Optimization of S-Band TRAPATT Oscillators

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***Abstract*—The optimization of *S*-band TRAPATT oscillators has been investigated experimentally from both the device and circuit points of view. Methods for selecting a device for optimum operation with a given circuit are discussed. A relatively straightforward circuit optimization technique has resulted in an increase in oscillator efficiency of between 5 and 8 percentage points, representing an RF power increase of approximately 20 percent.**

INTRODUCTION

SINCE the discovery of the TRAPATT mode of operation [1] there have been many reports of high-power and/or high-efficiency operation. However, very little has been reported on optimization conditions with regard to either the solid-state devices or the microwave circuits necessary for high-efficiency operation. In this paper experimental results are presented in which the optimization of *S*-band TRAPATT oscillators is considered from both the device and circuit points of view. In the first case a series of diodes are operated in the same microwave circuit yielding information on the type of device needed to optimize the oscillator performance. For the circuit investigation the circuit was altered in a systematic manner for operation with a given diode. The TRAPATT diodes were operated in a standard coaxial slug-tuned oscillator circuit under pulse bias conditions and were driven to a current density large enough to observe conversion efficiency saturation. In all tests a 1-μs pulsewidth and a 0.1-percent duty cycle were used to minimize the possibility of diode destruction due to thermal limitations.

DEVICE OPTIMIZATION

The operation in the same circuit of many diodes of both n^+-p-p^+ and p^+-n-n^+ structures [2] with varying breakdown voltages resulted in dc characteristics similar to those illustrated in Fig. 1. The characteristics of Fig. 1 were obtained with the oscillator tuned for maximum RF output power as a function of increasing bias current. The dc operating voltage exhibited a linear collapse with increasing current until a current level was achieved where the diode dc voltage became independent of the dc current. The uniformity of the dc characteristics as observed during the evaluation of a large number of diodes with varying breakdown voltages leads to the conclusion that the oscillator dc operating voltage is more dependent upon the circuit than upon the actual device used.

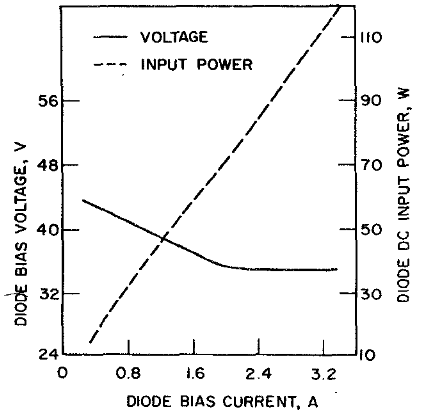

Fig. 1. Dc characteristics for coaxial slug-tuned TRAPATT oscillator.

DIODE VOLTAGE COLLAPSE

Based upon the preceding observation, the diode breakdown voltage should be an indication of the efficiency which can be expected from a TRAPATT diode at a given current level since the efficiency is related to the degree of voltage collapse experienced by the diode. To test this hypothesis a series of diodes with varying breakdown voltages were evaluated and the efficiencies obtained were plotted as a function of the degree of voltage collapse [i.e., versus $V_{\text{operating}}/V_{\text{breakdown}}$]. Fig. 2 illustrates the results obtained at 2.2 GHz. For a fixed bias current density an optimum voltage collapse ratio appears to exist although not shown for the higher J values. Similar results were obtained at 3.5 GHz. The existence of the optimum

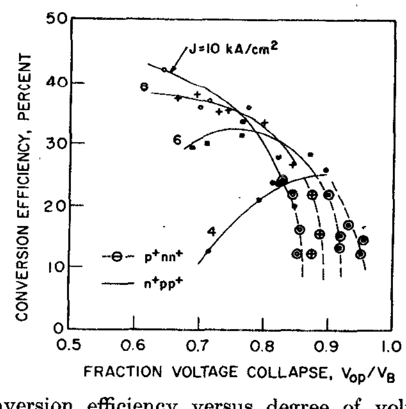

Fig. 2. Conversion efficiency versus degree of voltage collapse. (f = 2.2 GHz.)

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voltage collapse ratio is thought to be related to the voltage–current waveforms appearing across the device. The optimum condition probably occurs when the diode voltage returns to the breakdown value in one half the microwave period. Waveforms resulting in greater and lesser collapse ratios could represent the conditions where the voltage regains the breakdown value at times greater than and less than one half the microwave period. These conditions would result in the reduced efficiencies observed. The increase in the optimum collapse ratio (i.e., smaller V_{op}/V_B values) with increasing current is due to the greater plasma density generated and the corresponding greater speed at which the diode voltage collapses at high current densities.

