NON-LINEAR APPLICATIONS OF HEMT DEVICES

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ABSTRACT

This paper reviews the basics of AlGaAs/GaAs HEMT operation and large signal modeling. It also considers its application to the realization of three typical non-linear circuits, namely, an 18 GHz oscillator, a 12.5 GHz mixer and a 6 to 12 GHz frequency doubler. The performance presented by these HEMT components compares favourably to those presented by similar GaAs MESFET components.

INTRODUCTION

The last decade registered the introduction of a new microwave device, the High Electron Mobility Transistor or the Modulation Doped Field Effect Transistor, better known as HEMT or MODFET[1,2]. This type of transistor employs heterostructures constructed with different doping in order to create a quantum well. The latter confines the electrons in a quasi bidimensional layer in an undoped semiconductor resulting in high electron mobility. These transistors present higher power gain, lower noise figure and superior cut-off frequency when compared to conventional MESFETs[3].

These devices were initially applied in "chip" style to the design of mm-Wave components[6] for its superior high frequency characteristics. However, the maturing of the AlGaAs/GaAs technology led to reliable and repeatable devices at a rather low cost[4,5] and its application became important in chip or packaged styles in the microwave range. Thus, this type of device is the natural option for the design of low noise amplifiers operating in the frequency range from 1 to 60 GHz.

Considering the general HEMT characteristics it is easily verified that non-linear circuit functions such as oscillators, mixers and frequency multipliers can also be performed by this device. If their high frequency characteristics are also considered, then it is seen that these functions are readily extended to the milimeter wave band[7]. However the power compression performance of AlGaAs/GaAs HEMTs is 2 dB lower than that presented by MESFETs of equivalent gate area[8]. The main reason for this behavior is the higher transconductance nonlinearity presented by this device.

Recently, the HEMT technology was applied to the design of monolithic amplifiers[6] and the experimental results were very promising. So the way is open to integrate several circuit functions in the same "chip", emphasizing the interest on the non-linear application of HEMT devices.

This paper presents a brief description of the device operation and introduce a simple and computer efficient HEMT large signal model employing equivalent circuit. This model is accurate enough to predict the performance of most non-linear microwave circuits. Then, it is introduced the application of HEMTs to the design of some practical non-linear microwave circuits developed at the University of São Paulo. Finally, a brief survey is made of the non-linear applications of HEMTs reported in the literature.

HEMT OPERATION

The cross section of a HEMT employing an AlGaAs electron donor layer and a GaAs conducting channel is depicted in figure 1. It is a charge controlled semiconductor device, composed of three terminals. The control terminal is called gate and consists of a Schottky rectifying contact. The gate is placed in-between the ohmic drain and source contacts.

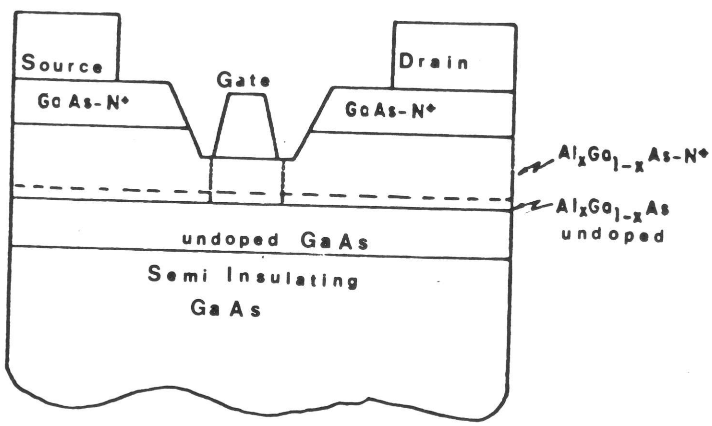

Fig 1 - Cross section of a AlGaAs/GaAs HEMT.

In this device GaAs and AlGaAs layers are grown over a semi-insulating GaAs substrate. Molecular Beam Epitaxy, MBE, or Metal Organic Chemical Vapour Deposition, MOCVD, process are employed to obtain high quality and high purity semiconductor layers.

