Short Papers

The Operation of S-Band TRAPATT Oscillators with Tuning at Multiple Harmonic Frequencies

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Abstract—**A simplified TRAPATT oscillator model that allows the investigation of arbitrary terminal waveforms was utilized to investigate realistic TRAPATT waveforms and the tuning conditions necessary for high-efficiency operation. The effects of the higher harmonics on oscillator frequency and efficiency were studied. Circuit impedance measurements of S-band TRAPATT oscillators support the theoretical predictions.**

INTRODUCTION

The operation of TRAPATT oscillators and amplifiers is strongly dependent upon the RF circuit characteristics. Since exact device computer models are relatively expensive to operate, they are not well suited for extensive investigation of arbitrary current or voltage waveforms or for device–circuit interactions. Therefore a great need exists for a simplified TRAPATT model which, while retaining the fundamental behavior of TRAPATT operation, could be used for a detailed investigation of oscillators and amplifiers including harmonic tuning effects. Such a model was developed [1] and employed to obtain a better understanding of the relationship between the diode and microwave circuit. The results of this investigation are presented in this paper. Circuit impedance measurements on an S-band TRAPATT oscillator confirm many of the theoretical predictions.

REALISTIC WAVEFORMS

Most of the TRAPATT-mode computer analyses [2]–[4] performed thus far were concerned with obtaining an understanding of the internal dynamics of the avalanche diode. These analyses generally assume a square-wave terminal current and calculate the diode terminal voltage. There is a question as to the accuracy of this type of analysis since the diode waveforms do not result in negative conductances at all frequencies for which current components exist. A more realistic TRAPATT-mode terminal-current waveform consisting of dc, fundamental, and second-harmonic components was suggested by Parker [5]. Third- and fourth-harmonic components were added in this investigation while at the same time negative conductances were maintained at all signal frequencies. Therefore all of the waveforms should be physically realizable.

The waveforms resulting from the situations where two and three harmonic currents are present in the input waveform are illustrated in Figs. 1 and 2. The addition of the third harmonic (Fig. 2) shapes the terminal current into a slightly narrower waveform with a greater amplitude high-current region. This result can have a significant effect on the frequency of operation since the plasma generation

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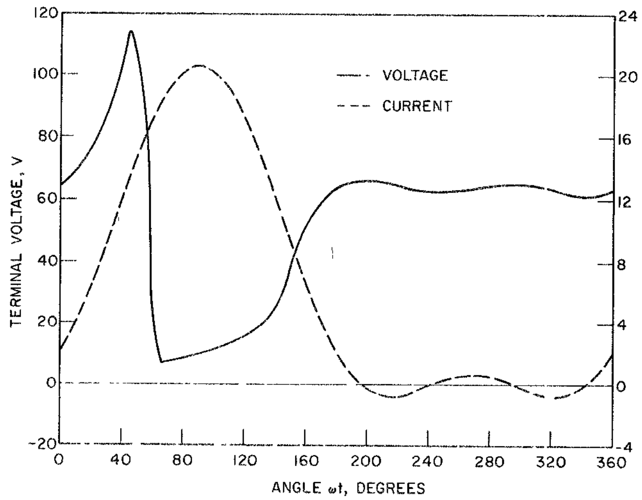

Fig. 1. Terminal voltage-current waveforms for an n^+-p-p^+ TRAPATT oscillator. Total diode terminal current density (JT) = 6360 + 10 000 sin ωt + 4240 sin $(2\omega t + 270°)$ A/cm². Thermally generated, reverse saturation current density (JCO) = 100 A/cm². f_1 = 3.64 GHz. η_1 = 27.4 percent.

