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The microwave large signal load line of an InGaP HBT*

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Abstract: The microwave dynamic load line characteristics of an advanced InGaP HBT are investigated experimentally and analyzed at small signal level and at large signal level for microwave power amplification. Investigation results show that the dynamic load curves are not always like an elliptic curve, and the current extreme points do not locate at voltage extreme points. The dynamic load curve current extreme point lines sit at the small signal load line up to the $P_{-3\mathrm{dB}}$ point, and the lines show a constant slope from a small signal up to the saturation power point. A method to calculate the realistically delivered power to load is presented which fits the test result well.

Key words: microwave dynamic large signal characteristics; InGaP HBT; microwave power
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1. Introduction

Indium gallium phosphide heterojunction bipolar transistors (InGaP HBTs) are advanced microwave power devices of power amplifiers in modern communication systems and radar systems[1−3]. At small signal level InGaP HBTs exhibit excellent linear characteristics for microwave signal amplification, but the performance becomes degraded at large signal level. Effective large signal level analysis is very complicated and difficult[4−6]. So accurate measurement and observation of the large signal characteristics are primarily important for characterizing InGaP HBT power performance and will be of benefit to microwave amplifiers[7, 8].

Traditionally, a load line is often used to set operation classification based on an ideal line. However the load curve in a realistic scenario, especially at a large signal level, degrades, as this paper observes. In this paper, the microwave dynamic load line characteristics of an advanced InGaP HBT transistor cell are investigated experimentally and analyzed at the small signal level, at the $P_{-1\mathrm{dB}}$ point, at the $P_{-3\mathrm{dB}}$ point, and at the saturation output power point as described in sections 2 and 3. Then a convenient method to calculate the delivered power to load based on the current extreme point lines of the dynamic load curves is presented, whose result agrees well with the measured data.

2. Dynamic load line characteristics

The transistor investigated here is an InGaP/GaAs npn type heterojunction bipolar transistor cell with an area of 1×10^{-3} mm^2. The transistor collector–emitter breakdown voltage is about 12 V. The transistor DC current gain is about 100, the transistor maximum oscillation frequency is around 110 GHz, and the cutoff frequency is about 40 GHz.

The transistor is measured on wafer by using a pair of PicoProbe ground-signal-ground (GSG) probes and Cascade test station in an AgilentN5242 nonlinear vector network analyzer system for maximum power output[9, 10]. Starting from a small signal power of –9.72 dBm through to saturated maximum power output the transistor dynamic load lines are measured and analyzed at the small signal level, at the $P_{-1\mathrm{dB}}$ point, at the $P_{-3\mathrm{dB}}$ point, and through to the saturation output power point at a frequency of 5.8 GHz as described in the following subsections.

2.1. At the small signal level

With injecting a small signal of –9.72 dBm at a frequency of 5.8 GHz, the transistor dynamic load line is measured as Figure 1 shows. It can be seen that the load line is a standard elliptical curve at the small signal level. The current extreme points of the load curve sit exactly at the major axis of the elliptical curve. The maximum current point is at the minimum voltage point and the minimum current point is at the maximum voltage point. The slope of the elliptical curve major axis is the inverse of the load resistance, and the minor axis is related to the reactance of the load impedance[11], which will be discussed in section 3 of this paper.

2.2. At the $P_{-1\mathrm{dB}}$ point

On increasing the injection power level from a small signal, the output power increases linearly but then the power gain

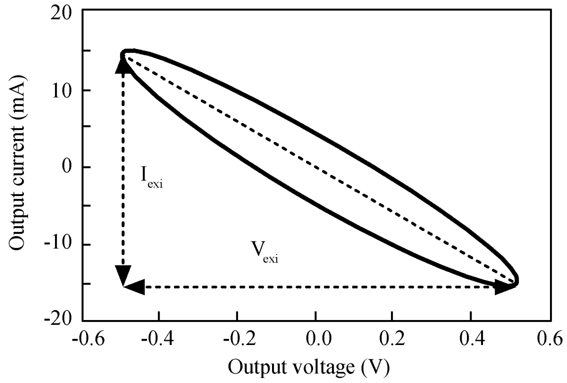

Fig. 1. Dynamic load line measured at the small signal level.