The depletion region of the Schottky barrier mets and eventually overlaps the depletion region associated with the heterostructure in the AlGaAs layer under the gate. Thus, the free carriers are retained as a bidimensional electron gas at the undoped GaAs side of the heterojunction interface. The current control from source to drain is effected by the gate bias that controls the carrier density on the bidimensional electron gas under the gate.

LARGE SIGNAL MODEL

The large signal device model represented in figure 2 is adequate to simulate the main non-linear characteristics of the HEMT and is readily applied to any time domain simulator[9]. This topology is similar to MESFETs non-linear model, but their elements represent different physical phenomena, requiring specific current-voltage relationships.

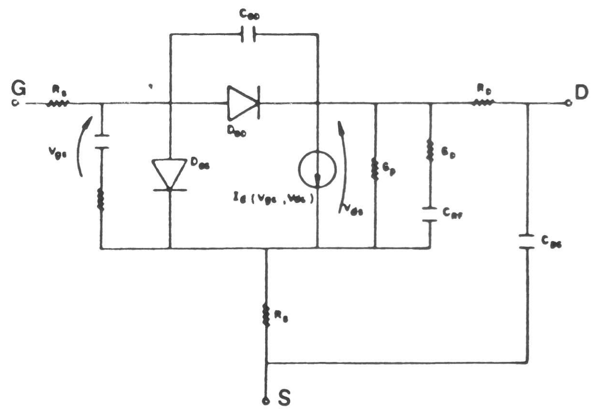

Fig 2 - Large signal model for FET devices.

The non-linearities presented in that model are: the drain current, the gate-source and gate-drain diodes and gate-source and gate-drain capacitances.

The drain current source $I_d(V_{gs},V_{ds})$ relates the static drain current with the intrinsic gate-source and drain-source voltages. Then, the partial derivatives of I_d in respect to V_{gs} and V_{ds} provides the intrinsic transconductance and output conductance respectively. This current source represents not only the electron conduction through the bidimensional gas but also the parasitic conduction through the AlGaAs layer for high gate-source voltages.The drain current can be expressed by the product of two functions, one dependent on the gate voltage and the other on the drain voltage, as described in equation 1.

$$I_d(V_{gs},V_{ds}) = F(V_{gs}).G(V_{ds}) \qquad (1)$$

The function F, in the case of HEMTs, must represent the charge control mechanism that is effected through the gate voltage, to simulate the carriers density saturation on the bidimensional gas and the generation of free carriers in the AlGaAs layer when the gate voltage is increased. Thus, different functions are required to represent the HEMT and MESFET characteristics, since in the latter the gate voltage controls the width of the depletion layer. These differences are better illustrated by the experimental characteristics of the drain current and the static transconductance for typical commercially available MESFET, NE700 by NEC, and HEMT, 2SK677 by SONY, presenting the same gate dimensions 0.5 x 300 μm^2 as depicted in figure 3. The most pronounced difference is the saturation of the drain current at high gate bias that results in poor transconductance performance.

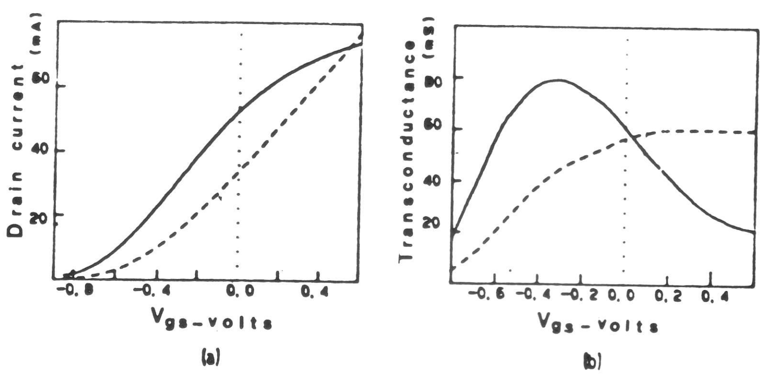

Fig 3 - (a) Drain current; (b) Transconductance as a function of gate voltage, at V_{ds} = 2V (——) HEMT 2SK677; (---) MESFET NE70083.