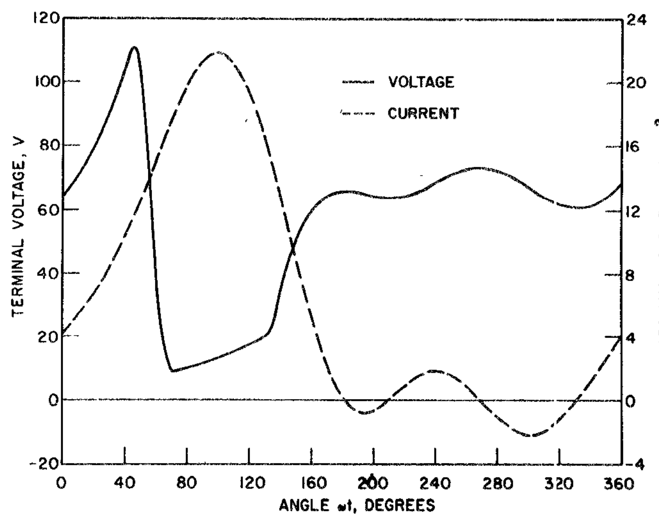

Fig. 2. Terminal voltage-current waveforms for an n^+-p-p^+ TRAPATT oscillator. JT = 6360 + 10 000 sin ωt + 4240 sin $(2\omega t + 270°)$ + 2120 sin $(3\omega t + 110°)$ A/cm². JCO = 100 A/cm². f_1 = 3.85 GHz. η_1 = 26.7 percent.

and rate of charge drainage are directly affected by the terminal current during this portion of the cycle. The higher harmonics can also result in larger displacement current values and correspondingly larger voltage fluctuations during the second half of the microwave period. The net result of the addition of the higher harmonics (i.e., the third and fourth harmonics which were investigated) appears to be a fairly minor reduction in efficiency with the possibility of a significant change in fundamental frequency depending upon the harmonic phase angles involved.

HARMONIC PHASE EFFECTS

Since the changing of harmonic phase angles is related to the tuning of experimental oscillators, it is necessary to understand how the phase angles affect oscillator performance. Therefore computations were performed in which the phase angles of the terminal-current harmonic components were varied to test their influence on the frequency and efficiency of the oscillator. This investigation yielded information directly related to the tuning conditions for high-efficiency oscillations.

The results of shifting the phase of the fundamental current component are illustrated in Figs. 3 and 4. A shift of 25° of the fundamental phase angle produced a change of only 160 MHz in the fundamental frequency (Fig. 3). 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 (Fig. 4). It is interesting to note the detuning effect of changing the fundamental phase such that the oscillator shifts from an almost pure fundamental output to a condition where the second harmonic is the dominant output signal. This is, of course, the condition for second-harmonic extraction. This study indicates that the fundamental efficiency is extremely sensitive to tuning conditions at the fundamental frequency, a result that is also observed experimentally.

The results obtained by shifting the phase angle of the second harmonic while holding all other phase angles constant are illustrated in Figs. 5 and 6. Again, the shift in phase angle is observed to have only a minor effect on the fundamental frequency which changed by only 150 MHz (Fig. 5). However, the phase shift is observed to again have a strong effect on the efficiencies obtained (Fig. 6). By shifting the second-harmonic phase angle by 90°, the fundamental efficiency varied from approximately 14 to 39 percent and the second-harmonic efficiency varied from approximately 14 to less than 1 percent. Again, the tuning effect is observed such that the oscillator shifts from a condition producing almost equal fundamental and second-harmonic signals (i.e., $\phi_2 \simeq 230°$) to a condition in which the fundamental is the only significant output signal. The second-harmonic tuning effects are explained in more detail elsewhere [1].

