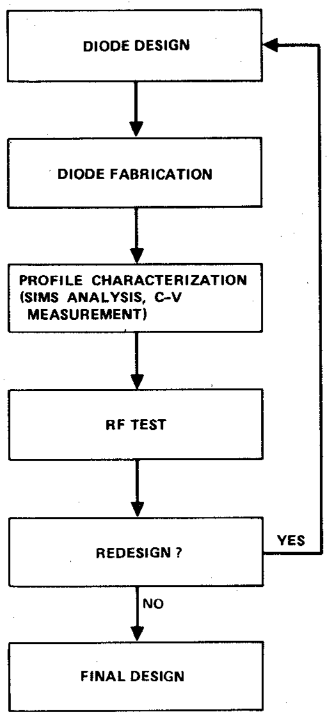

Fig. 1. Diode design optimization procedure.

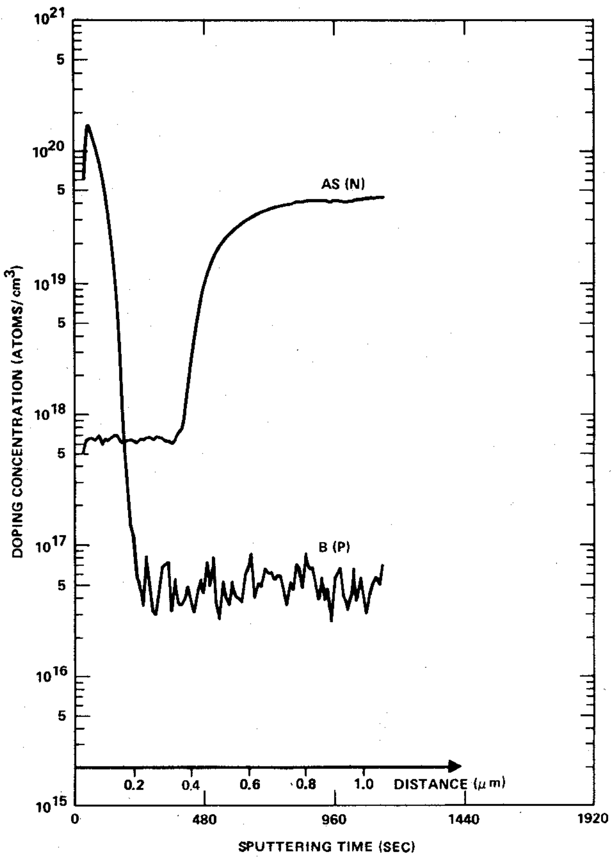

Fig. 2. Doping profile of a 200-to-250-GHz diode obtained from a SIMS analysis.

tion as to how the various parameters could be improved or optimized for maximum output power at the desired frequency. The final diode parameters after design optimization are summarized in Table I.

