High-Performance Second-Harmonic Operation *W*-Band GaAs Gunn Diodes

S. J. JEROME TENG, MEMBER, IEEE, AND ROBERT E. GOLDWASSER

Abstract—**High performances in output powers and dc-to-RF conversion efficiencies of second-harmonic operation *W*-band (75-110 GHz) GaAs Gunn diodes are reported. We demonstrate that output powers of 96 and 48 mW at 94 and 103 GHz, respectively, with a dc-to-RF conversion efficiency of 2.7 and 2.3 percent, have been achieved using single-diode GaAs Gunn oscillators. The operation of these diodes requires 2 to 4 W of dc power consumption.**

I. Introduction

The Gunn-diode oscillator has been proven to be a reliable microwave and millimeter-wave solid-state frequency source. The Gunn oscillator exhibits desirable characteristics, such as low FM noise, and it is suitable for such applications as local oscillators, injection-locked oscillators, or amplifiers. GaAs Gunn diodes are widely used in applications as frequency sources up to the *W*-band. Second-harmonic mode operation is commonly used for frequencies higher than about 65 GHz. Some experimental studies on the second-harmonic operation *W*-band Gunn diodes have been reported before [1]–[3]. In practice, in the fundamental-mode operation of GaAs diodes, we have achieved an output power of 110 mW at 70 GHz with a dc-to-RF conversion efficiency of 2.8 percent by using a coaxial-cavity resonator. This indicates that the cutoff frequency of the fundamental-mode GaAs Gunn diode is still higher than 70 GHz. However, as the operating frequency increases, the diode design and its physical constraint become critical. Also, the diode operating voltage, hence its dc power consumption, decreases as the operating frequency increases. This in turn limits the output power, even if the dc-to-RF conversion efficiency remains the same as that in the lower frequencies. Consequently, the second-harmonic operation offers a viable alternative in fabricating *W*-band Gunn oscillators.

In this letter, we report our results in the performance of second-harmonic operation *W*-band GaAs Gunn diodes. We demonstrate that not only is the second-harmonic operation a desirable option in fabricating *W*-band Gunn oscillators, but it also has achieved performances both in output power and dc-to-RF conversion efficiency that are comparable to those of the fundamental-mode *V*-band (50–75 GHz) GaAs diodes. Diode design and fabrication will be described, and discussions of the experimental results will be given. All results discussed herein refer to single-diode oscillators having 2 to 4 W of dc power consumption.

Manuscript received May 2, 1989; revised July 3, 1989.
S. J. J. Teng was with Alpha Industries, Inc., Central Microwave Subsidiary, St. Louis, MO 63043. He is now with Hughes Aircraft Company, Torrance, CA 90509.
R. E. Goldwasser is with Alpha Industries, Inc., Woburn, MA 01801.
IEEE Log Number 8930470.

II. Device Fabrication

The active layers of the fabricated GaAs diodes were grown in an $AsCl_3/H_2/GaAs$ vapor phase epitaxy system. A highly doped n^+ buffer layer ($n = 0.9$ to 1×10^{18} cm^{-3}) 2 μm thick was grown between the active layer and the highly conducting Si-doped n^+ GaAs substrate. Sulfur was used as the n-type dopant in the growth of the epitaxial layers. Due to second-harmonic mode operation, the active layer lengths of these Gunn devices are designed for the fundamental-mode operation in the *Q*-band (33–50 GHz) frequencies. The thicknesses of the active layers ranged from 1.6 to 2.5 μm. The doping concentrations of the active layers were in the range of 9×10^{15} to 2×10^{16} cm^{-3}. Since the Gunn diode is a transit-time device, the active layer length plays an important role in the diode's operation, especially in determining the diode's optimum operating frequency. Fig. 1 shows a design guideline for the active layer length versus its optimum operating frequency of GaAs diodes from 35 to 55 GHz. This design guideline is empirically derived based on measured velocity-field characteristics of GaAs [4] and our observed electrical properties of Gunn diodes, such as operating voltages.

The diode ohmic contacts were fabricated with alloyed Ni/AuGe metallizations. Gold layers were electroplated on both sides of the wafer before the wafer was scribed into 6 × 6-mil chips. Fabricated diode chips were then thermal-compressionally bonded into gold-plated copper stud packages, each with a ceramic ring. Gold wires or gold ribbons were then bonded from the diode to the top of the metalized ceramic ring. Diode trim etch was performed at this stage. Each diode was then hermetically sealed with a metal cap by using a solder ring.

III. Results and Discussions

Measured threshold voltages of the diodes range from 1.1 to 1.4 V. The diode threshold currents are made less than 1 A to ensure an efficient and reliable device operation. In higher frequency diodes, threshold currents are usually made less than 700 mA. The diode operating currents range between 400 and 800 mA. Low-field resistance of these diodes measures about 1 to 1.3 Ω. A large current drop-back from the threshold point does not necessarily mean a better device in performance; however, a sharp transition at the threshold point is desirable for good device performance.

Diodes are RF tested in a full-height *W*-band (WR-10)

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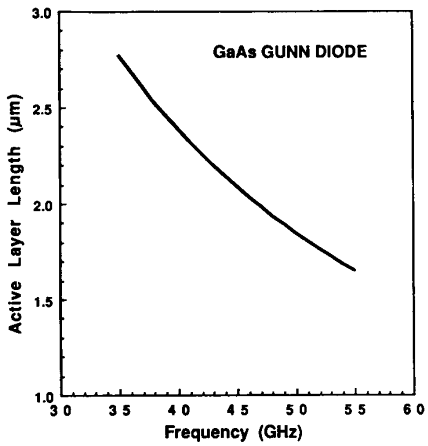

Fig. 1. A design guideline for active layer length versus operating frequency of GaAs Gunn diode.