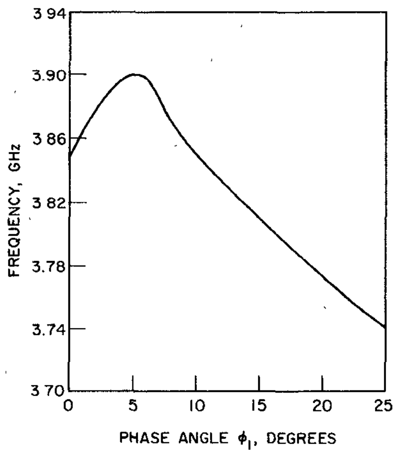

Fig. 3. Fundamental frequency versus fundamental phase angle relative to input current for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin(\omega t + \phi_1) + 4240 \sin(2\omega t + 300°) + 2120 \sin(3\omega t + 110°)$ A/cm². JCO = 100 A/cm².

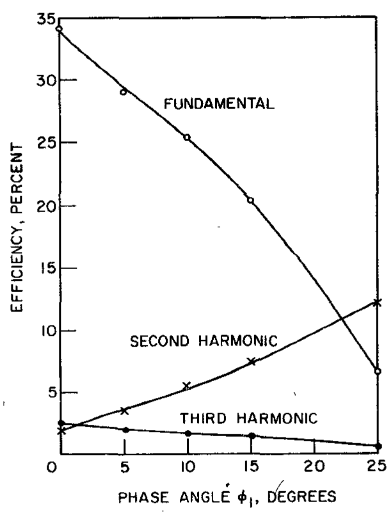

Fig. 4. Effect of the fundamental phase angle relative to the input current on the efficiency of an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin(\omega t + \phi_1) + 4240 \sin(2\omega t + 300°) + 2120 \sin(3\omega t + 110°)$ A/cm². JCO = 100 A/cm².

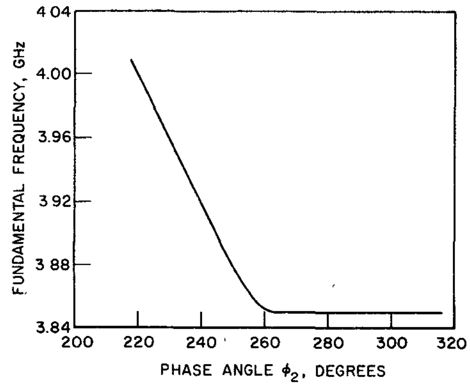

Fig. 5. Fundamental frequency versus second-harmonic phase angle relative to the input current for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin \omega t + 4240 \sin(2\omega t + \phi_2) + 2120 \sin(3\omega t + 110°)$ A/cm². JCO = 100 A/cm².

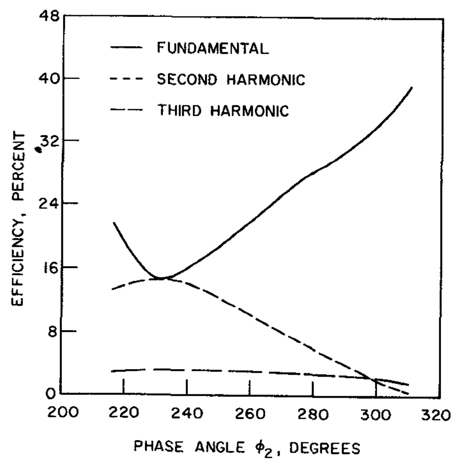

Fig. 6. Efficiency versus second-harmonic phase angle relative to the input current for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin \omega t + 4240 \sin(2\omega t + \phi_2) + 2120 \sin(3\omega t + 110°)$ A/cm². JCO = A/cm².

Extending these computations to the phase angle of the third harmonic yields the results illustrated in Figs. 7 and 8. The phase of the third harmonic is observed to have a major influence on the fundamental frequency (Fig. 7) but only a minor effect on the fundamental efficiency (Fig. 8). The fundamental frequency varies almost linearly over the 4.08–3.44-GHz range corresponding to a third-harmonic phase shift of 100°. For this same change in phase, however, the fundamental efficiency varied only by approximately six percentage points.

Similar results were obtained by adding a fourth harmonic and repeating the computations. The phase of the fourth harmonic was observed to cause a significant change in the fundamental frequency (e.g., a change of 420 MHz in the fundamental frequency for a shift of 100° in the fourth-harmonic phase) and a minor change in efficiency of only four percentage points.

