EFFICIENT, BROADBAND CIRCUIT PERFORMANCE OF MILLIMETER-WAVE IMPATT-DIODE POWER AMPLIFIERS*

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ABSTRACT

A new technique for evaluating and optimizing the operating circuit efficiency of IMPATT-diode amplifiers and oscillators is presented. This design approach has been used to realize a reliable, single diode Q-band IMPATT amplifier producing 1.5 Watts output from 43.5 to 45.5 GHz with 5 dB gain.

I. INTRODUCTION

The intrinsic performance capabilities of IMPATT-diodes are always limited by the efficiency of the embedding circuit which is required to permit useful operation of the device. Actual operating power losses in the embedding circuit are determined by the relationship between the intrinsic device properties and the circuit parameters. This paper presents a simple measurement technique for establishing the operating circuit efficiency of diode embeddings and gives guidelines for its maximization. Use of this procedure in the design and realization of a high-power mm-wave IMPATT amplifier is described.

II. DEFINITION AND EVALUATION OF CIRCUIT EFFICIENCY

Circuit efficiency characterizes the power transfer through a two-port network. This power transfer is less than unity for the lossy coupling circuits encountered in diode embeddings. Such an embedding can be represented as shown in Fig. 1, with the diode characterized by some operating impedance ZL. The circuit efficiency is the ratio of the powers crossing the two ports of the network, and its value depends on the terminal conditions which can be established by the value of ZL. Optimum efficiency occurs for the proper choice of load impedance.

There are two categories of load impedances for which optimum efficiency is important:

1. Case of Re[ZL]>0. Maximum η for this case is the same as the maximum available gain of the network (less than unity) and occurs for ZL equal to the so-called simultaneous conjugate match impedance for port 2 of the network. This value of ZL is labeled ZLm in Fig. 1 and the corresponding efficiency is η_0. The normalized input impedance for ZL=ZLm is zim, which is the complex conjugate of the simultaneous match source impedance.

2. Case of Re[ZL]<0. In this case the direction of power flow is reversed and the power crossing port 1 should be maximized with respect to that crossing port 2, or $1/\eta$ should be optimum. This occurs for the intuitively obvious case of ZL = -ZLm*, and gives the same maximum transfer efficiency, i.e., $1/\eta_0$. The corresponding impedance in the input plane is -zim*, with the reflection coefficients related as complex reciprocals.

The consequence of the above discussion is that optimum efficieny occurs for a passive load if the operating input reflection coefficient coincides with Γim, and for an active load if $\Gamma = 1/\Gamma$ im*. For IMPATT-diode amplifiers and oscillators, these points and the value of can be readily determined by a simple measurement. This allows the operating efficiency for any other load to be calculated, eventually leading to circuit optimization. The points zim and -zim* will be referred to as the passive and active "matchpoint" impedances [1], respectively.

Shown in Fig. 2 is the input reflection-plane geometry associated with determining Γim and η_0. The variable capacitance region of an IMPATT below breakdown forms a portion of a circular arc in the input plane, which can be extended to give a circle with center Γc and radius R. Values for zim or Γim η_0 can be determined from the circle parameters using the expressions given in Fig. 2 [2]. Also shown in Fig. 2 is a trajectory of an IMPATT biased above breakdown which passes through the optimal point $1/\Gamma^*$im. Maximum power transfer from the diode to the input terminals would occur at this point, although such coincidence is not easily achieved. In practice, iterative synthesis of the circuit is required to obtain close proximity of the active matchpoint and the IMPATT operating point. Guidelines for achieving this are suggested in the next section.

III. EFFICIENT Q-BAND IMPATT-DIODE AMPLIFICATION

An effective method of characterizing single-diode IMPATT amplifiers was given in [3] and made use of the reciprocal reflection coefficient of the circuit as a function of bias current and RF drive level. In the reciprocal plane ($\Gamma r = 1/\Gamma i$), the active matchpoint is zim* or Γ im*, and the unit circle represents a circuit efficiency of zero.

