INTERMODULATION CHARACTERISTICS OF X-BAND IMPATT AMPLIFIERS*

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Abstract

The intermodulation products produced when two equal amplitude signals are applied to the input of an X-band IMPATT diode amplifier have been measured. A Si p^+nn^+ IMPATT diode was operated in a double-slug-tuned reflection amplifier circuit that was tuned to provide 20 dB of small-signal gain at 9.340 GHz. The intermodulation tests consist of measurements of the magnitudes and frequencies of the amplifier output signals as a function of the input signal drive levels and frequency separations. The gain and single-frequency characteristics of the amplifier were also measured and are used along with the theoretical device and circuit admittance characteristics as a basis for explanation of the intermodulation results. A low-frequency dominance mechanism is found to exist in which the low-frequency signals are amplified more than the high-frequency signals. This mechanism becomes more significant as the amplifier drive level is increased.

Introduction

As a result of the inherent nonlinearity associated with large-signal operation of avalanche transit-time devices, the introduction of two or more signals into the input of an IMPATT amplifier results in the generation of intermodulation products in the amplifier output. Measurements have been made of the intermodulation products produced when two, equal-amplitude signals are applied to the input of an X-band IMPATT diode amplifier. The test results consist of measurements of the magnitudes and frequencies of the amplifier output signals as a function of the input signal drive levels and frequency separations. The results presented are typical for IMPATT devices of the p^+nn^+ structure. Use is made of the IMPATT diode and circuit admittance characteristics to explain the output behavior of the amplifier.

Circuit Description

The block diagram of Fig. 1 represents the basic reflection amplifier circuit used in these experiments. Input-output signal separation is provided by a coaxial three-port circulator. Amplifier tuning is accomplished through the positioning in the resonant cavity of two 20-Ω, copper tuning slugs; one being $\lambda/4$ at 8 GHz, the other $\lambda/4$ at 10 GHz. The diode, which is located in the end of the resonant cavity, is kept at an approximately constant temperature by a water-cooled heat sink. The primary measurement circuit consists of a precision attenuator/spectrum analyzer combination calibrated to read power levels at the input-output plane of the resonant cavity.

Discussion

The basic single-frequency operation of IMPATT amplifiers has been discussed by Haddad et al.[1] and is reviewed here for convenience. Figure 2 shows a typical admittance plot of an IMPATT device and a plot of the negative of the admittance of a one-slug-tuned reflection amplifier circuit for a stable circuit tuning condition. The power gain of a reflection amplifier can be expressed as

$$\text{Power Gain} = |\Gamma|^2 = \left|\frac{Y_{circuit} - Y^*_{device}}{Y_{circuit} + Y_{device}}\right|^2 ,$$

where Γ = the reflection coefficient and
Y = the admittance.

According to this expression stable amplification is possible as long as the diode admittance and circuit negative admittance curves do not intersect at a common frequency point. Because the denominator of the power gain expression can be represented by the distance between common frequency points on the circuit and diode curves, the intersection of the curves at a common frequency would produce a denominator of zero value, resulting in infinite gain and oscillation at the frequency of the intersection of the curves. It follows that the magnitude of the power gain possible for any tuning condition is dependent upon the distance between common frequency points on the diode and circuit negative admittance curves. For a fixed slug position where the amplifier is tuned for maximum small-signal gain, it is expected that an increase in the operating power level will result in a decrease in gain. The increased power level causes a shift in the diode operating point resulting in an increased distance between common frequency points on the device and circuit admittance curves, thereby increasing the denominator value of the power gain expression and thus reducing the gain. An increase in operating power level is also expected to result in a decrease in the frequency at which maximum gain occurs. Basically, this is due to an increasing device susceptance with increasing power level which reduces the resonant frequency of the amplifier-circuit interaction.[1]

Multifrequency operation results in the generation of sum-and-difference intermodulation products in the amplifier output. The decreasing gain and lowering of the frequency of maximum gain with increasing power levels are expected to provide a low-frequency dominance mechanism in which the low-frequency signals are amplified more than the high-frequency signals. This effect should become more pronounced as the drive level is increased. It is also expected that the intermodulation products will reduce the power available at the fundamental signals.

