Thermal Characterisation and Analysis of Two Tone Intermodulation Distortion in InGaP/GaAs DHBT

A Khan, C N Dharmasiri, T Miura, A A Rezazadeh

The Electromagnetics Centre, School of Electrical and Electronic Engineering, The University of Manchester, PO Box 88, Manchester, M60 1QD, United Kingdom

Email: a.rezazadeh@manchester.ac.uk

Abstract — **The effect of temperature (-25 to 100^{0}C) on two-tone Intermodulation Distortion (IMD) characteristics of InGaP/GaAs microwave DHBTs is studied. This is carried out through measurement with the results being compared to a simple analytical technique. The results indicated that varying the temperature has a significant impact on the IMD characteristics. The variations of small signal parameters with temperature, extracted from S-parameter measurements, are then used to carefully analyse the IMD characteristics and identify the physical origin of the change in the non-linearity. In addition, the effects of varying input power on the non-linearities has been studied. This analysis has been reported for the first time and is important in understanding the non-linear characteristics of the microwave device.**

I. INTRODUCTION

In a communication system signals in one channel can interfere with signals in an adjacent channel leading to Intermodulation Distortion (IMD) components. This occurs due to non-linearity of devices in the system and if these IMD components are close in frequency to the fundamental signals (i.e. the third order non-linearity) then filtering could be a problem. In order to provide high power and high efficiency the amplifier is normally operated with high current density, which increases the junction temperature. This will also affect the device parameters, such as capacitance and resistance, and one would expect a change in non-linear characteristics. It is suggested [1] that the non-linear capacitance and resistance are 180^0 out of phase and, in theory, cancel each other out exactly, leading to the high levels of linearity (at low levels of DC bias power) that is seen in HBTs. In this paper the non-linearity sources and their combined effect on the non-linearity of a device are studied. Although several authors have dealt with the causes of this non-linear behaviour in microwave devices, to the best of our knowledge detailed thermal analysis on non-linearity has not been discussed. This paper aims to provide this analysis.

II. EXPERIMETNAL DETAILS

Two-tone IMD measurements are made with two added sinusoidal signals of equal amplitude, with frequencies f_1 and f_2, where in the mid frequency range f_1 = 50MHz and f_2 = 51MHz. Low pass filters are added at the output of the frequency generators to give clean signals that are free from generator harmonics. Attenuators [3] are added in the three legs of the combiner to minimise reflections and amplifiers are added to offset the reduction in the signal level caused by the attenuators. The output signal is that observed across a 50Ω load at the collector, which is connected to a spectrum analyser. The InGaP/GaAs/InGaP microwave DHBT with the base-emitter junction area of $8 \times 20 \mu m^2$ probed on-wafer was enclosed in a cryostat chamber for a controlled thermal environment [2].

III. THEORETICAL ANALYSIS

We make the assumption that since the HBT b-c junction is reversed biased and virtually no current flows, the effect of the b-c diode can be made negligible. Therefore, one could approximate the equivalent HBT model [4] into a simple diode (b-e junction) in series with a resistor R as depicted in Figure.1. The two-tone signal is applied across a 50Ω load resistor to the series base and emitter resistance and the b-e dynamic resistance seen at the base terminal of the HBT. The b-e dynamic resistance is dominant at low collector currents and it is temperature dependent.

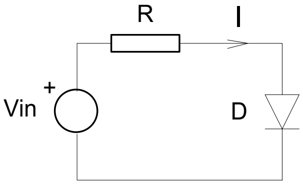

Fig 1. A simple e-b diode in series with a reistor R

The intrinsic base emitter junction voltage V_{BE}' is related to the applied voltage V_{BE} through the terminal resistances of the device as:

$$V_{BE'} = V_{BE} - R_B \cdot I_B - R_E \cdot (I_C + I_B) \qquad [1]$$

From Eqn. (1) at low I_B the effect of R_B can be neglected and assuming constant temperature:

$$\frac{\partial V_{BE'}}{\partial I_C} = \frac{\partial V_{BE}}{\partial I_C} - R_E \qquad [2]$$

This can be written in terms of transconductance, g_m:

$$\frac{1}{g_m} = \frac{nkT}{qI_C} + R_E \qquad [3]$$

where the first term of Eqn. (3) is the dynamic resistance, (R_{BE}), which at low I_C becomes significant and it is assumed temperature dependent. It can be shown that the third order non-linearity, derived from a diode model [4] at low power and low frequency, can be given by equation 4.

$$\frac{d^3I}{dV_{in}^3} = V_T \frac{\left(V_T I - 2I^2R\right)}{\left(IR + V_T\right)^5} \qquad [4]$$

where R is the total resistance (R_{BE} & R_E) seen between the base and emitter terminals and $V_T = kT/q$.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The calculated third order non-linearity as a function of collector current with varying temperature is plotted in Figure 2 using Eqn. (4).

