Up-Conversion in IMPATT Amplifiers

RAMESH K. GUPTA, STUDENT MEMBER, IEEE, AND COLIN G. ENGLEFIELD, MEMBER, IEEE

Abstract—**A simple technique has been presented to determine the up-conversion characteristics of IMPATT-diode amplifiers. The method uses the admittance characteristics of the device and the circuit of the amplifier. Theoretical results are given for a typical example and a comparison is made with experimental results obtained for actual amplifiers. Qualitative agreement is obtained.**

I. Introduction

IMPATT-DIODE amplifiers can be used as microwave up-converters by impressing an intermediate-frequency (IF) signal onto the bias circuit of the amplifier [1], [3]–[5]. High conversion gain can be obtained by use of such a scheme, even in the millimeter-wave region [4], [6].

The Read model has been extensively used for understanding and analysis of the conversion process in avalanche diodes. By solving the nonlinear differential equations describing particle current in IMPATT diodes (continuity equations for holes and electrons, and Poisson's equation), important qualitative results explaining the conversion phenomena have been reported [2]–[4]. The Read model is recognized as an imperfect representation of real diodes; therefore, the results are only approximate for practical devices.

This paper describes another approach to analyze the frequency-conversion characteristics of avalanche amplifiers in terms of familiar engineering concepts. The admittance characteristics of the diode and of the microwave circuit have been used for the study. Theoretical results are obtained for a typical example and qualitative agreement is obtained with experimentally observed results.

II. Analysis

Using the model of Laton and Haddad [7], the power gain of a one-port reflection-type IMPATT amplifier is given by

$$P = |\Gamma|^2 = \left|\frac{Y_L - Y_D^*}{Y_L + Y_D}\right|^2 \tag{1}$$

where Y_L and Y_D are the admittances of the circuit and of the diode, respectively, and Γ is the reflection coefficient of the amplifier. (For an amplifier, the real part of Y_D must be negative.) The asterisk indicates the complex conjugate.

Defining $Y_L - Y_D^*$ as the numerator vector N and $Y_L + Y_D$ as the denominator vector D, then

$$P = \left|\frac{N}{D}\right|^2. \tag{2}$$

Manuscript received February 16, 1977; revised May 31, 1977.

The authors are with the Department of Electrical Engineering, University of Alberta, Edmonton, Alta., Canada.

Bias-current modulation due to the IF signal will cause variations in the device admittance vector at the signal frequency. In general, the variation of Y_D with the bias current will be a complex nonlinear function that will cause both amplitude and phase variations in the microwave output signal.

The analysis may be simplified considerably, however, if we make the following assumptions. First, for small IF signals at frequency ω_1, we may assume that $\tilde{Y}_d$, the variation of Y_D, will be a linear function of the bias signal, so that we may write

$$\tilde{Y}_d = Y_{d_1} \sin \omega_1 t. \tag{3}$$

Second, it has been shown by Greiling and Haddad [8] that bias-current variations affect mainly the conductance of the diode; the device susceptance variation is relatively small. If we neglect the latter effect, then $\tilde{Y}_d$ in (3) becomes a real quantity.

Then (1) can be written

$$|\tilde{\Gamma}| = \left|\frac{Y_L - Y_D^* - Y_{d_1} \sin \omega_1 t}{Y_L + Y_D + Y_{d_1} \sin \omega_1 t}\right| \tag{4}$$

where the origin of the time variable can be chosen to make Y_{d_1} a negative quantity.

Equation (4) may be written

$$|\tilde{\Gamma}| = \left|\frac{N + |Y_{d_1}| \sin \omega_1 t}{D - |Y_{d_1}| \sin \omega_1 t}\right|. \tag{5}$$

The magnitude of Y_{d_1} must remain less than D if the amplifier is to be stable.

This equation may be expanded in a Fourier series to give a fundamental component of $\tilde{\Gamma}$ at ω_1 and higher frequency harmonics. Defining $\beta = |Y_{d_1}|/D$ and using $|\Gamma| = |N/D|$, we get

$$\begin{aligned} |\tilde{\Gamma}| = \Bigg| &\left[\Gamma + (1+\Gamma) \sum_{n=1}^{\infty} \frac{\beta^{2n}}{2^{2n}} {}^{2n}C_n\right] \\ &+ \sin \omega_1 t[1+\Gamma] \sum_{n=0}^{\infty} \frac{\beta^{2n+1}}{2^{2n}} {}^{2n+1}C_n \\ &+ \cos 2\omega_1 t[1+\Gamma]\beta^2[1+\Gamma+\cdots+\cdots] \\ &+ \text{higher frequency terms} \Bigg| \end{aligned} \tag{6}$$

where ${}^nC_m = (n!/m!\,(n-m)!)$. The microwave output signal is given by $\tilde{\Gamma}$ times the input signal

$$V_{out} = |\tilde{\Gamma}|\, V_{in} \sin \omega_p t \tag{7}$$

where ω_p is the microwave input or "pump" frequency.

