G-6

CONSTANT VOLTAGE BIASING OF IMPATT INJECTION-LOCKED OSCILLATORS

J. L. Chan
TRW Electronic Systems Group
One Space Park
Redondo Beach, CA 90278

Abstract

It is shown by analysis and experimental data that constant-voltage biasing is practical with IMPATT oscillators. Constant-voltage biasing offers a lesser possibility of a thermal runaway, as compared to the conventional constant-current biasing. The price for this thermal advantage is a degradation of output power with elevating ambient temperature.

Introduction

It is well known that in the avalanche breakdown mode, the IMPATT diode behaves very much like a zener diode; that is, as far as the bias supply is concerned, the IMPATT diode acts as a constant voltage device. For this reason a C-I (constant current) source has been traditionally used to bias IMPATT diodes for rf operations. Recently, it was reported[1] that an IMPATT diode operating in the amplifier mode has been successfully biased by a C-V (constant voltage) source with encouraging results. The report suggested that self-current limiting is possible with the amplifier mode but not with the oscillator mode since in the former, the diode current is limited by the finite rf power from the input. The report also claimed that by using C-V biasing, improved amplifier linearity and stability could be obtained while increasing the overall dc to rf conversion efficiency. Inspired by the report, it was decided to investigate the possibility and advantages (if any) of applying C-V bias to IMPATT amplifiers operating in the injection-locked oscillator mode.

Subsequent analysis and experiments showed that it is not only possible to use C-V biasing with IMPATT oscillators, but the combination offers a distinct advantage over the conventional C-I biasing. With C-V biasing, the IMPATT diode shows a lesser possibility of a catastrophic failure caused by thermal runaway. However, the output power decreases with elevating ambient temperature. Also, no improvement in rf performance and rf conversion efficiency was observed.

In the following sections, the thermal properties of C-I and C-V biasing will be discussed and compared. Some experimental results on C-V biasing will be presented.

Breakdown Voltage as a Function of Temperature

For any reverse-biased semiconductor junctions, Si and GaAs included, the decreased ionization rate at high temperature gives rise to a positive temperature coefficient of breakdown voltage. A good approximation of the breakdown voltage-temperature relationship was given as[2,3]

$$V_b = V_{bo}\left(1 + \beta\,(T_j - T_o)\right) \quad (1)$$

where V_b is the device breakdown voltage at a junction temperature of T_j, V_{bo} is the same at a reference junction temperature of T_o, and β is the normalized temperature coefficient defined by

$$\beta = \frac{1}{V_{bo}}\,\frac{dV_b}{dT_j} \quad (2)$$

Notice that the rise of the junction temperature, T_j, is caused by external heating (due to rise of the ambient temperature) and internal heating (due to power dissipation in the diode). Consider first the effect of external heating. Equation (1) can be rewritten as

$$V_b = V_{bo} + \Delta V_b; \quad \Delta V_b = \beta V_{bo}\,\Delta T \quad (3)$$

where $\Delta T = T - T_o$ is the relative ambient temperature in reference to T_o and T is the ambient temperature. Equation (3) states that a change in the ambient temperature in reference to T_o introduces a change in diode breakdown voltage, ΔV_b, in reference to V_{bo}. We shall say that ΔV_b is caused by external heating.

When avalanche breakdown occurs, bias current flows through the device junction. In case of an IMPATT diode, only a small fraction of the bias power is converted to the rf. The remaining bias power is dissipated at the junction as heat, and as a result, T_j rises. This process causes the voltage across the diode to increase above V_b in a manner identical to external heating. We shall express the increase in diode voltage as, in analogue to Eq. (3) and with the aid of a well-known heat equation

$$\Delta V_{d1} = \beta V_{bo}\,\theta_t\,(V_d I_d + P_i - P_o) \quad (4)$$

where ΔV_{d1} is the increase in diode voltage above V_b due to internal heating, θ_t is the thermal resistance from the diode junction to the ambience, V_d and I_d are the bias voltage and current, respectively, of the diode, P_i is the rf injection power, and P_o is the rf output power. Furthermore, during avalanche breakdowns, the space charge of the carriers distorts the electric field profile in the space-charge layer, giving rise to a positive electrical resistance[4]. This so-called space-charge resistance modifies V_d in addition to ΔV_b and ΔV_{d1}. The modification can be expressed as

$$\Delta V_{d2} = R_{sc} I_d \quad (5)$$

where R_{sc} is the space-charge resistance of the diode and can be determined experimentally[2].