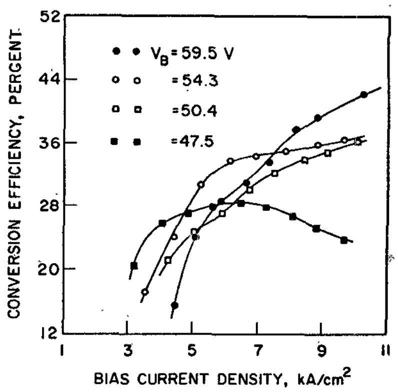

Fig. 3. Conversion efficiency for n^+-p-p^+ diodes with varying breakdown voltages. (f = 2.2 GHz.)

EFFECT OF DEPLETION-LAYER DOPING LEVEL ON RF PERFORMANCE

In order to investigate the effect of depletion-layer doping levels on the RF performance of TRAPATT oscillators, a series of TRAPATT diodes with breakdown voltages ranging from 47.5 to 59.5 V were tested. All of the diodes were n^+-p-p^+ devices and had depletion-layer widths of approximately 2 μm. The depletion-layer doping levels ranged from 0.6×10^{16} to 3.5×10^{16} cm^{-3}. The conversion efficiencies obtained are illustrated in Fig. 3 for operation at 2.2 GHz. At low current levels the highest doped diode (i.e., the diode with the lowest breakdown voltage) produced the greatest efficiency. Highly doped diodes also require lower threshold current levels to initiate TRAPATT operation than do lower doped devices. As the bias current is increased the behavior changes and the diode with the lowest doped depletion region (i.e., the diode with the highest breakdown voltage) produces the greatest efficiency. The highest efficiency achieved was obtained at high current levels with the diode having the lowest doped depletion region. Increasing the operating frequency to 3.5 GHz again resulted in similar behavior.

The behavior just described agrees with the theoretical predictions obtained from a computer model developed by Lee *et al.* [3]. Fig. 4 illustrates the theoretical behavior expected from 2-μm n^+-p-p^+ abrupt-junction diodes having depletion-layer doping levels of 0.4×10^{16} and 1.0×10^{16} cm^{-3}. The higher doped diodes initiate TRAPATT operation at lower current levels than the lower doped diodes because of the higher electric field in the avalanche region of the highly doped devices. The greater electric field in the avalanche region is a result of the slope of the electric field being proportional to the doping level in the depletion region according to Poisson's equation. The greater slope of the electric field leads to a reduction in the avalanche region width which in turn requires a higher electric field in the avalanche region in order to satisfy the breakdown condition [4]. The higher avalanche region electric field requires a smaller driving current to achieve the overvoltage required to initiate TRAPATT operation and, therefore, the highly doped devices require lower threshold current

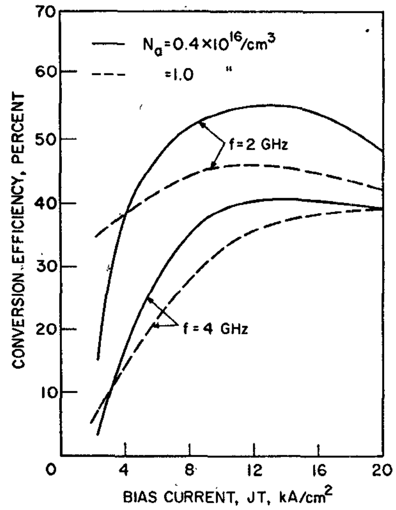

Fig. 4. Theoretical efficiency versus bias current for abrupt-junction 2-μm n^+-p-p^+ Si TRAPATT diodes.

levels. The lower doped devices are capable of greater efficiencies because larger RF voltages are allowed to develop across such diodes for a fixed current level. The large RF voltages can occur because the electric field throughout the drift region of the lower doped diodes is greater than the drift field in the higher doped structures.

These results suggest methods for selecting an optimized device for a given application. For example, if CW operation is desired, it appears that higher doped diodes should be selected since these devices produce the highest efficiency at low current levels. These diodes also require lower threshold current levels and lower dc operating voltages, both significant factors when considering CW operation. If, however, pulse operation is to be used and the greatest possible efficiency is desired, then lower doped diodes should be selected since these devices produce their optimum operation under these conditions.