In the literature there are several equations to represent the function F for MESFET devices. The one reproduced in equation (2) has been proposed to represent simultaneously MESFETs and HEMTs[10], by a suitable choice of the parameters.

$$F(V_{gs}) = \frac{\beta . (V_{gs} - V_T)^2}{1 + b(V_{gs} - V_T)} . \frac{1}{1 + X_K . \exp(X_e . V_{gs})} \qquad (2)$$

In this equation, the pinch-off voltage V_T and the fitting parameters β, b, X_K and X_e are determined through DC measurements and optimization procedures.

The function G must relate the drain current to drain voltage, and represent the behavior of the electrons velocity in the bidimensional gas, as a function of electric field. Since this dependence is the same for both devices, the same function applied to MESFETs is used here for the HEMT. This function is described by equation 3.a for the $I_{DS}XV_{DS}$ linear region and by equation 3.b for the saturated region.

$$G(V_{ds}) = \left[1 - \left(1 - \frac{\alpha . V_{ds}}{3}\right)^3\right]\left[1 + \lambda . V_{ds}\right] \quad : \quad 0 < V_{ds} < 3/\alpha \qquad (3.a)$$

$$G(V_{ds}) = \left[1 + \lambda . V_{ds}\right] \quad : \quad V_{ds} > 3/\alpha \qquad (3.b)$$

The static $I_d \times V_{ds}$ characteristics and the output conductance in fucntion of V_{ds} at $V_{gs} = 0$ for the same MESFET and HEMT devices described previously are represented in figure 4.

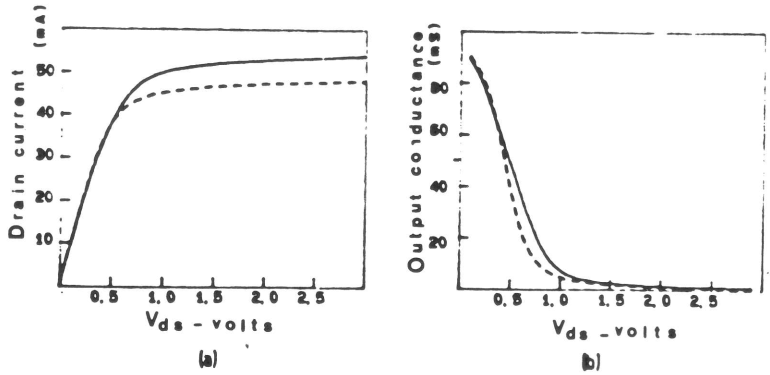

Fig 4 - (a) Drain current; (b) output conductance. in function of drain voltage at $V_{gs} = 0$. (——) HEMT 2SK677; (---) MESFET NE70083.

In the model of figure 1 it is observed the presence of two output conductances, namely G_P and G_D, which have been added to the model to take account respectively, of leakage currents through the substrate and dispersion on transconductance and output conductance as a function of frequency. The leakage corresponds to a small current that is added to the current source. However, the effect of frequency dispersion is much more important and can be evaluated by the experimental results displayed in figure 5, for the HEMT type 2SK677.

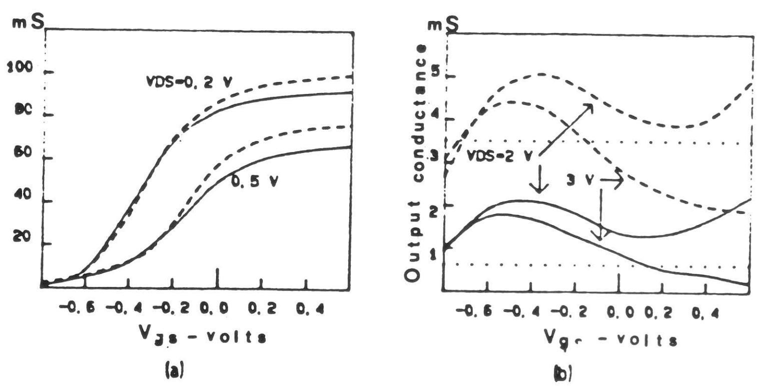

Fig 5 - Output conductance in fucntion of gate voltage (a) linear region; (b) saturated region. (——) static values; (---) RF values.