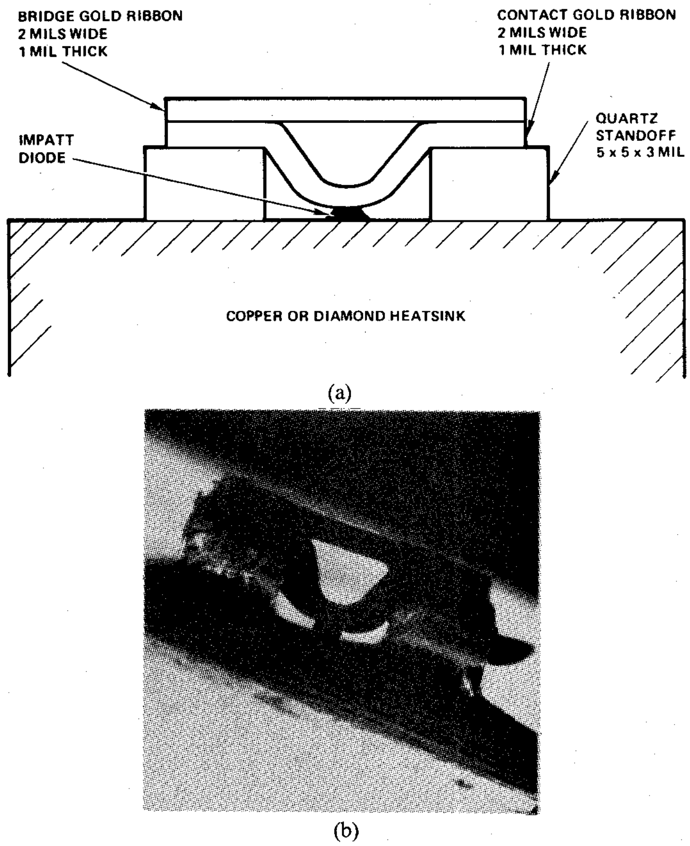

Fig. 3. Bridged double-quartz standoff package. (a) Schematic configuration. (b) Photo from scanning electron micrograph—magnification 200×.

TABLE I
SUMMARY OF DIODE DESIGN PARAMETERS

Frequency (GHz)	Operating Mode	Doping Concentration (cm^{-3})	Drift Region Thickness (μm)	Breakdown Voltage (volts)	Diode Diameter (μm)	Bias Current Density (kA/cm^2)
140	Pulsed	2×10^{17}	0.2	9.8	52	280
	CW	1.9×10^{17}	0.4	10.1	26	60
170	Pulsed	4×10^{17}	0.15	7.8	45	350
	CW	3.5×10^{17}	0.3	8.2	24	75
217	Pulsed	7×10^{17}	0.1	6.2	41	500
	CW	5×10^{17}	0.2	7.2	22	110

The diode area was determined by scanning electron micrography. It is interesting to note that the pulsed diodes tend to operate in a punch-through mode with a narrow drift region. Computer simulations indicated that the space charge effects are very strong for high frequency pulsed diodes and the resultant electric field profiles are thus similar to those from a Read-type diode.

The single-drift IMPATT profile was first formed by epitaxially growing an n layer on an n^+ arsenic-doped substrate, followed by a shallow p^+ boron diffusion forming a p-n junction. A typical doping profile obtained from SIMS analysis for a 200-to-250-GHz diode is shown in Fig. 2. It is evident that the junction grading is not a problem for a shallow p^+ diffusion.