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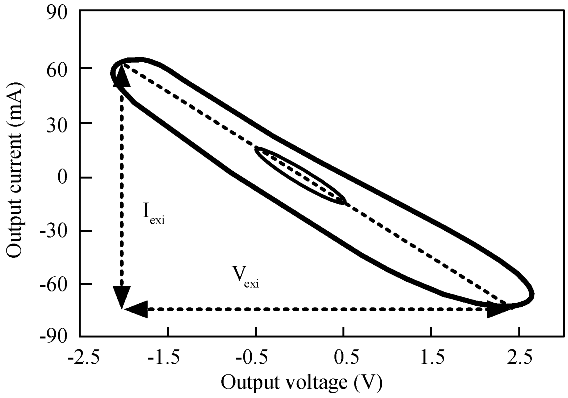

Fig. 2. Dynamic load line measured at the $P_{-1\mathrm{dB}}$ point.

will be compressed. At the $P_{-1\mathrm{dB}}$ point the dynamic load line is a long drawn elliptic curve as Figure 2 shows. For comparison, the small signal load curve is shown also inside the larger curve. At the $P_{-1\mathrm{dB}}$ point, the load curve's minimum current point is at the point of –73.088 mA, 2.377 V but not at the maximum voltage point; the maximum current point is at the point of 64.541 mA, –1.944 V but not at the minimum voltage point. As Figure 2 shows, the current extreme point line marked as the dashed line sits on the small signal load line but the voltage extreme point line which is not marked in the figure is not on the small signal load line. This means that the current extreme point line still sits at the small signal load line although the load curve is a nonideal elliptic curve at the $P_{-1\mathrm{dB}}$ point.

2.3. At the $P_{-3\mathrm{dB}}$ point

With continuous increase of the injection power from the $P_{-1\mathrm{dB}}$ point, the output power increases accordingly but the power gain is compressed in further. At the $P_{-3\mathrm{dB}}$ point, the dynamic load curve is clipped and degraded as Figure 3 shows. The small signal load curve is also shown in the figure for comparison. The load curve clipping is due to the current limitation of the transistor. The maximum current point is at the point of 67.968 mA, –2.406 V which is not at the minimum voltage point; the minimum current point is at the point of –86.312 mA, 3.015 V which is not at the maximum voltage point. It should be noted that the current extreme point line which is marked as the dashed line in the figure is still on the small signal load line, but the voltage extreme point line which is not marked in the figure is not on the small signal load line. So, the direction of the current extreme point line does not change from the small signal level up to the $P_{-3\mathrm{dB}}$ point with increasing injection power.

2.4. At the saturation output power point

With continuous increase of the injection power, the output power will be saturated soon after, and the dynamic load curve is degraded seriously and does not resemble an elliptic curve at all as Figure 4 shows. The small signal load line is also shown for comparison. It can be seen that the maximum current point is at the point of 64.772 mA, –3.056 V, not at the minimum voltage point; the minimum current point is at the point of –102.021 mA, 2.621 V, not at the maximum voltage point. The current extreme point connection line is no longer on the small signal level load line, but it is still in parallel with the small signal load line. The voltage extreme point line is not in parallel with the small signal load line. This means that the current extreme point line direction does not change and the load resistance does not change from a small signal up to the saturation output power level.

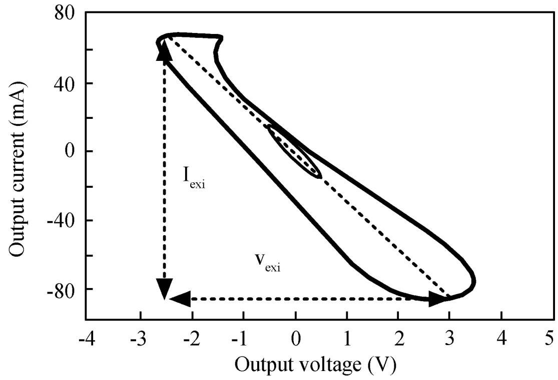

Fig. 3. Dynamic load line measured at the $P_{-3\mathrm{dB}}$ point.