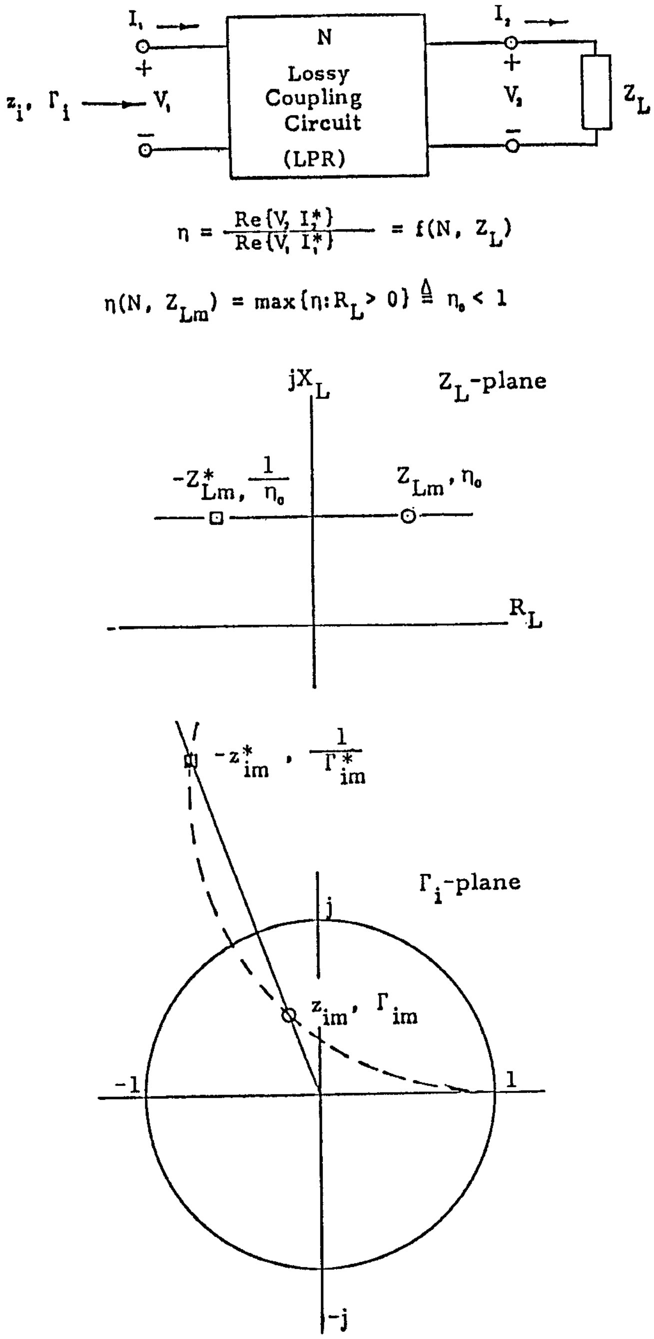
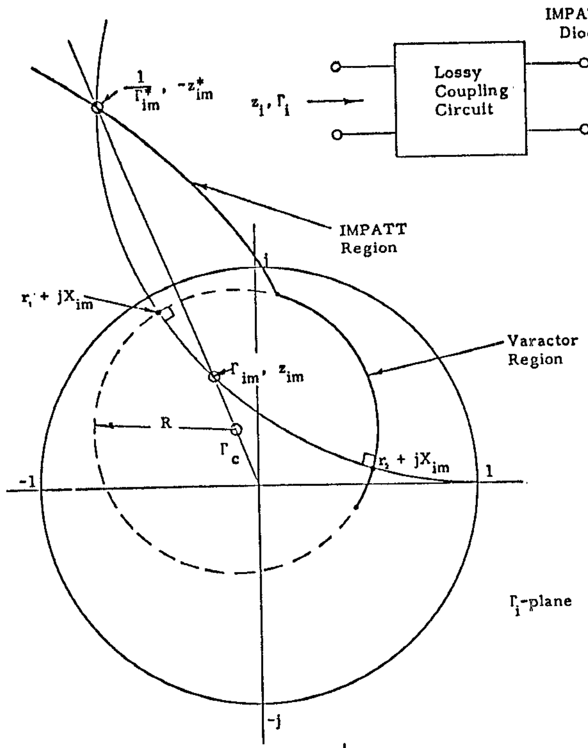


Figure 1. The stationary points of optimum circuit efficiency for both active and passive loads. The optimum loads are mirror images about the imaginary axis, as are the corresponding input impedances. Power transfer from port 2 to port 1 for the active case also has a maximum of η_0.

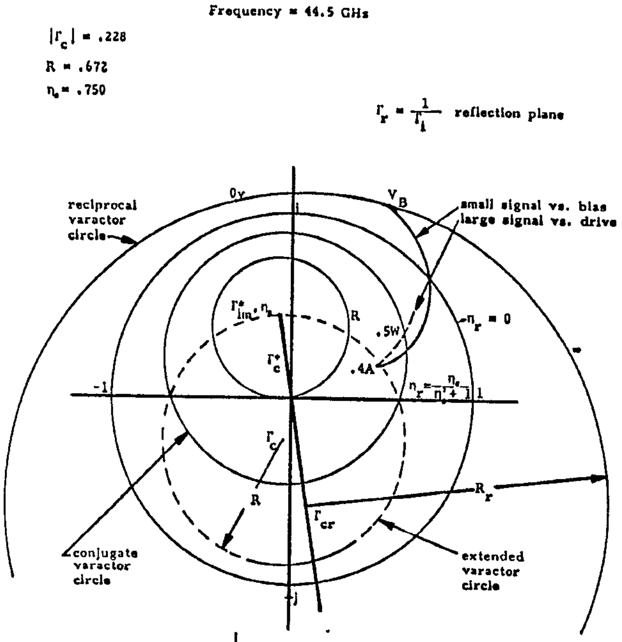


$$\eta_0 = K - \sqrt{K^2-1} = (\sqrt{r_2/r_1} - 1)/(\sqrt{r_2/r_1} + 1)$$
$$K = (1 + R^2 - |\Gamma_c|^2)/2R; \; K > 1$$
$$\Gamma_{im} = \Gamma_c/(1-R\eta_0); \; z_{im} = \sqrt{r_1 r_2} + jX_{im}$$

Figure 2. The geometry of an optimum circuit efficient IMPATT amplifier. Γ_{im} and z_{im} can be found from the parameters associated with the circle formed by extending the arc of the varactor region. The IMPATT trajectory will rarely intersect the point of maximum circuit efficiency ($-z^*_{im}$).