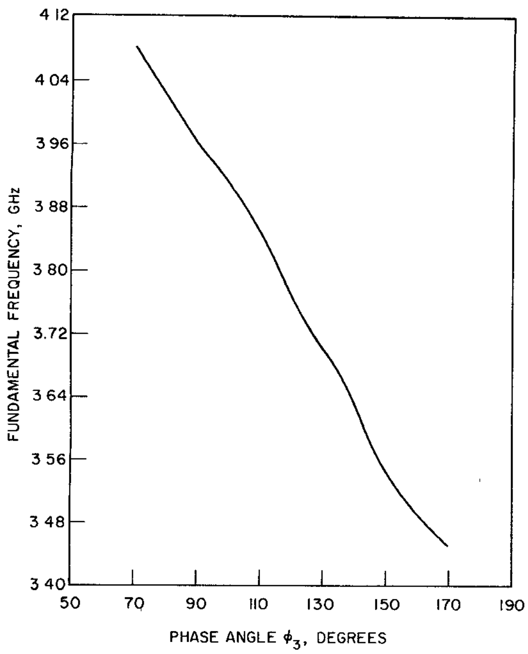

Fig. 7. Fundamental frequency versus third-harmonic phase angle relative to the input current for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin \omega t + 4240 \sin (2\omega t + 270°) + 2120 \sin (3\omega t + \phi_3)$ A/cm². JCO = 100 A/cm².

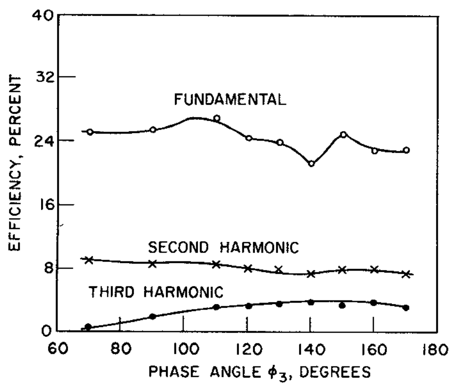

Fig. 8. Effect of third-harmonic phase angle relative to the input current on the efficiency of an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin \omega t + 4240 \sin (2\omega t + 270°) + 2120 \sin (3\omega t + \phi_3)$ A/cm². JCO = 100 A/cm².

HARMONIC AMPLITUDE EFFECTS

In order to completely establish the oscillator response to various harmonic tuning conditions, it is necessary to determine the effects of varying the harmonic amplitudes. Therefore a series of computations was conducted in which the magnitude of each harmonic was varied while all others were held constant.

Varying the magnitude of the fundamental from 75 to 125 percent of its original value resulted in a 260-MHz change in the fundamental frequency (Fig. 9). However, this same magnitude change resulted in an increase in efficiency from 6 to 38 percent (Fig. 10). The strong dependence of efficiency on fundamental amplitude is expected since the RF power generated is dependent upon the magnitude of the fundamental current. With a constant dc power input, the efficiency varies directly with the RF power generation.

The effects of varying the magnitude of the second-harmonic current from 0 to 200 percent of its original value are illustrated in Fig. 11 (frequency variation) and in Fig. 12 (efficiency variation). A strong frequency dependence is observed to exist. During these

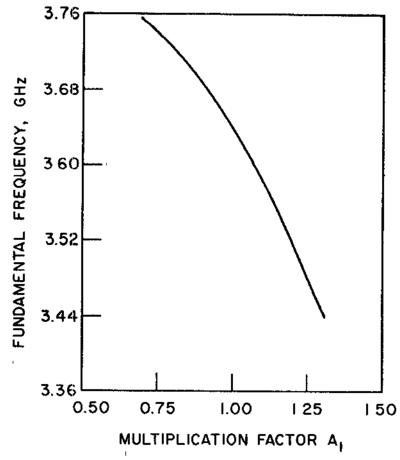

Fig. 9. Frequency versus fundamental current amplitude for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + A_1 \times 10\,000 \sin \omega t + 4240 \sin (2\omega t + 270°) + 2120 \sin (3\omega t + 110°) + 1500 \sin (4\omega t + 150°)$ A/cm². JCO = 100 A/cm².