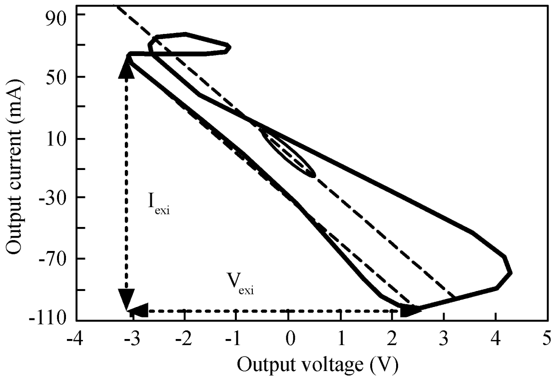

Fig. 4. Dynamic load curve measured at the saturation power point.

3. Discussion

3.1. Load curve and output power

The transistor collector current can be expressed as Eq. (1) using a Fourier series[11]:

$$i_{\mathrm{C}}(t) = I_{\mathrm{DC}} + I_{\mathrm{ACM}} \sum_{n=1}^{\infty} a_n \cos(n\omega t), \tag{1}$$

where I_{DC} is the collector DC current, I_{ACM} is the maximum current value of the collector current waveform, a_n are the Fourier coefficients of the collector current waveform, ω is the frequency, and t is the time.

The voltage can be expressed as Eq. (2)[11]:

$$v_{\mathrm{C}}(t) = V_{\mathrm{DC}} - \sum_{n=1}^{\infty} I_{\mathrm{ACM}} a_n \cos(n\omega t) R_{\mathrm{L}} + \sum_{n=1}^{\infty} I_{\mathrm{ACM}} a_n \sin(n\omega t) X_{\mathrm{L}}, \tag{2}$$

where v_{C} is the AC voltage, V_{DC} is the DC voltage, R_{L} is the load resistance, and X_{L} is the load reactance.

The last item in Eq. (2) causes the minor axes of the load curves in Fig. 1–4, and it will increase with increasing power. This means there will be more time during which the transistor operates at a higher current and higher voltage region in a whole period of time than that there is no $X_{\rm L}$. The last item in Eq. (2) causes also offsets of the voltage extreme points from the current extreme points at the large signal level.

The power delivered to load is the real power. From Eqs. (1) and (2), the output power can be expressed approximately as Eq. (3):

$$P_{\rm out} = \frac{1}{2} I_{\rm ACM}^2 a_1^2 {\rm Re}(Z_{\rm L}). \tag{3}$$

For class-A amplification, a_1 is about 1/2. The output power can be expressed as Eq. (4):

$$P_{\rm out} = \frac{1}{8} I_{\rm ACM}^2 R_{\rm L}. \tag{4}$$

From Fig. 1–4, it can be seen that the load curve current extreme point line value, $I_{\rm exi}$ equals about two times the amplitude of the load AC signal, $I_{\rm cm}$. The output power can be expressed as Eq. (5).

$$P_{\rm out} = \frac{1}{2} I_{\rm cm}^2 R_L = \frac{1}{8} I_{\rm exi}^2 R_{\rm L}. \tag{5}$$

From the figures it also can be seen that the load curve current extreme point line value, $I_{\rm exi}$ expresses approximately the maximum collector current value $I_{\rm ACM}$ at the small signal level, at the $P_{-1{\rm dB}}$ point, at the $P_{-3{\rm dB}}$ point and at the saturation power point respectively. So from both Eqs. (4) and (5), the actually delivered power to load at the small signal level and at the large signal level can be calculated as Eq. (6) if we have the actual value of $I_{\rm exi}$.

$$P_{\rm out} = \frac{1}{8} I_{\rm exi}^2 R_{\rm L}. \tag{6}$$

Following Eq. (6), the delivered power to load can be calculated at the small signal and large signal levels. Here, $R_{\rm L}$ is about 33.67 Ω for this device. The calculated delivered power is about 18.8 dBm at the $P_{-1{\rm dB}}$ point, 20.2 dBm at the $P_{-3{\rm dB}}$ point, and 20.8 dB at the saturation output power level. Figure 5 shows the measured powers and the calculated ones. It can be seen that two curves fit well.