Shown in Fig. 3 is a set of single- frequency characteristics of a Q-band IMPATT circuit as a function of bias and RF drive. The maximum circuit efficiency is .75, while the operating efficiency$\cong$.5. Improved efficiency would result if the entire IMPATT characteristics could be shifted CCW to proximity with Γ_{im}^*. This might be accomplished by increasing the package series inductance. The circular constant efficiency contours shown can be derived from the efficiency expression shown in Fig. 3. Contours easily established are the conjugate varactor circle ($r = \eta_0/(1+\eta_0^2)$) and the η = R circle which passes through the origin. An IMPATT oscillator would have an operating efficiency of R.

Improved performance of the Q-band amplifier over the 43.5 to 45.5 GHz band was accomplished by modifying the resonating structure near the packaged diode, resulting in a large signal operating efficiency of about .75. Silicon double-drift IMPATT devices on diamond heat sinks were used in these experiments, and the package could not be modified.



$$\eta = \frac{R_r(|\Gamma_r|^2 - 1)}{|\Gamma_r - \Gamma_{cr}|^2 - R_r^2}$$

Figure 3. Reciprocal reflection data for an IMPATT amplifier circuit showing device characteristics and constant circuit efficiency contours. The operating efficiency of the circuit at .5 Watt drive is about 0.5 with a reflection power gain of about 3 dB. This is a case where the IMPATT characteristics are shifted too far clockwise from Γ^*_{im} .

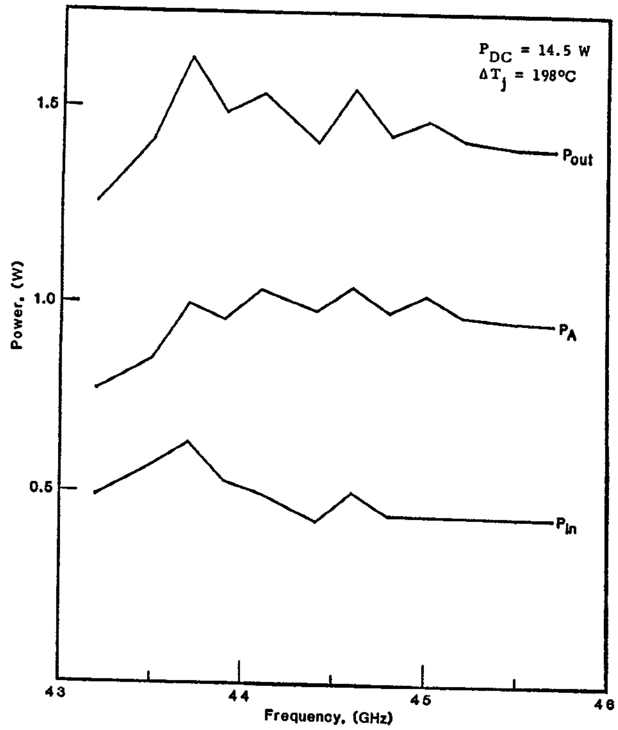


Figure 4. Input power, output power and added power (P_A) of the Q-band single diode amplifier. The input power was limited so that maximum added power could not be achieved. Peak added power efficiency is about 7 percent.

A typical frequency response of a Q-band IMPATT amplifier is shown in Fig. 4 over the 43 to 46 GHz band. Limited input drive power did not permit the added power to be maximized at all frequencies in the band. Peak added power is over 1 Watt, giving an operating dc to RF generation efficiency of about 7 percent. Using the operating circuit efficiency gives an intrinsic IMPATT efficiency of about 10 percent.

The single-diode unit amplifier described above is intended to be used as a unit building block in the development of a multi-watt power amplifier covering the 43.5 to 45.5 GHz band.

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REFERENCES

[1]. D. H. Steinbrecher, "Circuit Aspects of Non-Linear Microwave Networks", Proceedings of the 1975 IEEE Int. Symp. on Circuits and Systems, April 21-23, 1975, Boston, Mass., pp. 477-479.

[2]. D. F. Peterson and D. H. Steinbrecher, "Image-Optimized, Frequency-Scalable Mixers for Millimeter-Wave Applications", 1983 MTT-S Int. Microwave Symp. Tech. Digest, May-June 1983, Boston Mass., pp. 554-556.

[3] D. F. Peterson, "A Device Characterization and Circuit Design Procedure for Realizing High-Power Millimeter-Wave IMPATT-Diode Amplifiers", IEEE Trans. Microwave Theory and Techniques, vol. MTT-21, Nov. 1973, pp. 681-689.

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