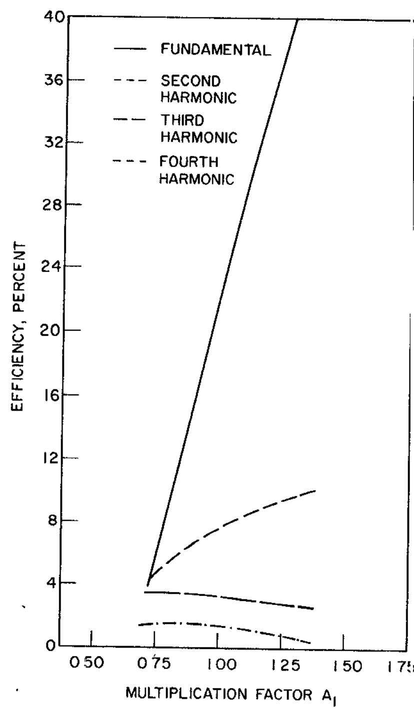

Fig. 10. Efficiency versus fundamental current amplitude for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + A_1 \times 10\,000 \sin \omega t + 4240 \sin (2\omega t + 270°) + 2120 \sin (3\omega t + 110°) + 1500 \sin (4\omega t + 150°)$ A/cm². JCO = 100 A/cm².

computations the fundamental frequency shifted linearly with the second-harmonic magnitude over a range of 1.4 GHz. Increasing the magnitude of the second-harmonic current resulted in a reduction in fundamental efficiency of approximately 6 percentage points and an increase in second-harmonic efficiency of 14 percentage points. A slight increase in third-harmonic efficiency and a slight decrease in fourth-harmonic efficiency were also observed.

Extending these calculations to the higher harmonics revealed that the magnitudes of the odd harmonics have a relatively minor effect on the frequency of operation while the even harmonics exert a strong influence. The even harmonics alter the fundamental oscillating frequency because they have a tendency to shape the terminal-current waveform during the first half of the RF cycle. Increasing the even harmonic amplitudes alters the terminal-current

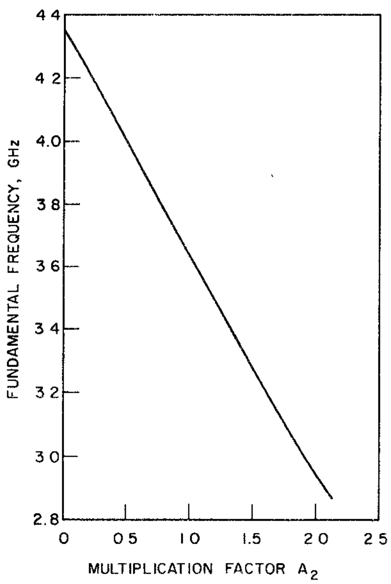

Fig. 11. Frequency versus second-harmonic current amplitude for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin \omega t + A_2 \times 4240 \sin (2\omega t + 270°) + 2120 \sin (3\omega t + 110°) + 1500 \sin (4\omega t + 150°)$ A/cm². JCO = 100 A/cm².