For the sake of closed-form solutions, we shall restrict ourselves to a first-order analysis in the next section by ignoring the terms involving P_i and P_o. (Notice that P_o is a function of I_d^2.) The error so introduced is acceptable since only a small fraction of the bias power is converted to P_o. ΔV_{d1} is now expressed as

$$\Delta V_{d1} \approx \beta V_{bo}\,\theta_t\,V_d I_d \quad (6)$$

The total voltage across an IMPATT diode under avalanche conditions can be written as

$$V_d = V_{bo} + R_{sc} I_d + \beta V_{bo}\,\theta_t V_d I_d + \beta V_{bo}\,\Delta T \quad (7)$$

A plot of Eq. (7) is shown in Fig. 1.

Thermal Properties of C-I and C-V Biasing

With C-I biasing, $I_d = I_o$ = constant, and the diode voltage as a function of temperature, by rearranging Eq. (7), can be written as

$$\begin{aligned} V_d &= \frac{1}{1 - \beta\theta_t V_{bo} I_o}\left(R_{sc} I_o + V_{bo} + \beta V_{bo}\,\Delta T\right) \\ &= a_1 + b_1\,\Delta T \end{aligned} \quad (8)$$

The junction temperature of the diode is found to be

$$\begin{aligned} T_j &= \theta_t\, I_o V_d + T \\ &= \theta_t\, I_o\,(a_1 + b_1\,\Delta T) + \Delta T + T_o \\ &= a_2 + b_2\,\Delta T \end{aligned} \quad (9)$$

For practical cases, the parameters a_1, a_2, b_1, b_2 are found to be positive. It is readily seen that with C-I biasing, both diode voltage and junction temperature rise with any temperatures above T_o (i.e., for $\Delta T>0$) and that thermal runaway due to internal heating takes place if the condition $\beta\theta_t V_{bo} I_o = 1$ is met.

On the other hand, with C-V biasing, $V_d = V_o$ = constant, and the diode current and junction temperature can be shown to be

$$I_d = \frac{1}{R_{sc} + \beta\theta_t V_{bo} V_o} (V_o - V_{bo} - \beta V_{bo} \Delta T)$$

$$= c_1 - d_1 \Delta T \quad \text{for } \Delta T \leq \Delta T_c \qquad (10a)$$

$$= 0 \quad \text{for } \Delta T > \Delta T_c \qquad (10b)$$

$$T_j = \theta_t I_d V_o + T$$

$$= \theta_t V_o (c_1 - d_1 \Delta T) + \Delta T + T_o$$

$$= c_2 + d_2 \Delta T \quad \text{for } \Delta T \leq \Delta T_c \qquad (11a)$$

$$= \Delta T \quad \text{for } \Delta T > \Delta T_c \qquad (11b)$$

Again, the parameters c_1, c_2, d_1, d_2 are found to be positive for practical cases. A new parameter, T_c, which we shall call the cut-off temperature, is introduced here and is defined as

$$T_c - T_o = \Delta T_c = c_1/d_1 = \frac{V_o - V_{bo}}{\beta V_{bo}} \qquad (12)$$

Equation (10) indicates that diode current decreases with elevating temperature. As the ambient temperature reaches T_c, the diode current goes to zero and remains zero for any temperature above T_c. On the other hand, the junction temperature increases with ambient temperature at a rate d_2. As the ambient temperature goes above T_c, the rate changes to unity. I_d and T_j under C-V bias are plotted against temperatures and are shown in Figs. 2 and 3.

Comparison of C-I and C-V Biasing

Although T_j increases with temperature when the diode has either C-I bias or C-V bias, T_j increases with temperature at a slower rate in the C-V case than in the C-I case as can be seen from the following inequality.

$$b_2 = 1 + \frac{\beta\theta_t I_o V_{bo}}{1 - \beta\theta_t I_o V_{bo}} > d_2 = 1 - \frac{\beta\theta_t V_o V_{bo}}{R_{sc} + \beta\theta_t V_o V_{bo}} \qquad (13)$$

The slower rate is due to the fact that, with C-V biasing, internal heating decreases with elevating temperature. Take a commercial IMPATT diode, HP 5082-0400, for example. The diode parameters were given as follows[5]:

$\beta = 1.17 \times 10^{-3}/°C$ $V_{bo} = 76.1$ V

$R_{sc} = 31$ ohms $V_d = 83.6$ V

$\theta_t = 16°C/W$ $I_d = 0.05$ A

If this diode were employed, we would have $b_2 = 1.08$ and $d_2 = 0.21$. The diode junction temperature would inincrease with temperature at a rate five times faster with a C-I bias than with a C-V bias. The price to pay for this thermal advantage is rf output. With C-V biasing, diode current decreases with temperature at the rate of d_1. Output power, consequently, decreases at a rate of $2d_1^2 \Delta T - 2C_1 d_1$.

Experimental Results on C-V Biasing

C-V biasing was applied on a single-diode injection-locked oscillator and a twelve-diode injection-locked oscillator. The single-diode oscillator has a K-band waveguide circuit and was capable of a one-watt output. The twelve-diode oscillator has a K-band waveguide cavity combiner circuit and was capable of a 15-watt output. All IMPATT diodes used were GaAs devices. The diode current was measured as a function of temperature. The results are shown in Figs. 4 and 5. The results show a downward trend of diode current with elevating temperature, as predicted by the theory. The current cut-off point was not verified, however, as it is apparently not within the temperature range of 10°C to 50°C used in the measurements. If the situation permits, measurements will be performed with a wider temperature range in the near future. Also, tests will be performed on silicon devices to determine the applicability of the theory. It should be noticed that no change in rf performance or stability was observed when the above circuits were switched to C-I biasing.

Conclusion

It has been shown by analysis as well as experiment that C-V biasing can be used in IMPATT oscillator circuits and that C-V biasing offers a superior thermal property over the conventional C-I biasing. Diode junction temperature rises with ambient temperatures at a slower rate in the C-V case than in the C-I case. However, the cost of this thermal advantage is that output power drops with elevating temperature. It is not uncommon that IMPATT diodes are biased to reach their maximum junction temperature so that maximum rf power can be extracted. In cases like this, C-V biasing may be preferred so as to prevent a catastrophic failure due to thermal runaway.

Acknowledgment

The author is indebted to his colleague, Jeffrey Douglass, for first suggesting the use of C-V biasing.

References

1. J. W. McClymonds, G. C. Dalman and C. A. Lee, "Constant-Voltage Bias Improves IMPATT Amps," Microwaves, July 1980, pp. 64-66.

2. R. H. Haitz, H. L. Stover and N. J. Tolar, "A Method for Heat Flow Resistance Measurements in Avalanche Diodes," IEEE Trans. Electron Devices, May 1969, pp. 438-444.