Spurious Oscillations

The circuit characteristic shown in Fig. 2 is somewhat idealized in that it allows for stable amplification at all frequencies regardless of the power level to which the diode is driven. A more typical characteristic would be one that in some manner "circled" through the diode admittance curves, thus allowing the curves to intersect at common frequency

* This work was supported by the National Aeronautics and Space Administration under Grant No. NGL 23-005-183.

points at certain drive levels. This would, of course, result in spurious oscillations occurring as the drive level is increased. Experimenting with coaxial IMPATT amplifiers revealed that spurious oscillations are a serious problem limiting the range over which the amplifiers can be operated. However, during these experiments the utilization of a two-slug-tuned resonant cavity resulted in sufficient circuit flexibility such that it was possible to achieve a tuning condition that eliminated spurious oscillations even when the diode was driven to saturation.

Results

Figure 3 illustrates the gain characteristics of an amplifier tuned to provide 20.4 dB of small-signal gain at a frequency of 9.340 GHz. As expected, an increase in the drive level resulted in a decrease in the maximum gain and its corresponding frequency. However, it is interesting to note that at frequencies below the maximum gain frequency it is possible to obtain increasing gain as a function of increasing drive level. This behavior can be explained from Fig. 2 where it is seen that at low frequencies it is possible for the distance between common frequency points on the diode and circuit curves to decrease with increasing drive level and thus results in increasing gain over certain operating ranges.

The intermodulation measurements consist of two sets of tests; one with an input signal (F_2) fixed at the maximum small-signal gain frequency and the other input signal (F_1) set at lower frequencies defined by separations of 3 MHz, 10 MHz, 30 MHz, 100 MHz and 200 MHz, and a second set of tests in which F_1 was fixed at the frequency of maximum small-signal gain and F_2 was set at higher frequencies defined by the above frequency separations. The results of the two sets of measurements are similar and therefore only the initial set is discussed in detail. Power output vs. power input data were recorded for all significant signals appearing in the amplifier output under both single-frequency (only one signal present at a time) and two-frequency (both input signals present) operation. The intermodulation products are defined as follows. First order: $F_3 = 2F_1 - F_2$, $F_4 = 2F_2 - F_1$. Second order: $F_5 = 3F_1 - 2F_2$, $F_6 = 3F_2 - 2F_1$. Third order: $F_7 = 4F_1 - 3F_2$.

Figure 4 shows the results of the $\Delta f = 3$ MHz test. At such small-frequency separations the gain is approximately the same and therefore the same output power is generated in both fundamental signals. When both input signals were present a complete spectrum of signals was generated in the output as expected. The two-frequency test resulted in less power output at the fundamental frequencies than in the single-frequency test with the difference appearing as power at the intermodulation frequencies. The first-order products F_3 and F_4 are the first to appear and have the same magnitude until higher drive levels are achieved where the shift of the gain characteristics favoring amplification at lower frequencies becomes significant. At the higher drive levels the low-frequency intermodulation products always have a greater magnitude than their high-frequency counterparts. This behavior is more apparent in the higher-order intermodulation products where due to the greater frequency separation the gain shift is more significant. The largest intermodulation signal, F_3, reaches a magnitude within 13 dB of the amplified fundamental signals.

The $\Delta f = 30$ MHz test (Fig. 5) clearly demonstrates the low-frequency dominance mechanism. The single-frequency curves indicate that first F_2 and then F_1 have the greatest output magnitude. This behavior is explained by the shift in the gain characteristics with increasing drive level. Since F_2 is fixed at the frequency of maximum small-signal gain it initially has the greatest output power. As the drive level is increased the peak gain frequency shifts downward until eventually F_1 has the greater output power. Increasing the drive level further results in equal output power in the two signals. This is due to the broadband nature of the amplifier at high drive levels where all signals, independent of their frequency relative to the gain characteristics, experience essentially the same gain. The two-frequency results indicate that the high-frequency fundamental signal F_2 loses proportionally more power to the intermodulation products than the low-frequency fundamental signal F_1. This occurs because the relatively greater gain at the lower frequency partially compensates for the power lost to the intermodulation products. Low-frequency dominance is clearly evident as the first-, second- and then third-order low-frequency intermodulation products all become larger than the first-order high-frequency product, with F_3 attaining a magnitude within 7 dB of the amplified F_2 signal.