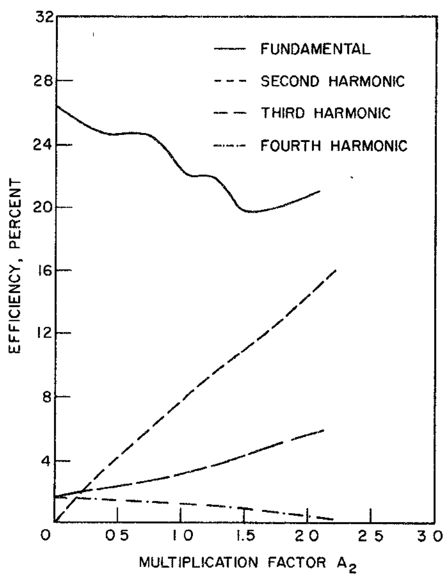

Fig. 12. Efficiency versus second-harmonic current amplitude for an n^+-p-p^+ TRAPATT oscillator. $JT = 6360 + 10\,000 \sin \omega t + A_2 \times 4240 \sin (2\omega t + 270°) + 2120 \sin (3\omega t + 110°) + 1500 \sin (4\omega t + 150°)$ A/cm². JCO = 100 A/cm².

waveform so that a large electron-hole plasma is generated after a relatively long period of time. The oscillation frequency is therefore decreased. The increase of the harmonic magnitudes does not have a major influence on the fundamental efficiency although a slight decrease is observed as the harmonic amplitudes increase. The efficiency of the fundamental, however, is obviously directly controlled by the magnitude of the fundamental current.

EXPERIMENTAL MICROWAVE CIRCUIT MEASUREMENTS AND COMPARISON WITH THEORETICAL PREDICTIONS

In order to determine the effects of the RF circuit on TRAPATT oscillator performance, a coaxial S-band TRAPATT oscillator was tuned to produce high- and low-efficiency conditions at two S-band frequencies. The diode was then removed from the circuit and replaced with a connector that was fabricated to provide a continuous transition from the oscillator cavity to a network analyzer. In this manner it was possible to measure the RF circuit as seen by the diode and package without the necessity of moving the tuning slugs or disassembling the circuit. The circuit impedances were then transformed through a package model to obtain the impedances as they appear at the diode chip.

Although it is rather difficult to obtain close correspondence between an experimental operating point and one computed theoretically unless the voltage and current waveforms are measured, some observations and comparisons with theory can be made by measuring the circuit impedance. Therefore the oscillator was first tuned to produce high- and low-efficiency conditions at a fixed frequency. The circuit impedances were measured through frequencies near the high end of X band. The circuit impedance measurements were limited to five harmonic frequencies for the oscillator operating at approximately 2.2 GHz and to three harmonic frequencies for the oscillator operating at approximately 3.5 GHz.

An understanding of the relationship between the RF circuit impedances and the efficiency of the oscillator can be obtained from the impedance results presented in Table I and the theoretical results presented earlier. The first three harmonic impedances are presented in Table I for oscillators tuned to essentially the same frequency (i.e., 2.21 and 2.27 GHz) under high- and low-efficiency conditions (i.e., 35 and 22 percent, respectively). The theoretical results indicate that the oscillator efficiency is very sensitive to the magnitude of the fundamental current. The fundamental efficiency is also dependent upon the phase angles of the fundamental and second-harmonic currents. The results of the circuit measurements presented in Table I support these conclusions. A high efficiency (i.e., 35 percent) is obtained for the 2.21-GHz oscillation because its fundamental impedance has a smaller magnitude than that of the 2.27-GHz oscillation. This allows a larger fundamental component of current to flow and helps produce a higher efficiency. The fundamental phase angle for the 2.21-GHz oscillation also favors a higher efficiency since the circuit impedance phase angle (at the fundamental) corresponds to a diode phase angle of 158.5° as compared to 144.8° for the 2.27-GHz oscillation. The diode voltage–current angle for the 2.21-GHz oscillation is, therefore, closer to the ideal 180° phase difference for negative-resistance devices, which helps to produce the higher efficiency. The theoretical results also indicate that RF power at the harmonic frequencies generally occurs at the expense of the fundamental signal, although this effect can be minimized by proper circuit tuning. Nevertheless, the heavy loading of the second-harmonic signal for the 2.21-GHz oscillation probably prevents a significant second-harmonic current from flowing which in turn helps in achieving the high fundamental efficiency.