CIRCUIT OPTIMIZATION

For the circuit optimization investigation a conventional slug-tuned coaxial circuit that selects the operating frequency by a low-pass filter located approximately a half-

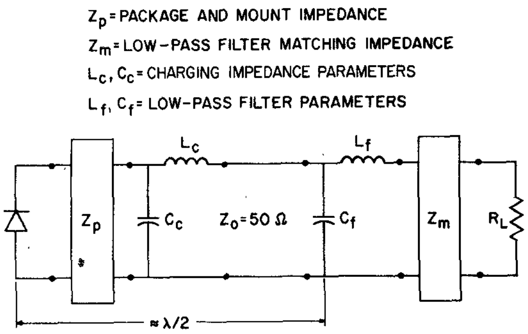

Fig. 5. TRAPATT oscillator equivalent circuit.

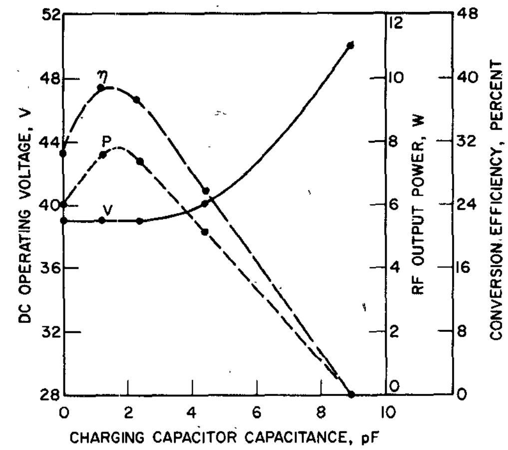

Fig. 6. Charging capacitor characteristics of the TRAPATT oscillator with an n+-p-p+ diode. (I_{dc} = 0.5 A, f = 2.1 GHz, diameter = 0.00476 in.)

wavelength away from the diode was utilized. The circuit can be modeled by that illustrated in Fig. 5. The RF circuit was modified by changing the characteristic impedance of the first slug in the low-pass filter and the characteristic impedance of the coaxial line immediately adjacent to the diode. Tests were conducted to determine the optimum circuit configuration and the optimum circuit oscillator results were compared to the nonoptimum ones.

CHARGING CAPACITANCE BEHAVIOR

Evans [5] has shown that it is sometimes necessary to include extra charging capacitance in the immediate vicinity of the diode in order to get efficient oscillator performance. The extra capacitance is required since the 50-Ω line is not able to supply the large conduction current required when the diode voltage collapses.

To investigate this behavior the oscillator was operated with a series of slugs located directly over the diode. The characteristic impedances of the slugs were selected so that the extra charging capacitor had values ranging from 0 pF (i.e., the 50-Ω line) to approximately 9 pF. The results obtained for an n+-p-p+ diode are shown in Fig. 6. The 50-Ω line allows TRAPATT performance but since there is not enough charging capacitance the oscillator performance is degraded. An optimum performance condition occurs at approximately 1–2 pF. For capacitor values above 2 pF the RC time constant for the oscillator is too great and the diode voltage cannot collapse fast enough thereby degrading the oscillator performance. Increasing the size of the diode (Fig. 7) increases the amount of charge required. In this instance the 50-Ω line is less able to sustain TRAPATT oscillations than the previous example and even poorer performance results. Since the diode requires more conduction current the optimum performance point is shifted to a larger capacitance value (approximately 4.5 pF). Increasing the capacitor above approximately 5 pF again results in too great an RC time constant.

A possible explanation of the capacitance behavior can be obtained by examination of the circuit of Fig. 5 and the waveforms illustrated in Fig. 8. If the diode is initially slightly below the diode breakdown voltage with very little conduction current flowing and suddenly a constant terminal current is allowed to flow through the diode, the diode voltage will increase with a slope approximately proportional to the inverse of some capacitance value. Most simplified TRAPATT analyses [6]–[8] consider the capacitance value to be the depletion-layer capacitance. In an actual oscillator the capacitance is the total of the depletion-layer capacitance, the package and mount capacitance, and any charging capacitance in the immediate vicinity of the diode. Since all of the capacitors are in