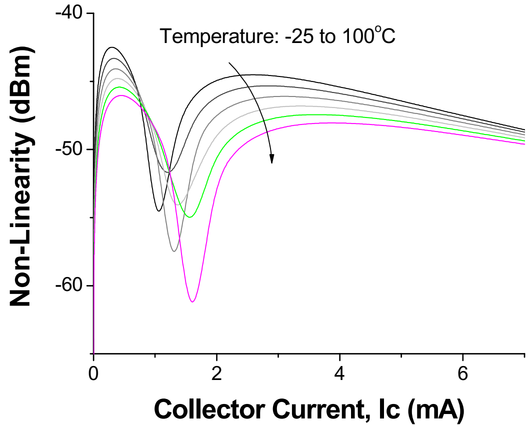

Fig. 2: Calculated third order non-linearity against collector current for the 8x20μm^2 one finger DHBT with varying temperature. Here R_{BE} is independent of T

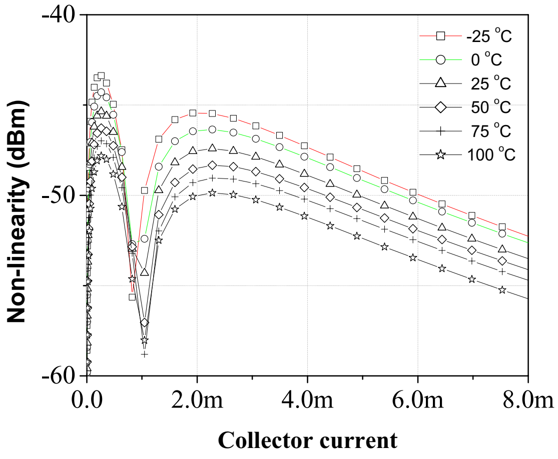

Fig. 3: Calculated third order non-linearity against collector current for the 8x20μm^2 one finger DHBT with varying temperature. Here R_{BE} is dependent of T

Figure 4 shows the measured 3rd order non-linearity of the InGaP/GaAs DHBTs with varying temperature from –25 to 100 °C. which show a minimum that stays at a constant collector current. The calculated results show a variation in the position of the minima (Figure. 2), however this effect is improved by incorporating the temperature dependence of R_{BE} in Eqn (4) as depicted in Figure 3.

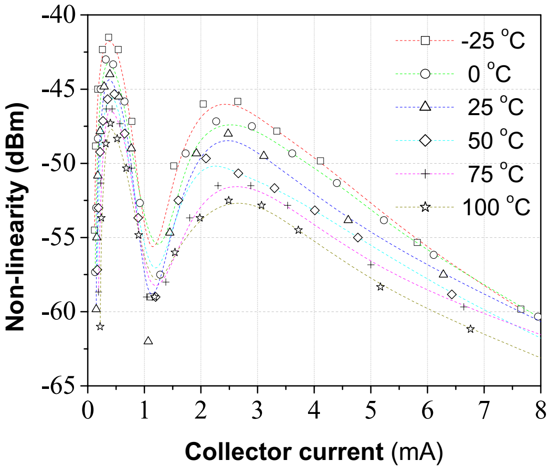

Fig. 4: Measured third order non-linearity against collector current for the 8x20μm^2 one finger DHBT with varying temperature (Vce = 3V, R_L = 50Ω, F1=50 MHz, F2 = 51MHz).

It can be deduced [4] from Eqn. (4) that the third order non-linearity minimum (the point of optimum DC bias) is given by:

$$I_0 = \frac{V_T}{2R} \qquad [5]$$

From Eqn. (5) it can be seen that as the thermal voltage, V_T, increases the resistance must also increase in order for the non-linearity minimum to stay at a constant collector current. To examine this effect, terminal resistances as a function of temperature were extracted, as shown in Figure 5, and it is clear that R_E is almost constant with increasing temperature indicating that temperature dependence arises purely from R_{BE}.

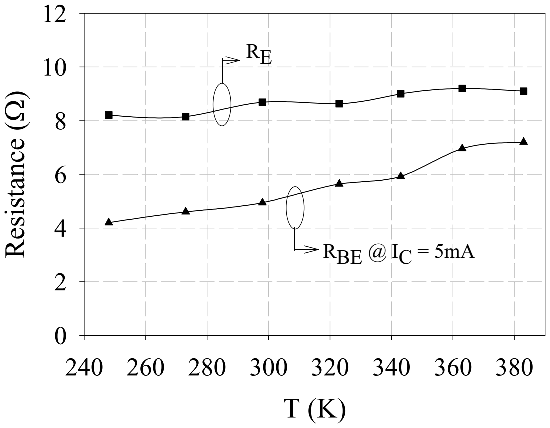

Fig 5. Variations of extracted base and emitter resistances with increases in device temperature.

