# HARMONIC TUNING EFFECTS OF TRAPATT OSCILLATORS*

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## Abstract

A simplified computer model of a TRAPATT oscillator has been utilized to investigate harmonic tuning effects. The results of an investigation of realistic waveforms provide insight into the tuning conditions necessary for high-efficiency operation. Circuit impedance measurements of an S-band TRAPATT oscillator support many of the theoretical predictions.

## Introduction

Since the operation of TRAPATT oscillators and amplifiers is generally characterized by the presence of several harmonically related signals across the device, it is necessary to establish the effect of the different harmonics on the oscillator or amplifier performance. A simplified computer model[1] of a TRAPATT oscillator has been developed for this purpose. The simplified model calculates the diode terminal voltage for an input current waveform consisting of dc, fundamental and any number of harmonic frequency signals. Since the model is able to calculate the diode response to an arbitrary as well as the usual square current waveform input, the model is well suited to the study of harmonic tuning conditions.

This paper presents the results of an investigation of the harmonic tuning effects of an S-band TRAPATT oscillator. Diode waveforms which produced negative conductances at all signal frequencies were investigated. Calculations were performed in which the phase and magnitude of each input signal frequency were varied in a systematic manner so that the effect of each change on the oscillator performance could be determined. This investigation yielded information directly related to the microwave circuit tuning conditions necessary for high-efficiency operation. Circuit impedance measurements of an S-band TRAPATT oscillator have confirmed many of the theoretical predictions.

## Harmonic Tuning Conditions

Since the changing of harmonic conditions is related to the tuning of experimental oscillators, it is desirable to understand how the harmonics affect oscillator performance. Therefore, a series of computations were performed using the TRAPATT current waveform suggested by Parker[2] as a starting point. This waveform is composed of dc, fundamental and second-harmonic signals and produces negative conductances at all signal frequencies. This waveform is of interest since it allows the existence of oscillations at the second harmonic where TRAPATT oscillators generally produce significant power. It was possible to add a third and fourth harmonic to the original waveform and still obtain negative conductances at all frequencies.

Varying the phase angle of the fundamental signal resulted in a considerable effect on the efficiency of the oscillator (Fig. 1). A shift of 25 degrees of the fundamental phase angle produced a change of only 160 MHz in the fundamental frequency. However, the same phase shift caused a decrease in fundamental efficiency from approximately 35 to 6 percent while the second-harmonic efficiency increased from 2 to 12 percent. It is interesting to note the detuning effect of shifting the fundamental phase so that the oscillator shifts from an almost pure fundamental output to a condition where the second harmonic is the dominant output signal. The detuned condition is interesting since it represents the tuning related to second-harmonic extraction. The terminal voltage and current waveforms representing this condition are shown in Fig. 2. The low fundamental efficiency is obtained because the terminal current has a large component of negative displacement current during the second half of the RF period which prevents the diode voltage from reaching the breakdown value until the end of the RF cycle. Extending the calculations to the amplitude of the fundamental signal revealed that this parameter also has a significant effect on the oscillator efficiency, as expected, but only a relatively minor effect on the operating frequency.

Varying the phase of the second harmonic also resulted in a significant effect on the oscillator efficiency (Fig. 3). The tuning effect of the second harmonic is clearly observed in Fig. 3. The oscillator output signal changes from a condition producing approximately equal fundamental and second-harmonic power to a situation where the fundamental is the only significant output signal. The terminal waveforms resulting from tuning the second harmonic are illustrated in Figs. 4 and 5 for high and low fundamental efficiency conditions, respectively. Again, the second half of the RF period is observed to significantly affect the oscillator efficiency. High efficiency is obtained when the voltage in the second half of the cycle is enhanced with a fundamental component essentially in antiphase with the fundamental component of the terminal current (Fig. 4). However, when the second half-cycle voltage is depressed with a fundamental component in phase with the fundamental component of current a low efficiency results (Fig. 5). Extending the calculations to the amplitude of the second harmonic revealed that this parameter has only a minor influence on the fundamental efficiency but it exerts a significant influence on the operating frequency (Fig. 6) of the oscillator.