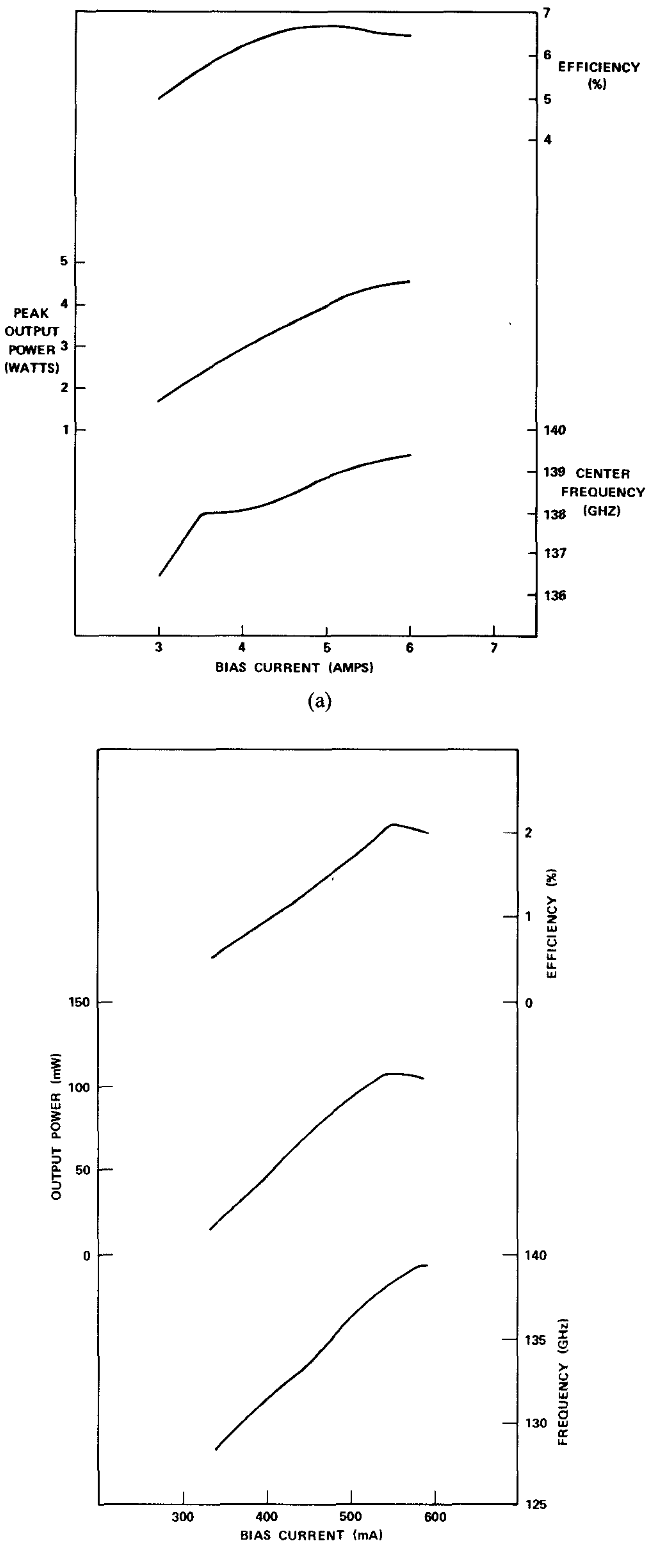

Fig. 6. Output power, frequency, and efficiency (a) for a pulsed diode, (b) for a CW diode.

GHz, 150 mW at 152 GHz, 75 mW at 170 GHz, 50 mW at 217 GHz, 50 mW at 245 GHz, and 12 mW at 255 GHz were achieved. The CW diodes were mounted on diamond heatsinks. Typically, the CW diode has a zero voltage capacitance of 0.5 to 1 pF, and the pulsed diode has a capacitance of 1.5 to 2.5 pF.

The output power and frequency as a function of bias current for the 140-GHz diodes are shown in Fig. 6. It can be seen that the power output and oscillation frequency increase as the bias current is increased. For CW diodes, more than 10-GHz tuning range can be achieved by changing the bias current.

IV. Read-Type IMPATT Diode Fabrication and Performance

The Read-type IMPATT diode was fabricated by epitaxially growing the n^+-n layer on top of the n^+-substrate, followed by a p^+-diffusion. Fig. 7 shows a SIMS profile measurement of the Read IMPATT structure before the p^+ diffusion. The depth of p^+ diffusion is critical and can be evaluated by the measured device breakdown voltage. If the diffusion is too deep, the device becomes a low-frequency single-drift IMPATT diode with a breakdown voltage of more than 15 V. If the diffusion is too shallow, the resultant breakdown voltage will be very low (a few volts). The breakdown voltage of our device was 9.6 V, indicating that the p^+ diffusion is at the grading region of the n^+-n transition.

RF testing indicated this diode lot operates in a wide-frequency range. Peak output power of 2.5 W at 138 GHz (4-percent efficiency) and 220 mW at 208 GHz (0.7-percent efficiency) has been observed for pulsed operation. CW output power of 20 mW at 125 GHz (0.3-percent efficiency) and 5 mW at 177 GHz (0.1-percent efficiency) has also been achieved from this diode lot. The operating voltage is only 10 percent higher than the breakdown voltage compared to more than 20 percent in a single-drift or double-drift IMPATT diode. It is believed that potentially higher efficiency can be achieved with further optimization in the diode and circuit design.