Increasing the frequency separation to 100 MHz results in less interaction between the fundamental signals in that there are fewer intermodulation products generated. The only significant products produced are the first-, second- and third-order low-frequency signals. The two-frequency results show that it is possible for the output power of one of the fundamental signals to decrease as the drive level is increased. This is caused by the gain actually increasing with increasing drive level at the lower frequencies (Fig. 3). The strong amplification of the low-frequency intermodulation signals requires significant power transferral from the fundamental signals. Since F_2 experiences the relatively greater decrease in gain with increasing drive level it supplies most of the power required by the intermodulation signals. Thus, in order to satisfy the output power requirements, the high-frequency fundamental signal F_2 experiences a decreasing output power over a portion of the input power range. At this frequency separation the largest intermodulation signal F_3 attains a magnitude within 6 dB of the amplified F_2 signal.

Conclusions

Multisignal operation of IMPATT amplifiers results in the loss of available output power at the fundamental signals. The lost power appears in signals at intermodulation frequencies. IMPATT amplifiers are characterized by a decrease in the peak gain and a lowering of the peak gain frequency with increasing drive level providing a low-frequency dominance mechanism in which the low-frequency signals are amplified more than the high-frequency signals. The magnitude of the intermodulation signals is dependent upon the frequency separation between the fundamental signals and also upon the position of the signals relative to the amplifier gain characteristics. Increasing the frequency separation between the fundamental signals results in a decreasing interaction between them such that fewer intermodulation products are generated.

Reference

1. G. I. Haddad et al., "Microwave Solid-State Device Studies," Report No. RADC-TR-70-261, Contract No. F30602-68-C-0043, Electron Physics Laboratory, The University of Michigan, Ann Arbor, pp. 101-113, November 1970.

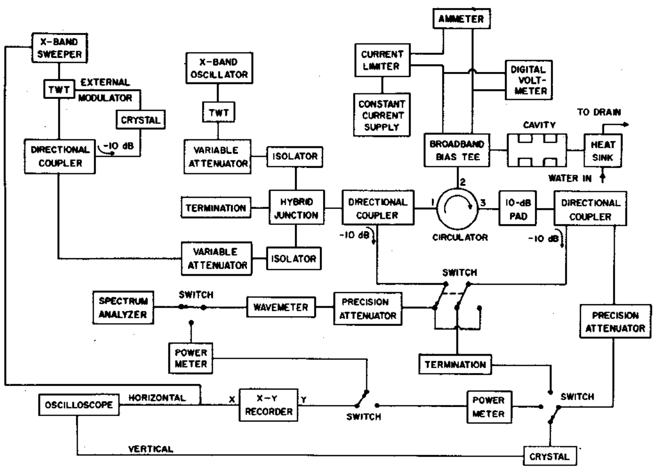

FIG. 1 REFLECTION AMPLIFIER CIRCUIT, TWO-FREQUENCY OPERATION.

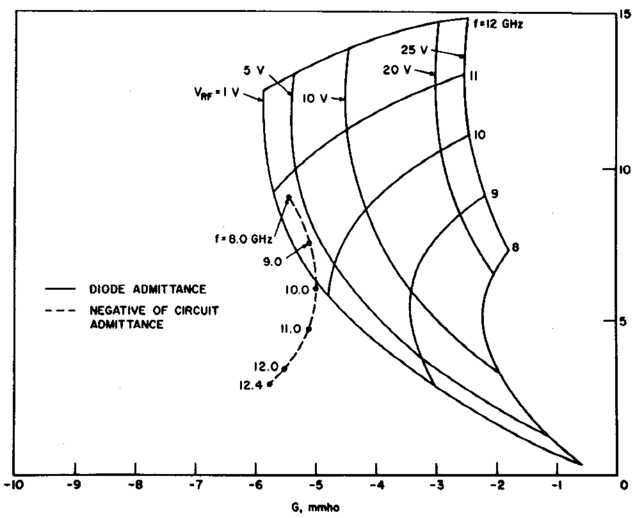

FIG. 2 THE DIODE ADMITTANCE FOR DIFFERENT VALUES OF V_{RF} AND FREQUENCY AND THE NEGATIVE OF THE CIRCUIT ADMITTANCE VS. FREQUENCY AT THE PLANE OF THE DIODE.