According to the theoretical predictions, the frequency of the

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)
	η = 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
	η = 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

fundamental oscillation is dependent to a major extent upon the tuning conditions of the third- and possibly higher harmonic frequencies. From the oscillator circuit measurements presented in Table I, the essentially identical frequencies of the two oscillations are expected since the two third-harmonic phase angles differ by only approximately 7° (i.e., $\phi_3 = 275$ and 281.7°).

An understanding of the frequency-determining characteristics of the RF circuit upon the TRAPATT oscillator can be obtained from the circuit impedances presented in Tables II and III. The RF circuit impedances measured for the first three harmonics of an n^+-p-p^+ oscillator operating at two different frequencies (i.e., at approximately 2.2 and 3.6 GHz) for approximately the same efficiency (i.e., $\eta = 35$ and 28 percent) are presented in Table II. 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 the fundamental. The theoretical results indicate that the frequency of the oscillator is determined to a major extent by the third- and higher harmonic phase angles. This effect is clearly observed in the results presented in Table II. The phase angles for the two oscillations differ by approximately 21° for the fundamental, approximately 43° for the second harmonic, and approximately 200° 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.

The theoretical results indicate that the magnitude of the second-harmonic signal can also have a significant effect on the oscillator frequency. An example of this type of operation is observed in the circuit impedance measurements presented in Table III. In this example both the magnitudes and the phase angles of the fundamental impedances are essentially identical for both frequencies. This result is consistent with the measured efficiencies which differ by only three percentage points for the two oscillations (i.e., 22 percent for the 2.27-GHz oscillation and 19 percent for the 3.48-GHz oscillation). The relatively small magnitude of the second-harmonic impedance for both signals indicates that significant current is allowed to flow at these frequencies and that, therefore, the second-harmonic amplitude has the potential of significantly affecting the oscillator performance. The presence of the relatively strong second-harmonic frequency was confirmed by spectrum analyzer observations and is probably a factor in the low efficiencies obtained. The smaller second-harmonic impedance magnitude of the 2.27-GHz oscillation indicates that a larger current would be allowed to flow at this frequency for this oscillation than for the corresponding situation at the higher frequency. The larger second-harmonic current is consistent with the lower operating frequency as presented earlier. The approximately equal efficiencies for the two oscillations are also consistent with the approximately equal second-harmonic phase angles.

It is difficult to directly compare the effect of the third-harmonic phase angles on the oscillator results presented in Table III because the third harmonic of the higher frequency oscillation probably does not exist due to the heavy resistive loading (i.e., normalized impedance magnitude of 2.66) of the third-harmonic impedance.

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)
η = 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
η = 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

TABLE III
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)
η = 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
η = 19 Percent, f = 3.48 GHz		
$Z_1 = 0.18 - j0.11$	0.211	328.6
$Z_2 = 0.04 - j0.18$	0.185	282.5
$Z_3 = 1.75 - j2.0$	2.660	311.2

SUMMARY AND CONCLUSIONS

Many different waveforms resulting in negative conductances at all signal frequencies were investigated with the aid of a simplified TRAPATT oscillator computer model. It was determined that although many different waveforms result in TRAPATT-mode operation, they all are characterized by a high magnitude current during the first half-cycle and a low magnitude current during the second half-cycle.

A study of the harmonic effects on oscillator performance revealed that the fundamental frequency of oscillation is primarily dependent upon the amplitude of the second-harmonic current and the phase angles of the third and higher harmonics. These parameters have a significant influence on oscillator frequency because they shape the form of the terminal current during the first half-cycle when the electron-hole plasma is being generated and drained from the diode. The higher harmonics, however, have only a minor influence on oscillator efficiency.

The efficiency of the oscillator is determined primarily by 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.

Circuit impedance measurements of an experimental coaxial S-band oscillator support the theoretical predictions.

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