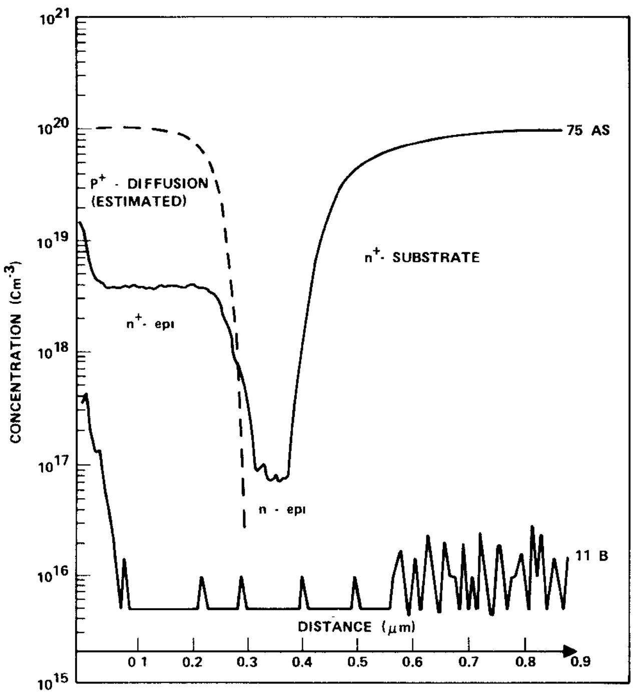

Fig. 7. Read IMPATT diode profile measurement.

V. 140-GHz Power Combiner Development

Our combiner design was based on the waveguide resonant cavity combiner developed by Kurokawa at X-band frequencies, [7]. A schematic diagram of the combiner design is shown in Fig. 8. There are, however, certain noteworthy departures from the conventional low frequency circuit design, which are as follows.

1) An oversized waveguide was used. The cavity width, which is 0.100 in, is wider than the standard WR-7 waveguide width of 0.065 in for the 110-to-170-GHz frequency range.

2) The diode spacing in the longitudinal direction is one guide wavelength and not a half guide wavelength.

3) The distance from the cavity opening to the first diode row is $5\lambda_g/4$ and not $\lambda_g/4$.

4) The cavity is formed by the sliding short and the discontinuity due to the transition from the change of waveguide width. This transition introduces an inductance element at the interface plane.

5) Eccosorb terminations with a flat end (mismatched type) were used instead of those with a tapered end (matched type).

6) The diodes were not mounted at the edge of the waveguide; instead, they were located close to the center line of the waveguide.

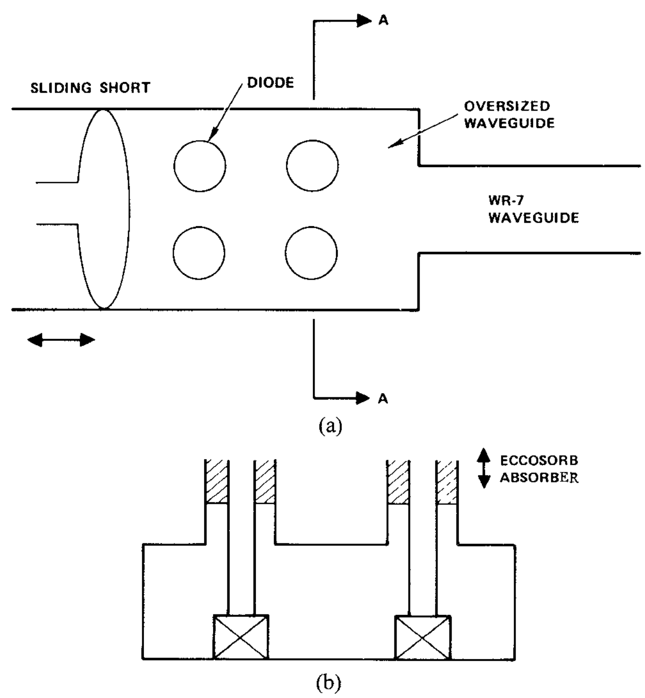

Fig. 8. 140-GHz four-diode combiner circuit. (a) Top view. (b) Cross-sectional view at AA.