0018-9480/78/0100-0028$00.75 © 1978 IEEE

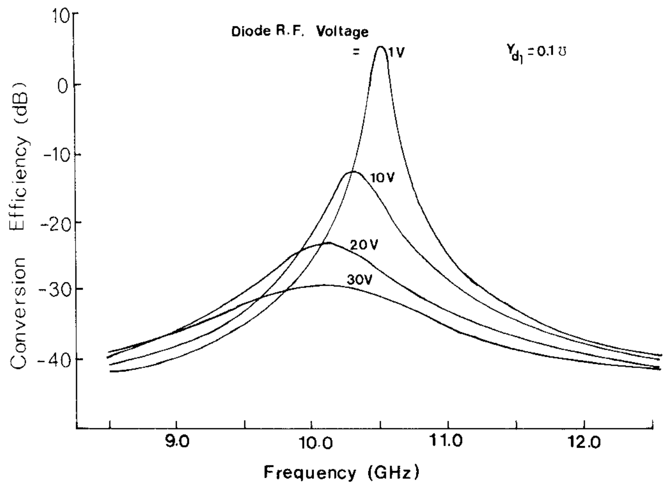

Fig. 1. Theoretical conversion efficiency versus RF frequency at different RF power levels.

If ω_1 is small then the admittances presented to the sideband frequencies will be equal, and the first sideband microwave-conversion efficiency, defined as

$$\eta = \frac{\text{up-converted (sideband) power}}{\text{input microwave power}}$$

will be given by

$$\eta = 20 \log \left| \left[\tfrac{1}{2}(1 + \Gamma) \sum_{n=0}^{\infty} \frac{\beta^{2n+1}}{2^{2n}} \, {}^{2n+1}C_n \right] \right|. \tag{8}$$

Equation (8) is a convergent series and for known values of β, the conversion efficiency η can be calculated.

III. Typical Example

Using the admittance data of Laton and Haddad [7] as a typical example, theoretical results for η have been obtained for different values of Y_D, frequency, and Y_{d_1}. Y_D depends upon the bias-current frequency, and microwave-power level, and these values were taken directly from the device-circuit admittance diagram. For the purposes of this study, Y_{d_1} has been assumed to depend only on bias-signal level. A plot of conversion efficiency as a function of frequency at different input microwave levels is shown in Fig. 1. The conversion characteristics are similar to amplifier gain characteristics. The shift in gain maxima and broad-banding with increase in microwave signal level is quite apparent.

The conversion efficiency as a function of $|Y_{d_1}|$ is plotted in Fig. 2. The efficiency increases with increase in $|Y_{d_1}|$, that is with increase in the IF signal. It is to be noted that at small microwave input levels, where the amplifier has larger gain, the conversion efficiency is also larger. The conversion-efficiency bandwidth is comparable to the amplifier bandwidth. The variation with frequency is a direct result of the variation of Y_L and Y_D, so that the conversion characteristics are similar to the amplifier gain characteristics.

IV. Experimental Results

Experimental results were obtained for two IMPATT amplifiers, a single-tuned narrow-band coaxial-cavity amplifier and a relatively broad-band double-tuned waveguide amplifier. The device used in both cases was an X-band HP5082-0435 IMPATT diode. The narrow-band amplifier has a small-signal gain of 15 dB at -20-dBm input and 9.975-GHz center frequency and a 3-dB bandwidth of 10 MHz. An intermediate frequency of 10 MHz was used (because of the amplifier being narrow-band). The conversion efficiency for the lower sideband versus input frequency at input levels of -10, -5, 0, and $+5$ dBm is plotted in Fig. 3. A very weak IF signal (0.2 V_{p-p}) was used.