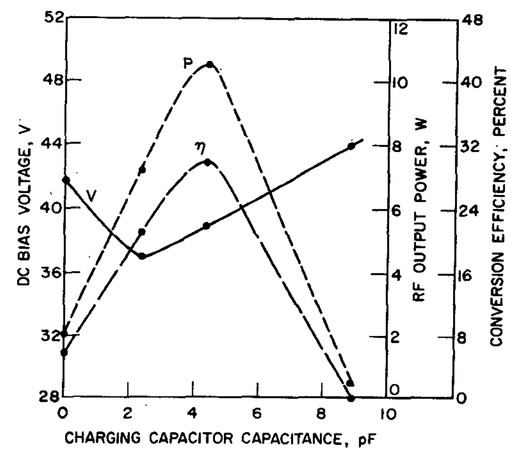

Fig. 7. Charging capacitor characteristics of the TRAPATT oscillator with an n+-p-p+ diode. (f = 2.2 GHz, diameter = 0.00642 in.)

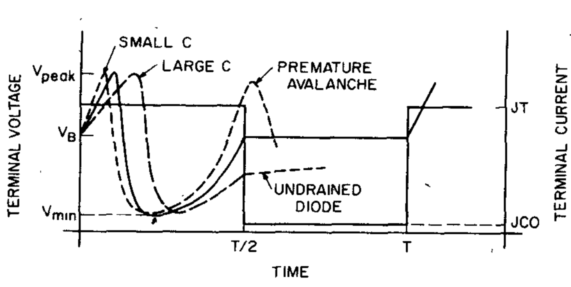

Fig. 8. TRAPATT oscillator waveforms illustrating effects of too large and too small charging capacitance values.

parallel the total value can be controlled by changing the charging capacitance. Considering the waveforms of Fig. 8 for simplicity it can be seen that optimum efficiency occurs when the diode voltage returns to the breakdown value in one half the microwave period. If the terminal current is held unchanged and the total capacitance value is reduced the diode voltage will increase more rapidly causing the voltage collapse to occur sooner in the RF cycle. Since the plasma is drained at a rate determined by the terminal current the diode voltage is allowed to reach the breakdown voltage before the external current is "turned off." This results in premature avalanche and reduced efficiency. If, however, the total capacitance is increased, the diode voltage will change at a reduced rate causing the voltage collapse to occur later in the RF cycle. In this instance the terminal current is not able to completely drain the diode of plasma before the terminal current is "turned off" and reduced efficiency again results. In this manner it can be seen how the microwave circuit parameter values are able to alter the voltage–current waveforms appearing across the diode.

LOW-PASS FILTER CAPACITANCE BEHAVIOR

Extending these experiments to the first slug in the low-pass filter provides the results shown in Fig. 9. If the capacitance is too small the reflection coefficient is too small and some of the harmonics of the fundamental are passed on to the microwave load, thereby degrading the oscillator performance. Similar results have been obtained and discussed by Evans [5] for TRAPATT oscillators operating at frequencies slightly below 1.0 GHz. If the first slug is too capacitive most of the microwave power is trapped in the cavity and very little power is passed on to the load. This type of behavior probably results in the most efficient voltage–current waveforms appearing across the diode since the higher harmonics of the fundamental are all trapped in the microwave cavity. However, since very little power is passed on to the load the measured efficiency is low. The optimum capacitor value is approximately 4.5 pF. As might be expected, the optimum capacitor value remains constant, independent of the particular diode tested.

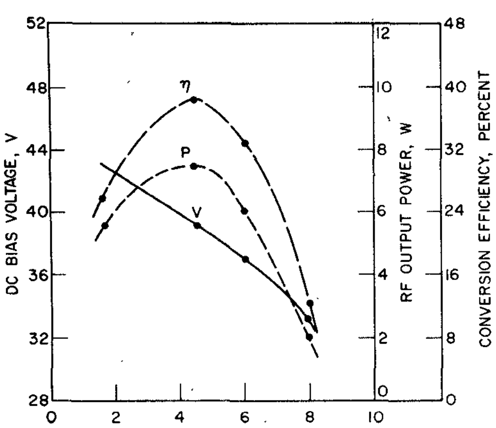

Fig. 9. Filter capacitor characteristics of the TRAPATT oscillator with an n$^+$-p-p$^+$ diode. (I_{dc} = 0.5 A, f = 2.2 GHz, diameter = 0.00476 in.)