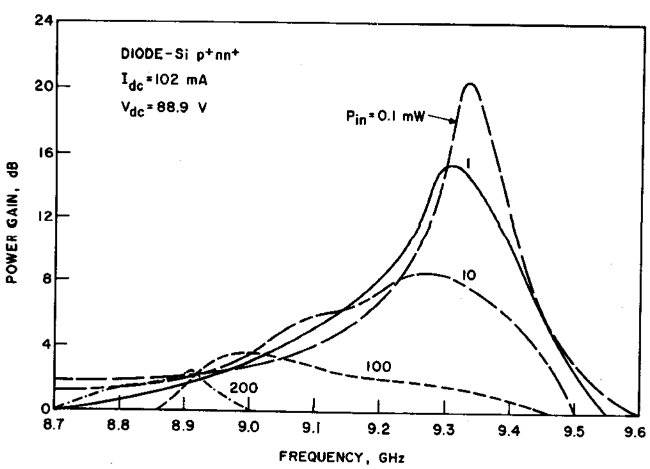

FIG. 3 IMPATT AMPLIFIER GAIN CHARACTERISTICS.

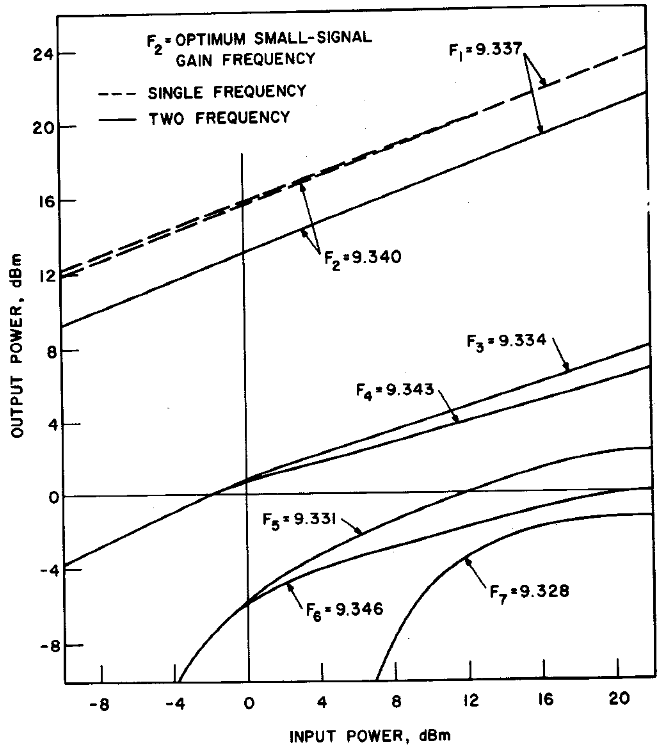

FIG. 4 DYNAMIC CHARACTERISTICS FOR IMPATT AMPLIFIER, TWO EQUAL AMPLITUDE INPUT SIGNALS. (Δf = 3 MHz)

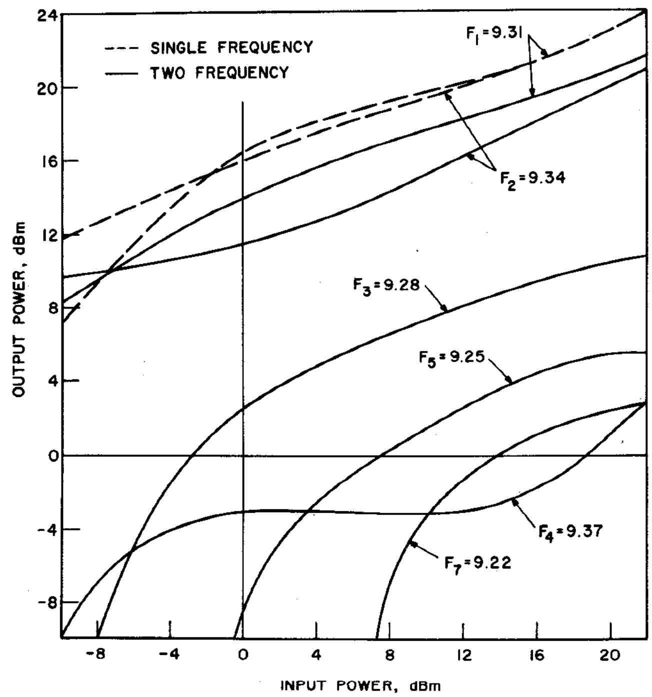

FIG. 5 DYNAMIC CHARACTERISTICS FOR IMPATT AMPLIFIER, TWO EQUAL AMPLITUDE INPUT SIGNALS. (Δf = 30 MHz)