The action of the gate diodes is rather complex to be represented by a simple circuit, since two diodes back-to-back are needed to account for the Schottky barrier -

metal/AlGaAs and the heterojunction - AlGaAs/GaAs. However, this representation is required only on strongly overdriven operation, where a high forward conduction operation becomes important. For most practical microwave applications, the overdriven case is rarely met, so that single diodes may represent a low forward conduction of the gate.

The C_{GS} and C_{GD} capacitances represents the charge variation under the gate due to variations on the gate and drain voltages. In MESFETs these capacitances are associated to the charge variation in the depletion layer, while in HEMTs this capacitance is due to the modulation of the charge contained in the bidimensional electron gas and in the AlGaAs layer. For gate voltage near the pinch-off, the gate capacitance depends exclusively on the bidimensional electron gas, since the AlGaAs is completely depleted and behaves as the dielectric of a parallel plate capacitor. The gate capacitance is then an inverse function of the distance between the electron gas and the gate metal, decreasing as the gate voltage approaches pinch-off. For higher gate voltages, the electron gas density tends to saturate which results in the decrease of its capacitance. However the charge variation in the AlGaAs layer, results in a further increase in the total gate capacitance.

For practical purposes the gate-source capacitance can be approximated by the capacitance of a reverse biased Schottky diode, while the gate-drain capacitance can be assumed constant in the active region of operation. The measured capacitance in function of gate voltage compared to the one predicted by a diode is depicted in figure 6.

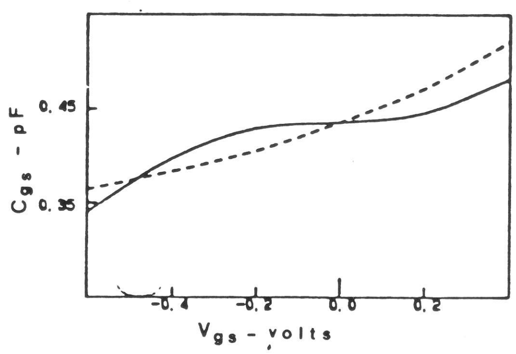

Fig 6 - Gate-source capacitance X gate voltage.
(——) experimental; (---) Schottky diode

NON-LINEAR APPLICATIONS

Initially, HEMT devices were developed for linear applications in particular for low noise amplifiers[2], due to its superior noise performance compared to MESFETs. As communication and radar systems increase its operating frequency far into the millimeter wave range, this type of device appears as the real option not only for amplifier design, but also for other type of non-linear circuits such as oscillators, mixers and frequency multipliers.

The main sources of nonlinearity are those associated with the drain current source, i.e. the transconductance and output conductance. The heterostructure used in HEMTs results in higher mobility which reflects in higher transconductance, a parameter that has a major effect both in the linear and non-linear device performance. The input capacitance is a non-linear parameter that is important when designing milimeter wave components.

In the following section it is shown three typical non-linear applications of the 2SK677 HEMT device by SONY, namely an 18 GHz oscillator, a 12.5 GHz mixer and a 6 to 12 GHz frequency doubler.

18 GHz OSCILLATOR

In the design of the 18 GHz HEMT oscillator the reverse channel mode of operation was employed[10], conducting to a simple circuit topology depicted in figure 7. This approach has been widely used in GaAs MESFET oscillators, and it was found that its advantages holds true for the HEMT. Thus, negative resistance is generated on the HEMT ports at high frequencies in this mode of operation. A dielectric resonator is coupled to the gate to satisfy the oscillating conditions.