The tuning conditions of the third and higher harmonics were found to have a major influence on the frequency of the oscillator (Fig. 7) but only a minor effect on the efficiency (Fig. 8). The higher harmonics affect the frequency because they have a strong wave-shaping influence on the terminal current during the first half of the RF period when the electron-hole plasma is generated and drained from the diode. Since the plasma generation and drainage are very sensitive to the magnitude of the terminal current, the higher harmonics can have a significant influence on the time required to complete the RF period and, therefore, the oscillator frequency.

## Circuit Impedance Measurements

In order to determine experimentally the effects of the RF circuit on TRAPATT oscillator performance, an S-band oscillator was tuned to produce high- and low-efficiency conditions at two S-band frequencies. Using a network analyzer, the circuit impedance as seen by the diode chip was measured.

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The circuit impedances for the first three harmonics are presented in Table I for oscillators tuned to essentially the same frequency under high- and low-efficiency conditions. The 2.21-GHz oscillation produces a higher efficiency (i.e., $\eta$ = 35 percent) because the magnitude and phase angle of the fundamental impedance allow a significant current to flow with a favorable phase angle that approaches the ideal 180-degree diode V-I phase shift for negative-resistance devices. Significant current does not flow at the second harmonic due to the heavy circuit loading as represented by the large $Z_2$ value. The 2.27-GHz oscillation has a slightly smaller fundamental current and a significant second-harmonic current and therefore produces a lower efficiency (i.e., $\eta$ = 22 percent). The operating frequencies of the two oscillations are equal primarily because the third-harmonic phase angles are the same.

The circuit impedances for the first three harmonics are presented in Table II for oscillators tuned to produce approximately the same efficiency at two different frequencies. The slightly higher efficiency of the 2.21-GHz oscillation is due primarily to the smaller magnitude of the fundamental impedance and the more optimum fundamental phase angle as previously discussed. The relatively heavy loading of the second-harmonic signal for the 2.21-GHz oscillation also helps enhance the efficiency of this signal. This phenomenon is due to the fact that harmonic power generally exists at the expense of fundamental power although this effect can be minimized by proper circuit tuning. The theoretical results indicate that the frequency of the oscillator is determined to a major extent by the tuning conditions at the third and higher harmonics. This effect is clearly observed in the results presented in Table II. The phase angles for the two oscillations differ by approximately 21 degrees for the fundamental, 43 degrees for the second harmonic and 200 degrees for the third harmonic. It is therefore concluded that the major shift in the third-harmonic phase angle is directly related to the increase in the frequency of the oscillator from 2.21 to 3.60 GHz

Table I
Circuit Impedance Comparison for TRAPATT Oscillators Tuned for High and Low Efficiencies at a Constant Frequency

| Circuit Impedance Normalized to 50-Ω Line | Normalized Magnitude | Phase Angle (Degrees) |
|---|---|---|
| $\eta$ = 35 Percent, f = 2.21 GHz | | |
| $Z_1$ = 0.18 - j0.07 | 0.194 | 338.5 |
| $Z_2$ = 0.9 - j0.7 | 1.140 | 322.1 |
| $Z_3$ = 0.04 - j0.46 | 0.462 | 275.0 |
| $\eta$ = 22 Percent, f = 2.27 GHz | | |
| $Z_1$ = 0.17 - j0.12 | 0.208 | 324.8 |
| $Z_2$ = 0.06 - j0.115 | 0.130 | 297.5 |
| $Z_3$ = 0.03 - j0.145 | 0.148 | 281.7 |

Table II
Circuit Impedance Comparison for TRAPATT Oscillators Tuned to Different S-Band Frequencies with a Constant Efficiency

| Circuit Impedance Normalized to 50-Ω Line | Normalized Magnitude | Phase Angle (Degrees) |
|---|---|---|
| $\eta$ = 35 Percent, f = 2.21 GHz | | |
| $Z_1$ = 0.18 - j0.07 | 0.194 | 338.5 |
| $Z_2$ = 0.9 - j0.7 | 1.140 | 322.1 |
| $Z_3$ = 0.04 - j0.46 | 0.462 | 275.0 |
| $\eta$ = 28 Percent, f = 3.60 GHz | | |
| $Z_1$ = 0.21 - j0.19 | 0.283 | 317.9 |
| $Z_2$ = 0.05 - j0.315 | 0.320 | 279.0 |
| $Z_3$ = 0.34 + j1.75 | 1.780 | 79.0 |