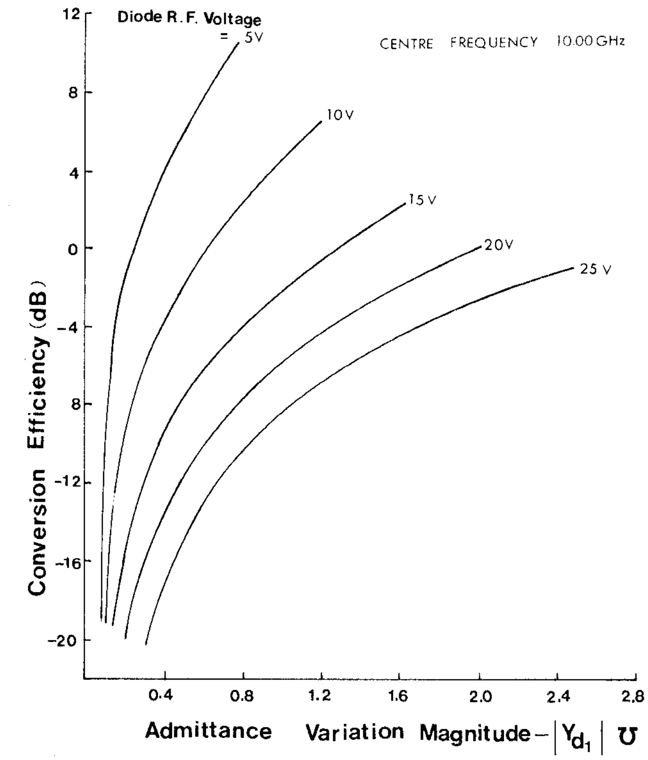

Fig. 2. Theoretical conversion efficiency versus device—admittance variation magnitude $|Y_{d_1}|$, at different microwave input levels.

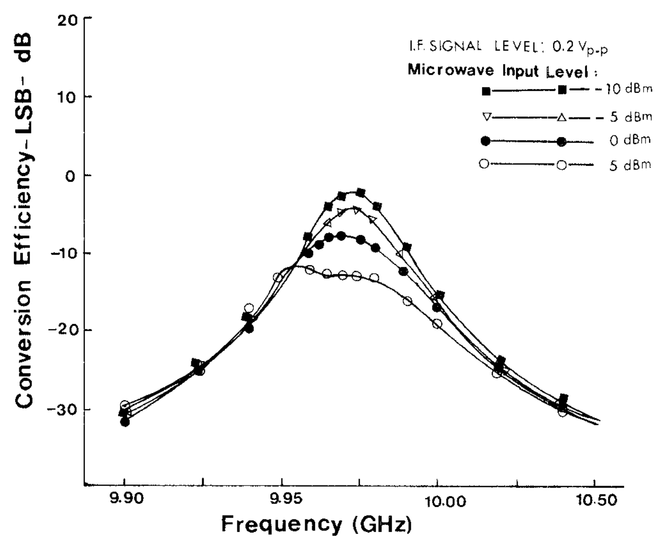

Fig. 3. Conversion efficiency (LSB) versus microwave frequency at different input power levels. Bias current: 29.5 mA.

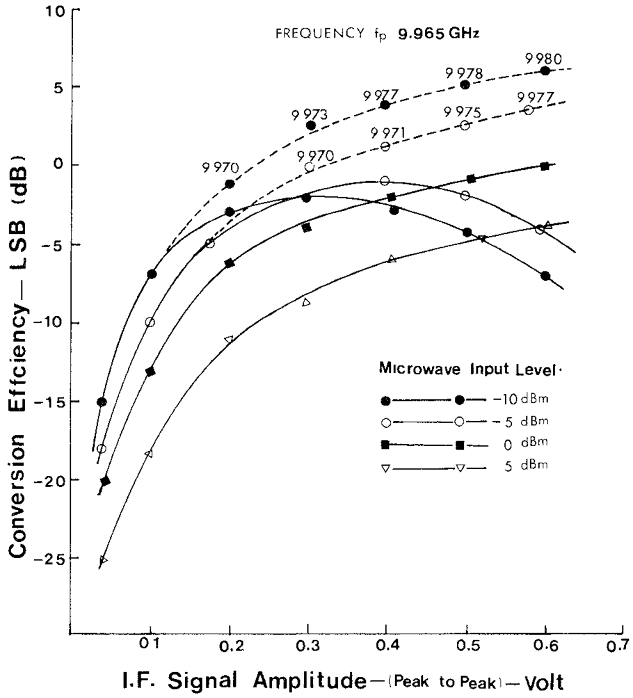

Fig. 4. Conversion efficiency (LSB) versus IF-signal amplitude at different input power levels Bias current: 29 5 mA

The conversion efficiency as a function of increasing IF-signal amplitudes at −5-dBm microwave input level and 9.965-GHz center frequency is plotted in Fig. 4. At larger microwave inputs (0 dBm, 5 dBm) results are qualitatively comparable to those theoretically expected. For small inputs (−10 dBm, −5 dBm), the conversion efficiency follows the theoretically expected curves only for very small IF signals, after which the measured gain drops off instead of increasing further, as expected. A readjustment of the center frequency, however, so that this frequency component is maximized, gives the dotted curves. These can be qualitatively compared with those expected. These results indicate that there is a shift in admittance characteristics of the device for strong IF signals, which causes a detuning of the amplifier. This is particularly noticeable for small microwave input signals, because the small-signal gain is more sensitive to changes in Y_D. A proper analysis for this case would have to include these changes.