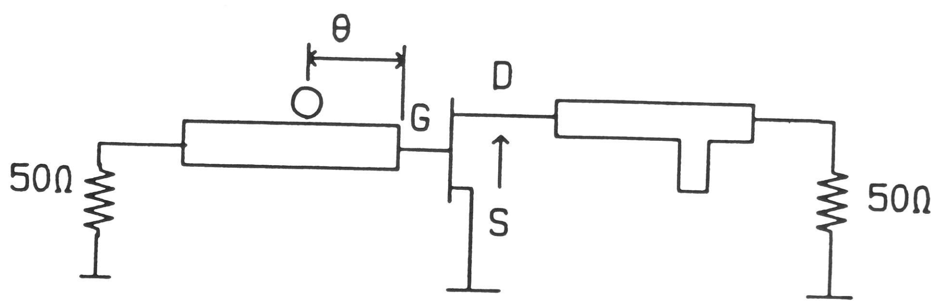

Fig 7 - Topology for the 18 GHz oscillator.

The drain circuit is matched to the 50 ohms output load by means of a single stub. The large signal model presented earlier was implemented into SPICE simulator, and was used to determine the optimum load impedance for maximum output power. An output power of + 14.5 dBm was obtained from the simulations for a resistive load of 15 Ohms.

This circuit was constructed on alumina and soft substrates as displayed in figure 8. A soft substrate was applied to the drain, since it would ease the matching circuit adjustment. In the gate an alumina substrate was used, since it presents a flat surface to the dielectric resonator and is more stable over the temperature range from 0 to 60° C.

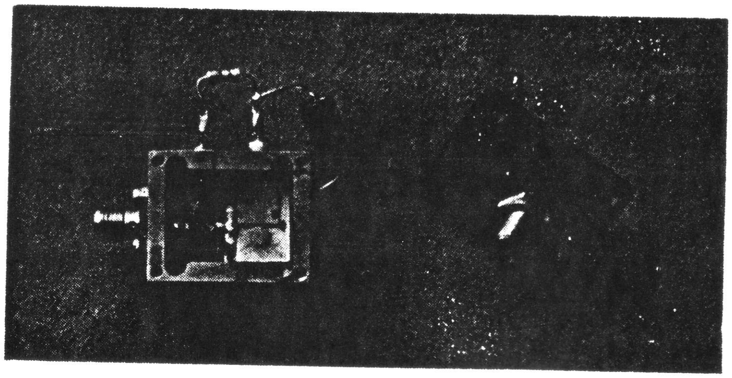

Fig 8 - Photo of the 18 GHz oscillator

Adjustment of the oscillating frequency was provided by the screw located in the upper lid. The experimental results obtained for this prototype are described in table I which shows the successful operation of a HEMT as an oscillator.

Frequency range	17.5 - 18.5 GHz
Output Power	+ 11 dBm
Temperature stability	1.6 ppm/°C
External "Q"	1500
Phase Noise @ 10KHz	-70 dBc/Hz
Frequency pulling @ 1:1.5	2.1 MHz

Table I - 18 GHz Oscillator Performance

12.5 GHz MIXER

In conventional MESFET mixers, the device is biased in class B mode and a high LO dynamic voltage is applied to the gate, modulating the transconductance as a function of time, $g_m(t)$. The mixing effect takes place at the drain, since a low RF voltage also applied to the gate appears in the drain multiplied by $g_m(t)$. This approach is also applied to HEMT mixers, and the transconductance compression usually observed in this device, does not affect appreciably the mixer performance[11].

Following this approach a simple mixer was designed for converting the 12250 - 12750 MHz RF band to the 900 - 1400 MHz IF band with a LO operating at 11.35 GHz. The topology for the HEMT mixer is presented in figure 9. The drain circuit consists of a $\lambda/4$ open stub at the LO frequency at a distance O_2 from the lead, such that the effective device impedance is series resonated by the virtual ground imposed by the stub. This conventional procedure assures that the dynamic drain voltage is zero for the LO signal and the dynamic current remains in the saturated region.