Furthermore, the gradient of the linear region after the minima is greater in the measured results (Figure 4) than in the improved calculated data (Figure 3). One reason for this discrepancy is the exclusion of capacitive effects [1], which increases with increasing ambient temperature (as shown in Figure 6). The shift in the magnitude of the non-linearity with temperature, in both the calculated and measured data, is due to a reduction in the e-b junction diode voltage, V_{jBE} with temperature as shown in Figure 6.

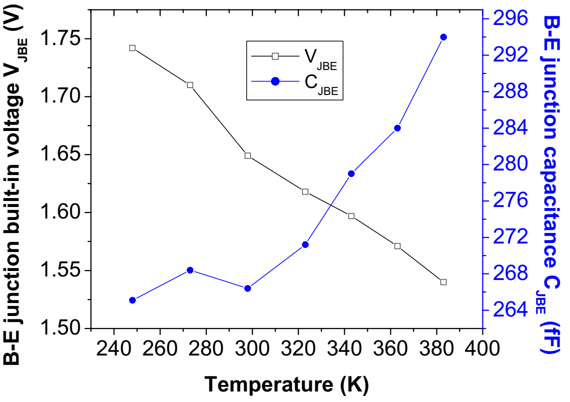

Fig 6. Variations of extracted base-emitter capacitance and build-in voltage as a function of temperature from s-parameter measurements.

Figure 7 shows the measured variation of the third order minima with input power to the device. As the input signal level of the device is increased, the collector current increases which results in stronger non-linear behaviour.

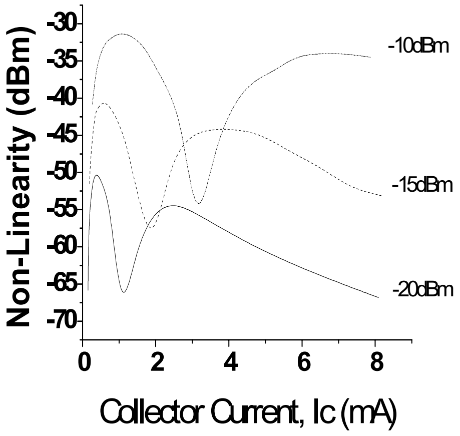

Fig.7: Measured third order two-tone intermodulation distortion versus collector current for the 8x20μm^2 one finger DHBT with varying input bias (Vce = 3V, R_L = 50Ω, F1=50 MHz, F2 = 51MHz).

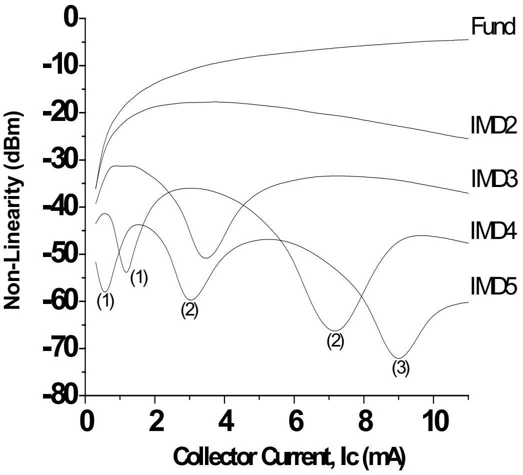

Fig.8: Measured two-tone IMD up to fifth order versus collector current for the 8x20μm^2 one finger DHBT with varying input bias (P_{in} = -10dBm, Vce = 3V, R_L = 50Ω, F1=50 MHz, F2 = 51 MHz).

Figure 8, shows the measured non-linear results up to fifth order which is used along with the modelled results to obtain the normalised values of the positions of the minima (shown in *Table 1*). Normalisation means the positions of the minima become independent of the input power to the device leading to more accurate comparisons. Examining the data in *Table 1* for normalised minima it is clear that the ratios are similar for both measured and calculated results. This suggests the usefulness of the simple Eqn (4), which provides a valuable insight into the non-linear behaviour of the measured devices.

Minima	**Normalised minima**	
	Measured	**Calculated**
3rd order	1.00	1.00
4th order trough 1	0.35	0.27
4th order trough 2	2.22	2.68
5th order trough 1	0.15	0.2
5th order trough 2	0.89	0.80
5th order trough 3	2.71	2.04

Table 1: Normalised minima with respect to the third order minima from measurements and calculations.

V. CONCLUSION

We have predicted the temperature dependence of the IMD characteristics in InGaP/GaAs DHBTs using a simple diode model. This model is verified by examining the normalised positions of non-linearity minima. It is also shown that the variation of small signal capacitance and resistance with temperature needs to be accounted for in order to predict the measured data. The effects of changes in input power on the non-linearity characteristics of the InGaP/GaAs DHBT have also been analysed. These analyses are important for understanding the IMD characteristics of these devices when the ambient temperature changes.

ACKNOWLEDGEMENT

The authors wish to acknowledge the technical assistance of Keith Williams for measurement set-up.

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