## Conclusions

The harmonic tuning effects of S-band TRAPATT oscillators have been investigated both theoretically and experimentally. It has been determined that the efficiency of the oscillator at the fundamental frequency is dependent upon the phase angles of the fundamental and second-harmonic signals and the amplitude of the fundamental current. These parameters have a significant influence on the shape of the terminal waveforms, especially the second half-cycle voltage which is extremely important in determining oscillator efficiency. The third and higher harmonics and the magnitude of the second-harmonic signal have a significant influence on oscillator frequency because they shape the waveform of the current during the first half of the RF cycle when the electron-hole plasma is generated and drained from the diode. The higher harmonics, however, have only a minor influence on oscillator efficiency. Microwave circuit impedance measurements of an S-band TRAPATT oscillator support the theoretical predictions.

## References


1. Trew, R. J., Haddad, G. I. and Masnari, N. A., "A Simplified Model of a TRAPATT Diode Oscillator," IEEE Trans. on Electron Devices (submitted for publication).
2. Parker, D., "TRAPATT Oscillations in a p-i-n Avalanche Diode," IEEE Trans. on Electron Devices, vol. ED-18, No. 5, pp. 281-293, May 1971.


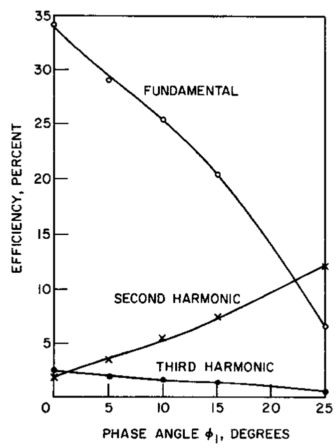


FIG. 1 EFFECT OF THE FUNDAMENTAL PHASE ANGLE RELATIVE TO THE INPUT CURRENT ON THE EFFICIENCY OF AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin ($\omega t + \phi_1$) + 4240 sin ($2\omega t$ + 300 DEGREES) + 2120 sin ($3\omega t$ + 110 DEGREES) A/cm$^2$ AND JCO = 100 A/cm$^2$]

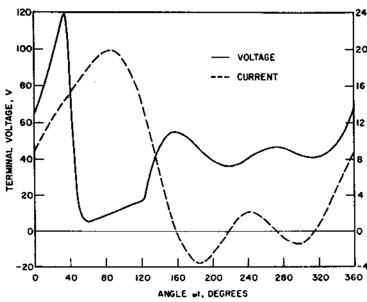


FIG. 2 TERMINAL VOLTAGE-CURRENT WAVEFORMS FOR AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin ($\omega t$ + 25 DEGREES) + 4240 sin ($2\omega t$ + 300 DEGREES) + 2120 sin ($3\omega t$ + 110 DEGREES) $A/cm^2$, JCO = 100 $A/cm^2$, $f_1$ = 3.74 GHz AND $\eta_1$ = 6.5 PERCENT]

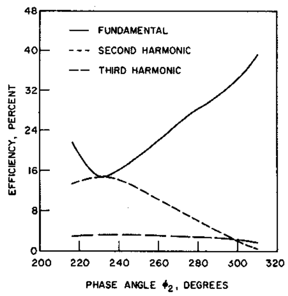


FIG. 3 EFFICIENCY VS. SECOND-HARMONIC PHASE ANGLE RELATIVE TO THE INPUT CURRENT FOR AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin $\omega t$ + 4240 sin ($2\omega t + \phi_2$) + 2120 sin ($3\omega t$ + 110 DEGREES) $A/cm^2$ AND JCO = 100 $A/cm^2$]