COMPARISON OF OPTIMIZED AND NONOPTIMIZED RESULTS

When the optimized oscillator results are compared to the nonoptimized ones [2] significant improvement is observed to exist as shown in Fig. 10. At 2.2 GHz the maximum output power was increased from 16 to 17.8 W and the maximum efficiency was increased from approximately 36 to 44 percent. The experimentally obtained efficiency is observed to approach the theoretical efficiency curve predicted from the computer results obtained by Lee *et al.* [3] for a 2-μm abrupt-junction Si n$^+$-p-p$^+$ diode. At a frequency of 3.5 GHz the results are even closer to the theoretical predictions as shown in Fig. 11. At this fre-

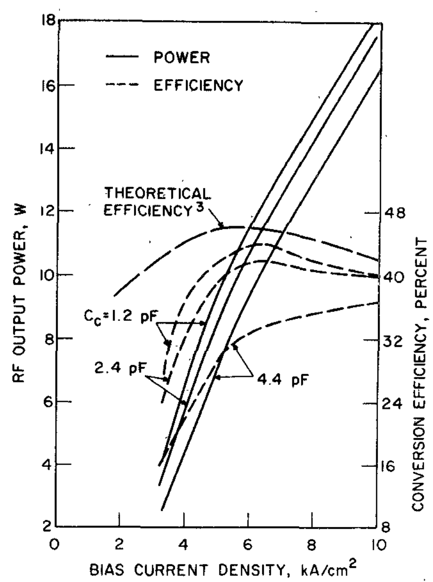

Fig. 10. TRAPATT oscillator power efficiency characteristics for an n$^+$-p-p$^+$ diode. (f = 2.2 GHz, diameter = 0.00476 in.)

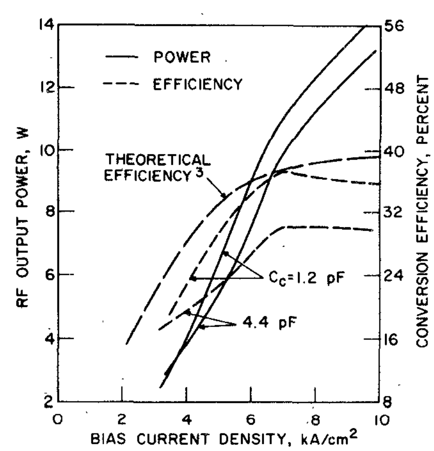

Fig. 11. TRAPATT oscillator power efficiency characteristics for an n$^+$-p-p$^+$ diode. (f = 3.5 GHz, diameter = 0.00476 in.)

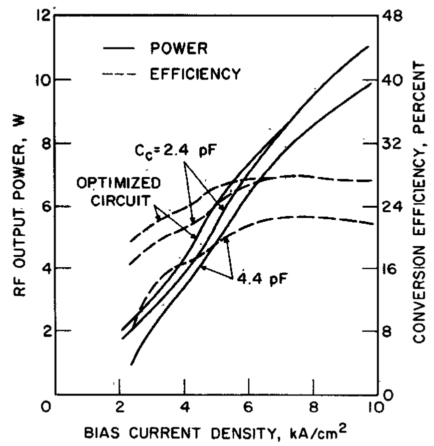

Fig. 12. TRAPATT oscillator power efficiency characteristics for a p^+-n-n^+ diode. (f = 2.2 GHz, diameter = 0.00486 in.)

quency the RF power was increased from 13 to 14 W and the maximum efficiency was increased from 30 to 37.5 percent. When these experiments were performed on a p^+-n-n^+ diode the results shown in Fig. 12 were obtained. At 2.2 GHz the RF power was increased from 9.6 to 10.8 W and the efficiency was increased from 23 to 28 percent.

CONCLUSIONS

Techniques for optimizing S-band TRAPATT oscillators have been experimentally demonstrated. It has been shown that the dc operating voltage of TRAPATT oscillators is dependent mainly upon the microwave circuit and therefore how the diode breakdown voltage can be used as an indicator of the efficiency to be expected for a particular application from a given oscillator. The effect of diode depletion-layer doping levels on RF performance has been demonstrated. The use of a relatively straightforward circuit optimization approach has resulted in significant improvement in the operation of S-band TRAPATT oscillators. By adjusting the critical values of the charging and filter capacitors it has been possible to obtain from 5 to 8 additional percentage points of efficiency, an increase of approximately 20 percent in the RF power. The experimental results are observed to approach the theoretical limits obtained from detailed computer simulations.

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