Similar results were obtained for a relatively wide-band waveguide amplifier. When the IF was varied, keeping the center frequency fixed, the curves of Fig. 5 were obtained. For the three different center frequencies used, it is clear that the maximum conversion efficiency results when the microwave input signal lies within the passband of the amplifier. The up-converter response seems to be determined by both the center-frequency gain of the amplifier and the response of the microwave circuit at the sideband frequency. The results indicate that a wide-band up-converter will require a wide-band amplifier. Similar experimental results have been

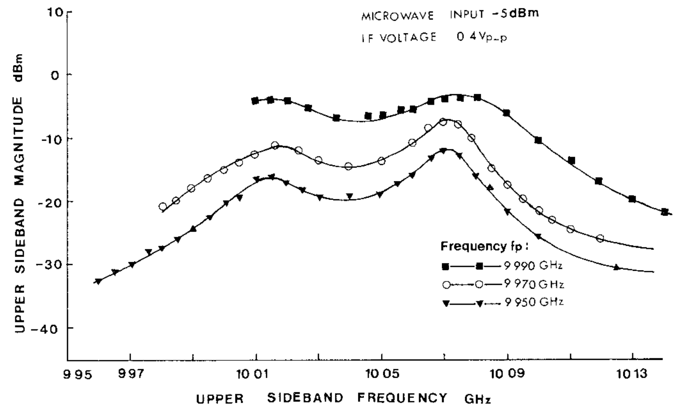

Fig. 5 Upper sideband magnitude versus frequency for fixed center frequencies and varying IF Bias current: 30 mA.

obtained by Rolland *et al.* [4]. At 33.5 GHz, they obtained a 3-dB bandwidth of 680 MHz using a wide-band waveguide reflection-type amplifier.

V. Conclusions

By impressing the IF signal onto the bias, an IMPATT amplifier may be used as an up-converter with gain. The bandwidth of the up-converter will be comparable to that of the amplifier. To obtain good conversion efficiency both the input microwave signal and the up-converted output signal must be within band of the amplifier. The conversion gain depends upon the microwave-signal level, IF-signal level, and frequency.

Acknowledgment

The authors wish to thank the workshop staff in the Department of Electrical Engineering, University of Alberta, for fabricating the IMPATT-amplifiers, and J. Fearn for assistance with the experimental work. They also wish to thank Dr. A. Javed for many helpful discussions.

References

[1] M. J. Ahmed, "Avalanche-diode amplifier upconverter," *Electron. Lett.*, vol 9, pp 490–491, Oct 1973.
[2] W J Evans and G. I. Haddad, "Frequency conversion in IMPATT diodes," *IEEE Trans. Electron Devices*, vol. ED-16, pp 78–87, Jan. 1969
[3] M. E Hines, "Large signal noise, frequency conversion and parametric instabilities in IMPATT diode networks," *Proc. IEEE*, vol 60, pp. 1534–1548, Dec. 1972
[4] P Rolland *et al.*, "New modes of operation for avalanche diodes: Frequency multiplication and upconversion," *IEEE Trans Microwave Theory Tech.*, vol. MTT-24, pp 768–775, Nov 1976
[5] R K Gupta, "A study of upconversion phenomena in IMPATT amplifiers," M Sc. thesis, Univ. Alberta, Edmonton, Alta., Canada, Sept. 1976
[6] S. Kita and N. Kanmuri, "Millimeter-wave up-converter using a germanium avalanche," *Electron. Commun. Japan*, vol. 53-B, pp 86–93, 1970
[7] R W. Laton and G I Haddad, "Characteristics of IMPATT-diode reflection amplifiers," *IEEE Trans Microwave Theory Tech.*, vol MTT-21, pp 668–680, Nov 1973.
[8] P T Greiling and G I Haddad, "Large signal equivalent circuit of avalanche transit time devices," *IEEE Trans. Microwave Theory Tech.*, vol MTT-18, pp 842–853, Nov 1970.