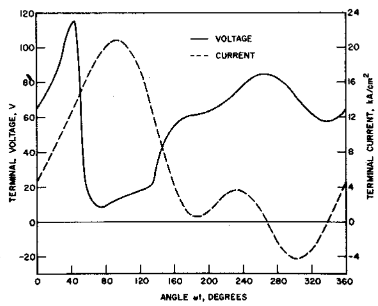


FIG. 4 TERMINAL VOLTAGE-CURRENT WAVEFORMS FOR AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin $\omega t$ + 4240 sin ($2\omega t$ + 300 DEGREES) + 2120 sin ($3\omega t$ + 110 DEGREES) $A/cm^2$, JCO = 100 $A/cm^2$, $f_1$ = 3.85 GHz AND $\eta_1$ = 34.3 PERCENT]

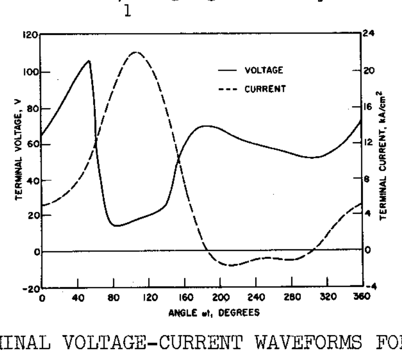


FIG. 5 TERMINAL VOLTAGE-CURRENT WAVEFORMS FOR AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin $\omega t$ + 4240 sin ($2\omega t$ + 230 DEGREES) + 2120 sin ($3\omega t$ + 110 DEGREES) $A/cm^2$, JCO = 100 $A/cm^2$, $f_1$ = 3.96 GHz AND $\eta_1$ = 14.5 PERCENT]

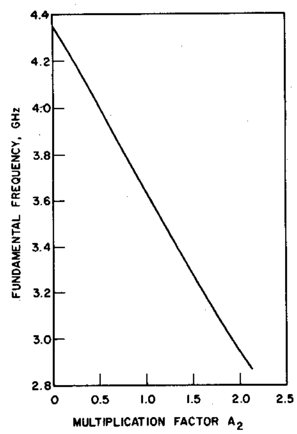


FIG. 6 FREQUENCY VS. SECOND-HARMONIC CURRENT AMPLITUDE FOR AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin $\omega t$ + $A_2$ × 4240 sin ($2\omega t$ + 270 DEGREES) + 2120 sin ($3\omega t$ + 110 DEGREES) + 1500 sin ($4\omega t$ + 150 DEGREES) $A/cm^2$ AND JCO = 100 $A/cm^2$]

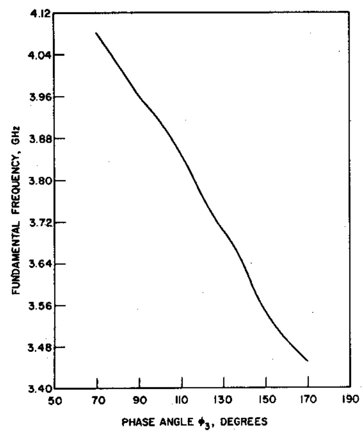


FIG. 7 FUNDAMENTAL FREQUENCY VS. THIRD-HARMONIC PHASE ANGLE RELATIVE TO THE INPUT CURRENT FOR AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin $\omega t$ + 4240 sin ($2\omega t$ + 270 DEGREES) + 2120 sin ($3\omega t + \phi_3$) $A/cm^2$]

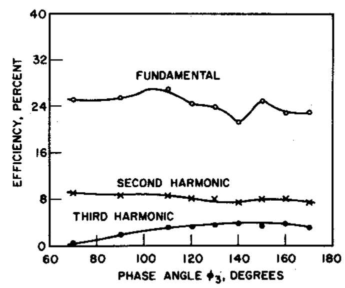


FIG. 8 EFFECT OF THIRD-HARMONIC PHASE ANGLE RELATIVE TO THE INPUT CURRENT ON THE EFFICIENCY OF AN $n^+pp^+$ TRAPATT OSCILLATOR. [JT = 6360 + 10,000 sin $\omega t$ + 4240 sin ($2\omega t$ + 270 DEGREES) + 2120 sin ($3\omega t + \phi_3$) $A/cm^2$ AND JCO = 100 $A/cm^2$]