The reasons for the first three modifications are primarily due to the mechanical limitations imposed by the dimensions of the diode modules. The last three modifications are similar to the W-band combiner design and are discussed in a previous paper [8].

The two most important tuning elements are the position of the sliding short and the Eccosorb terminations. Several different p-i-n diameters and diode separations in the transverse plane have been used to optimize the circuit. It was found that a p-i-n diameter of 0.022 in and diode

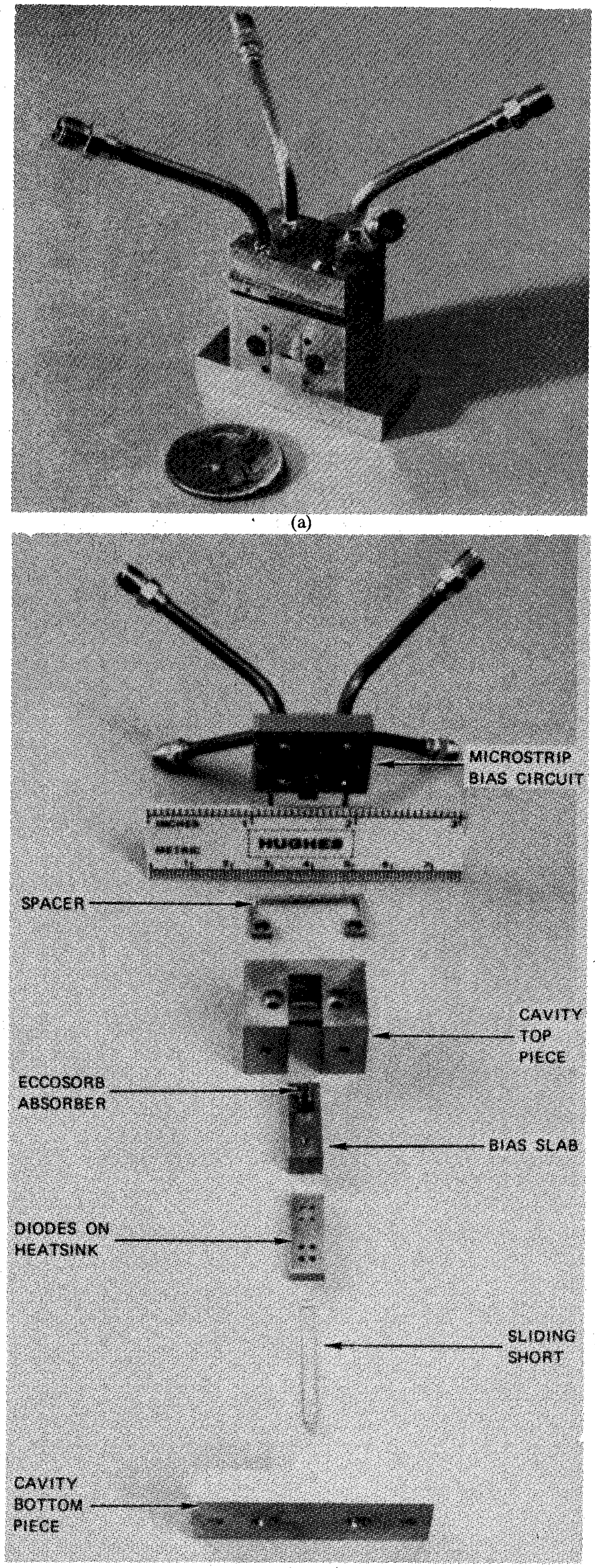

Fig. 9. 140-GHz four-diode combiner. (a) Assembled waveguide circuit. (b) Disassembled waveguide circuit.