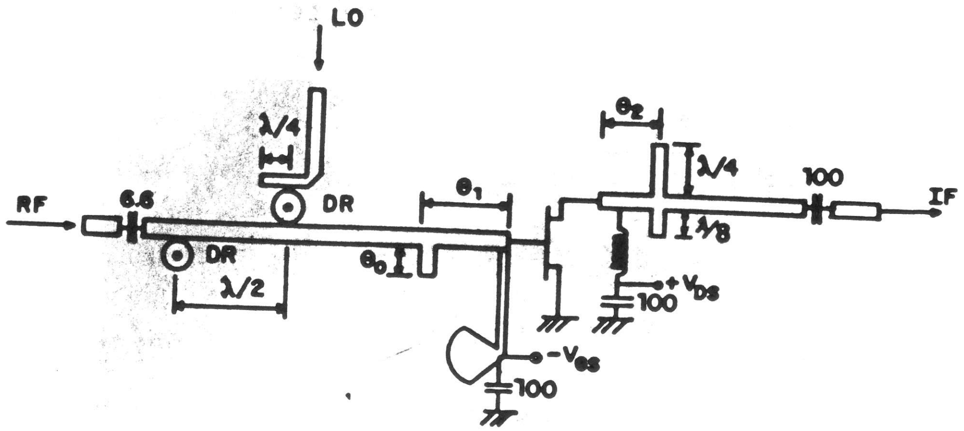

Fig 9 - Topology of the HEMT mixer

The λ/8 open stub shorts to ground the second harmonic voltage. The IF impedance was not matched at the output for stability reasons. The gate is matched by an open stub located approximately at λ/2 from the gate at the LO frequency. The LO and RF signals are applied to the gate by means of a bandpass and a bandstop filter constructed by means of dielectric resonators. All circuits were manufactured employing thin-film technology. This type of mixer presented a conversion gain of 4 dB in a bandwidth of 500 MHz, as shown in figure 10.

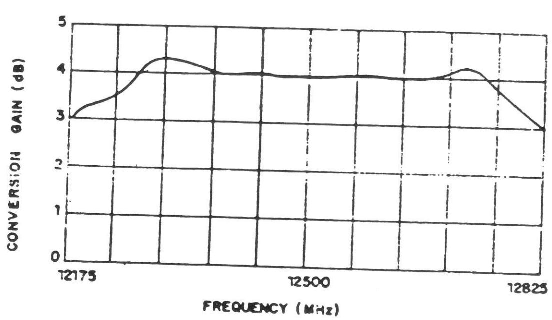

Fig 10 - Conversion gain as a function of frequency

The SSB noise figure for this type of mixer is shown in figure 11, where it is observed a minimum of 3.8 dB and a maximum of 4.5 dB within the RF band. This noise performance is roughly 2 dB better than that obtained with MESFET mixers, confirming the superiority of HEMTs for this type of application.

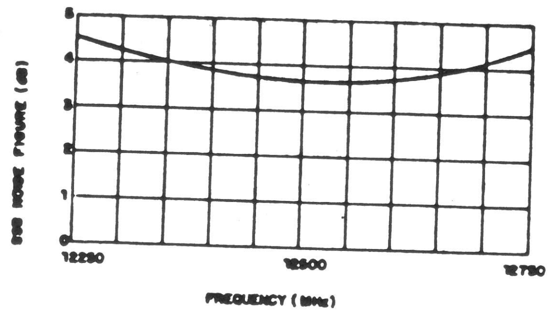

Fig 11 - SSB Noise Figure Frequency Response

FREQUENCY MULTIPLIER

The most efficient way to build a FET frequency multiplier is to bias the gate near the pinch-off for clipping the drain current. Then, the second harmonic generated in this distorted current is extracted by a convenient filter placed at the drain terminal. A test circuit for doubling the 6 GHz frequency that follows this approach is represented in figure 12[12].