3.2. Output power versus input power

As an approximation, the input power can be expressed as[11]:

$$P_{\rm in} = \frac{1}{2} \omega^2 C_\pi^2 (r_{\rm bb} + \omega L_{\rm E} + R_{\rm E}) V_{\rm be}^2, \tag{7}$$

where $r_{\rm bb}$ is the transistor base series resistance, C_π is the base emitter junction capacitance, $L_{\rm E}$ is the emitter series inductance, $R_{\rm E}$ is the emitter series resistance, and $V_{\rm be}$ is the base emitter junction AC voltage.

The output AC current can be expressed as

$$I_{\rm ACM} = g_{\rm AC} V_{\rm be}, \tag{8}$$

where $g_{\rm AC}$ is the AC transconductance.

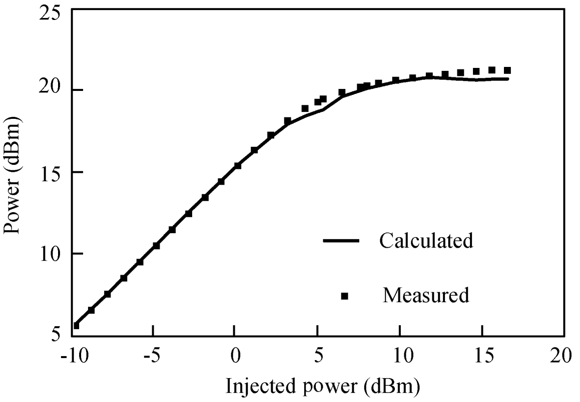

Fig. 5. Delivered power to load of the InGaP HBT cell calculated and measured.

The transistor output current $I_{\rm ACM}$ is dependent on the voltage of the base emitter junction and transconductance. The output power can be obtained as Eq. (9) by Eqs. (4), (7) and (8) as follows:

$$P_{\rm out} = \frac{1}{8} I_{\rm ACM}^2 R_L = \frac{1}{8} g_{\rm AC}^2 V_{\rm be}^2 R_{\rm L}$$

$$= \frac{1}{4} \frac{g_{\rm AC}^2 R_{\rm L}}{\omega^2 C_\pi^2 (r_{\rm bb} + \omega L_{\rm E} + R_{\rm E})} P_{\rm in}. \tag{9}$$

This is an approximate expression for the output power versus input power. The output power is related to the input power, the transconductance and transistor parameters. The output power is not always proportional to the input power because the transconductance decreases at the large signal level.

4. Conclusion

In this paper, the microwave dynamic load line characteristics of an advanced InGaP HBT are measured and investigated at the small signal level and the large signal level. The conclusions include the following: (1) the dynamic load curve shapes are strongly dependent on the power levels. The load curve is an elliptical curve just at the small signal level; after that, the load curves are degraded and will not stay elliptical at the $P_{-1{\rm dB}}$ point, at the $P_{-3{\rm dB}}$ point and at the saturation power point. (2) At the large signal level, the current extreme points do not locate at voltage extreme points again. (3) The load reactance is a factor causing the load curve to be unlike a straight line, and causing the positions to be offset between the current extreme points and the voltage extreme points. (4) The current extreme point line position does not shift with increasing power from the small signal level up to the $P_{-3{\rm dB}}$ point. The current extreme point line slope does not change from the small signal level through to the saturation output power point with increasing power level. In contrast, the voltage extreme point line does not obey this. (5) Based on this, an approximate method to calculate the real delivered power to load at the large power level is presented here, which agrees very well with the test data.

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