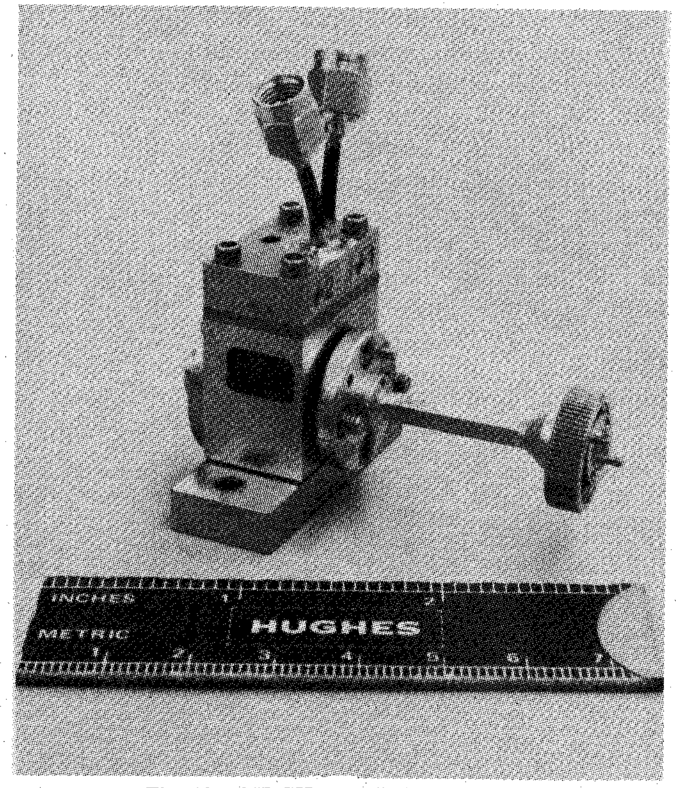

Fig. 10. 217-GHz two-diode combiner.

separation of 0.070 in provided the best performance. A peak output power of 9.2 W at a center frequency of 139.3 GHz has been achieved from the four-diode combiner. The diodes used for the combiner were selected to have similar output power (3 to 4 W) and frequency. The diodes were operated with 100-ns pulsewidth and 25-kHz repetition rate. Frequency chirp of less than 2 GHz and power variation across the pulse of less than 1 dB were achieved. The hardware of this combiner is shown in Fig. 9.

This four-diode combiner was converted to a two-diode combiner by the insertion of two plug-in p-i-n's into the two unused holes in the bias slab. A peak output power of 5.2 W at a center frequency of 142.2 GHz has been accomplished.

VI. 217-GHz Power Combiner Development

A two-diode combiner for 217-GHz operation has also been developed, as shown in Fig. 10. As in the 140-GHz combiner, an oversized waveguide (0.065×0.02 in) was used. The diode separation in the transverse plane is 0.040 in and the bias p-i-n diameter is 0.017 in. Since the operating frequency of the combiner was always lower than that of an individual diode due to the loading effects, diodes operating at higher individual frequencies were selected for the combiner. With this arrangement, peak output power of 1.05 W at 216 GHz was accomplished using 230-GHz 600-mW diodes.

VII. Conclusions

Single-drift IMPATT diodes have been developed for the 110-to-260-GHz frequency range in CW and pulsed modes of operation. The diodes were in a rugged bridged double-quartz standoff package. Read-type IMPATT diodes were also fabricated and operated over a wide frequency range. Power combiners that delivered state-of-the-art power output were demonstrated at 140 and 217 GHz.

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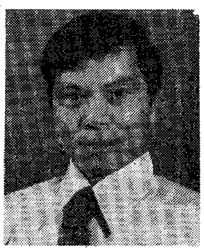

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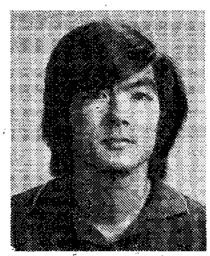

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