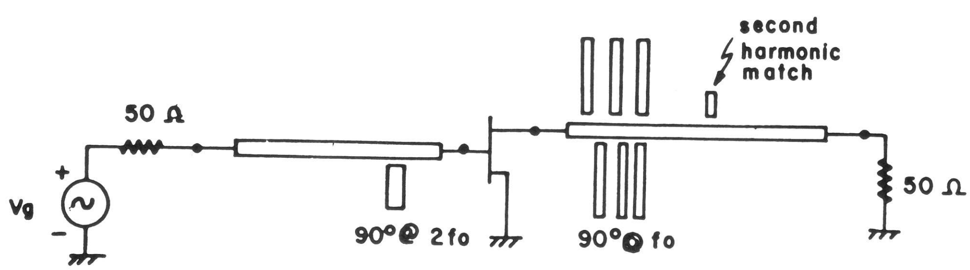

Fig 12 - Test circuit for the 6 to 12 GHz doubler.

The drain filter is composed by a set of 90° open stubs at the fundamental frequency, which blocks the fundamental and third harmonic and are transparent at the second harmonic. The large signal input impedance must be matched to the generator impedance so that the dynamic gate voltage is maximized and as a consequence the multiplication efficiency is optimized. The input circuit employed 45° open stubs at the fundamental frequency which reflect the second harmonic to the gate, and simultaneously matches the fundamental frequency.

The HEMT was inserted in this circuit and after some adjustements it was found that this device can provide 10 dB multiplication gain and + 8.5 dBm output power at this frequency, as shown in figure 13. The power performance is roughly the same obtained from a GaAs MESFET, but the gain performance is 2 dB better. In fact this gain is comparable to the one obtained with dual gate GaAs MESFETs.

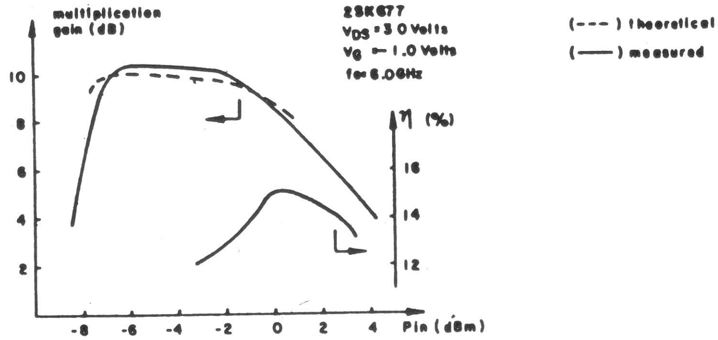

Fig 13 - Multiplication gain versus input power

In this figure it is also shown the theoretical results for this multiplier obtained by computer simulation using SPICE. The correlation between both results confirms the accuracy of the large signal HEMT model presented in this paper.

CONCLUSIONS

A brief description of the HEMT operation and an accurate large signal model has been presented. This model was easily implemented into SPICE for simulating the non-linear applications of HEMTs.

It has also been shown that HEMT devices can be applied to the design and fabrication of non-linear components. In the literature it can already be found other examples of non-linear application of HEMTs at microwave frequencies. For instance, a 70 MHz to 11 GHz up-converter has been reported, which presented 3 dB conversion gain and + 7 dBm output power at 1 dB gain compression[13]. A HEMT drain mixer operating at 11.76 GHz was reported[14], and presented a conversion gain of 4.5 dB and a noise figure of 6.5 dB. The most important non-linear applications of HEMTs reported at mm-Wave are: a mixer capable of converting the 44.5 GHz to 3 GHz with 0 dB conversion gain and a SSB noise figure of 8 dB[7] and a 44.5 GHz oscillator presenting 0 dBm output power with 3% efficiency[7].

Thus, it is now possible to construct high performant communication systems based on HEMT components in most functions, and it can be expected in the near future complete HEMT based monolithic integrated microwave or mm-Wave subsystems.

It should be emphasized that the devices used in this context were developed essentially for low noise applications. It is expected that superior performance can be obtained with devices specifically developed for non-linear operation.

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