3. G. Gibbons, "Avalanche-Diode Microwave Oscillators," Clarendon Press, Oxford, 1973.

4. S. M. Sze and W. Shockley, "Unit-Cube Expression for Space Charge Resistance," BSTJ, May-June 1967, pp. 837-842.

5. AN 935, "Microwave Power Generation and Amplification Using IMPATT Diodes," Hewlett-Packard Application Note.

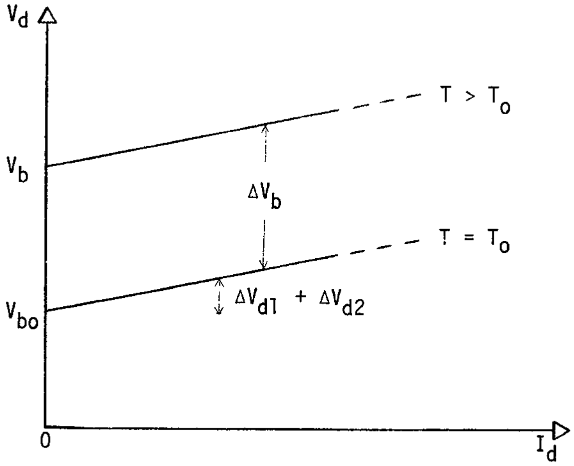

Figure 1. Diode Breakdown Voltage Characteristic

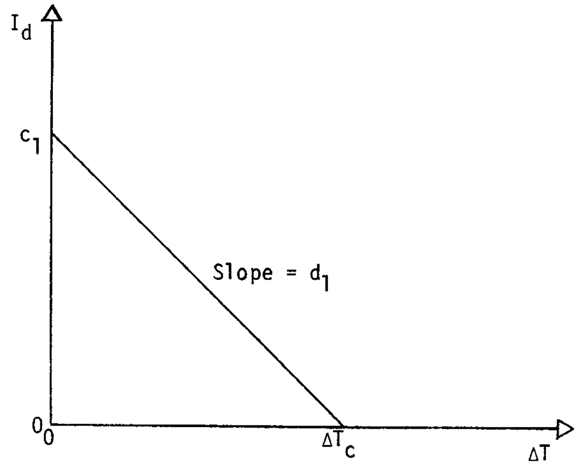

Figure 2. Diode Current vs. Temperature, C-V Bias

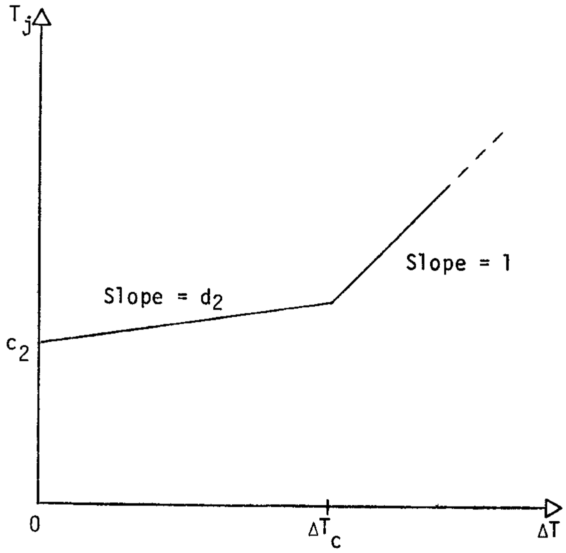

Figure 3. Diode Junction Temperature vs. Temperature, C-V Bias

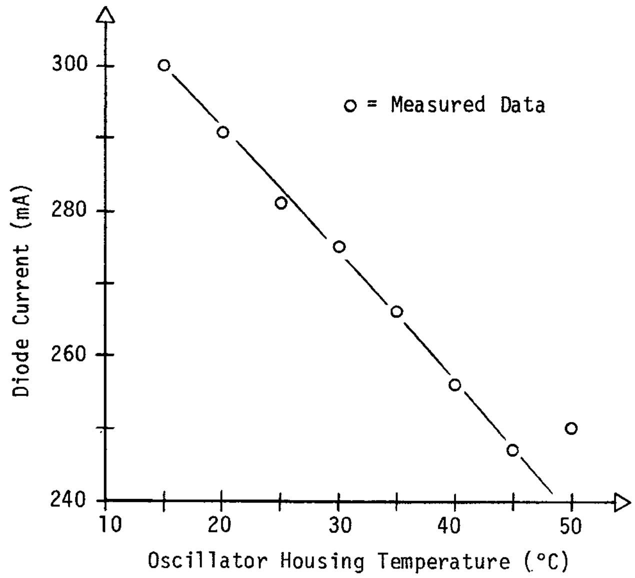

Figure 4. Thermal Property of C-V Biasing, Single-Diode Circuit

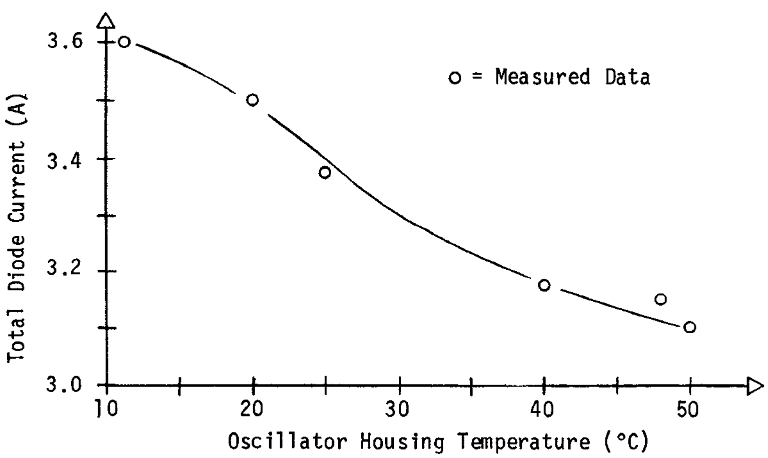

Figure 5. Thermal Property of C-V Biasing, Twelve-Diode Combiner