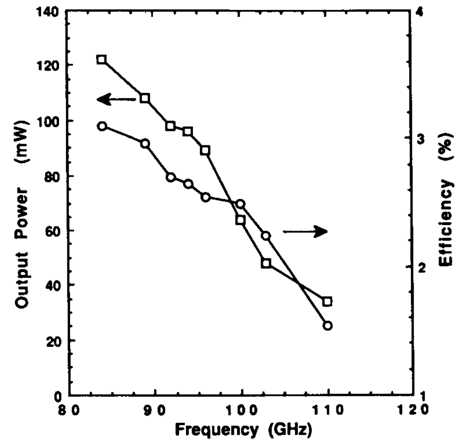

Fig. 3. Measured output powers and their dc-to-RF conversion efficiencies versus frequency of various W-band GaAs Gunn oscillators.

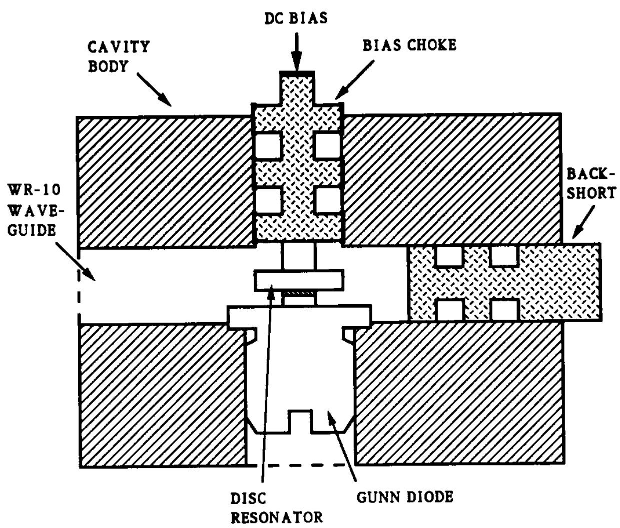

Fig. 2. Cross-sectional view of a radial-line resonator in a full-height W-band (WR-10) waveguide fixture.

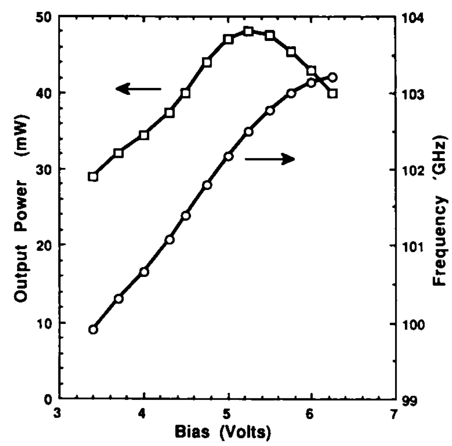

Fig. 4. Output power and frequency versus diode bias voltage of a 102.5-GHz Gunn oscillator.

waveguide fixture having a radial-line resonator [2], [3], a movable backshort, and a dc low-pass filter. Fig. 2 illustrates the oscillator circuit used. The resonator's disc or cap is situated directly on top of the diode. The waveguide circuit extracts the resonator's second-harmonic frequency and the diode's fundamental Q-band frequency is suppressed due to the higher cutoff frequency (59.0 GHz for TE_{10} mode) of the W-band waveguide. The movable backshort adjusts the coupling of the output power from the radial-line resonator, and little frequency change has been observed due to the backshort adjustment. The output frequency is controlled mainly by the Q-band resonator; consequently, the output frequency depends on the dimension and position of the radial-line resonator and the characteristics of the diode. For example, as the thickness of the cap increases, the second-harmonic frequency decreases.

Fig. 3 shows the measured oscillator output powers and their dc-to-RF conversion efficiencies versus frequencies in the W-band range. We have achieved output powers of 96 and 48 mW at frequencies of 94 and 103 GHz, with a dc-to-RF conversion efficiency of 2.7 and 2.3 percent, respectively. A typical diode performance at 110 GHz is 34 mW with an efficiency of 1.6 percent, as shown in Fig. 3. Output power and efficiency are in a trade-off relationship. The output power levels reported in Fig. 3 do not represent the highest attainable values because our diodes' dc power consumptions are limited to 2 to 4 W. Nor is the reported efficiency the highest achievable value. This is especially true in the higher end of the W-band frequencies where a smaller diode area is desirable for good performance. Thus higher efficiency results from lower dc power consumption and, consequently, lower output power. For example, we have obtained an output power of 60 mW with an efficiency of 3.4 percent at 98 GHz.

The operating characteristics of the Gunn diodes are illustrated in the following example. Fig. 4 shows the output power and frequency in relation to the diode bias voltage of a 102.5-GHz Gunn oscillator. The peak power of 48 mW occurs at a bias of 5.3 V. The output power turns on after bias reaches about 2.5 V. Between bias voltages of 3.5 and 6 V, as shown in Fig. 4, the output frequencies are tuned continuously from 100 to 103 GHz. Meanwhile, the diode operating current remains relatively flat at about 400 mA. This Gunn oscillator can be used either as a mechanical- or bias-tuned oscillator. It also can be used as a phase-locked oscillator when the diode bias voltage is linked to a phase-lock mechanism.

IV. Conclusion

We have reported the state-of-the-art performances, both in output power and dc-to-RF conversion efficiency, of second-harmonic operation *W*-band GaAs Gunn diodes. Diode fabrication and its testing and operation have been described. Due to the capability of higher output powers, such applications as varactor-tuned *W*-band Gunn oscillators can be readily achieved with a wider tuning bandwidth and a higher output power. This widens the realm of device applications for GaAs Gunn diodes in the millimeter-wave frequencies.

Acknowledgment

The authors thank E. V. Deogracias for contributing some of the RF test results.

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