Design of PHEMT Diodes for MMIC Mixer Applications

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Abstract

This paper presents a simple approach for optimizing the dimensions of PHEMT diodes as well as predicting their mixer performance up to millimeter wave frequencies. It also introduces a new diode model and compares its properties with previous conventional models. The simulation results are compared with experiments carried out with a single ended diode mixer at Ku-band.

Introduction

Traditionally, the design of MIC mixers started with the selection of an appropriate balun or considerations on how the available balun approaches can be improved in order to meet the target specs. Then the Schottky diodes, either Silicon or GaAs, were selected from a choice of high barrier, medium barrier and low barrier, depending on the available LO power. If high dynamic range was required, use of two diodes in series was and still is a common practice. The advent of MMIC technology changed this approach because designers can now select the diode size and thereby trade off RF power, LO power and impedance match for improved overall performance. The common drawback of MMIC diodes is that they are obtained from the Schottky barriers used in FETs, which have inferior performance compared to discrete diodes. The use of PHEMT technology for millimeter wave applications provides diodes which behave different than regular Schottky diodes, since they consist of a Schottky barrier in series with a heterojunction. The current description of this structure has been simulated by an exponential diode equation and the reactance by an exponential junction capacitance equation. A recent publication showed that PHEMT capacitance is more adequately described by a hyperbolic tangent [1]. However, it is found that neither of them describe the non-linear mixing performance with a reasonable degree of accuracy.

The objective of this paper is to describe the development of a simple PHEMT diode model and the discussion of its accuracy and simulation time compared with previous conventional models. It was developed for use with commercial software packages such as MDS, ADS or Libra. The paper also introduces a new approach to design diode mixers for specific attributes such as dynamic range control or impedance matching. A few experimental results with a single ended diode mixer are presented to corroborate the models used. The extracted models and the measured data were obtained from Fujitsu's PHEMT millimeter wave process, and the conclusions are believed to be applicable to other PHEMT process.

PHEMT Diode Model

The schematic circuit for the diode model is illustrated in figure 1. The current source Id is described by the conventional exponential diode equation, requiring the parameters saturation current, Io, and ideality factor, n. These parameters can be determined from the measured current-voltage characteristic. The series resistance, Rs, can also be obtained from the I-V characteristic, assuming it is constant for an applied forward voltage [2]. Referring to a FET model, this resistance comprises the gate resistance, plus the parallel combination of the source and drain resistors. The voltage dependent junction capacitance is in parallel with the intrinsic diode. The other reactive elements are parasitics. Ls takes into account the transmission line effect of the interdigital diode structure, and Cp takes into account the pads used to connect the gate fingers and the drain-source ohmic contacts.

The diode was characterized by means of DC and S-parameter measurements. The DC diode conductance for a 2x50 μm active area is depicted in Figure 2. The diode conductance, obtained from S-parameters at several bias points, measured at 100 MHz, is in the same plot. It shows a good agreement with the DC measurement. In the same plot, the conductance calculated from the current equation shows a good agreement with experimental results up to 1.2 volts. Above this voltage, the diode starts to be heavily turned on and a divergence is observed between theoretical and experimental results. This difference can be attributed to the non-linear nature of the series resistance [3]. As a matter of fact, it was found that a simple linear voltage dependent resistor is adequate to simulate the measured conductance at forward voltages higher than 1.2 volts. For simplicity the resistor is linear for the simulation presented in this paper. This is a resonable assumption because it trades off convergence speed vs a few tenths of dB in conversion loss.

The conventional way to simulate non-linear diode capacitance is to use a junction capacitance, implemented in most non-linear simulators. A recent publication showed that near turn on voltages the capacitance follows a hyperbolic tangent law and is considered constant for further positive voltages [1]. However, it was found that from the turn-on voltages up to a high bias condition, the capacitance is not yet fully shorted by the diode and exhibits an increasing exponential characteristic. This effect is illustrated in figure 3, which was obtained from S-parameters as a function of bias voltages. It can be observed the capacitance in regions I and III roughly meets the conventional exponential junction capacitance, but it deviates considerably in region II. An analytical equation was developed to describe the capacitance characteristic.

$$C_j(V) = \left(C_1 + C_2 \cdot \tanh\left[\frac{V + a_2}{b_2} \right] + C_3 \cdot \exp\left[a_3 \cdot \left(V - \Phi_{bi} \right) \right] \right) \tag{1}$$

The first part of this equation is a constant representing capacitance for voltages smaller than –1.0 volt. In region II the constant capacitance is added to the capacitance of a tanh function, resulting in the capacitance step observed in the figure. With increasing voltage, the exponential part of the equation dominates the junction capacitance.

Design of PHEMT Diodes

The use of PHEMT diodes as mixing elements places several restrictions on its use compared to conventional Silicon diodes. They include power handling capability, high series resistance and a complex capacitance vs voltage dependence. In spite of these drawbacks, MMIC designers have control of some of the diode parameters that can be optimized for a specific application. These diode parameters are gate width, gate length and number of fingers. They have a direct impact on the mixer performance. A means to identify their trade-offs can be obtained by employing the prototype circuit of figure 4.

Instead of a power source that is usual in microwave circuits, a large signal voltage source (representing the LO signal) in series with a small signal voltage generator (representing the RF signal) are connected directly to the diode’s anode. The cathode is shorted to ground by means of capacitor C at the LO and RF frequency. The capacitor is a high impedance for the IF signal which is developed in the load resistor R_L. The RF choke is the DC return for the diode, and presents high impedance at the IF frequencies. The idea behind this simple circuit is to apply the LO and RF signals directly to the diode and analyze the resulting current components at the several mixing frequencies. Therefore, there are no frequency restrictions and results can be obtained at any desired frequency without designing a matching circuit. The power relations at the desired frequencies $\omega = n\omega_{LO} + m\omega_{RF}$, are obtained from the definition of power expressed in equation 2:

$$P(\omega) = \mathrm{Re}\{V(\omega) \times I(\omega)^*\}/2 \qquad \text{with } n, m = \pm1, -\pm2, \ldots \tag{2}$$

The large signal impedance, Z_{LO}, and small signal impedance, Z_{RF}, are also directly available by relating the applied voltages to the resulting currents at the LO and RF frequencies.

$$Z_{LO} = V_{LO}/ I(\omega_{LO}) \quad \text{and} \quad Z_{RF} = V_{RF}/I(\omega_{RF}) \tag{3}$$

Notice this is an ideal mixer circuit where all non desired harmonics, mixing products and image signals are shorted to ground. However, it does provide important information concerning the required LO power, conversion loss, compression characteristics and diode dimensions.

Results

Figure 5 shows how a diode mixer can be dimensioned for specific targets, such as P_{1dB}, using the circuit of figure 4. The conversion loss is simulated as a function of LO power for a constant low RF voltage and as a function of RF power for constant LO voltage. This simulation has to be repeated for different gate dimensions, and the one presenting the best performance is then selected. The plot of figure 5 was obtained from a 4x50 μm^2 diode which provided a P_{1dB} of 7.8 dBm, when driven by an LO power equal to

+10.5 dBm. A minimum LO power of +7 dBm is required to obtain a reasonable conversion loss of 5 dB. It is also observed the conversion loss slightly degrades for higher LO drive and the upper limit is determined by the power handling capability of the diode. The P_{1dB} is also a function of LO not shown in the plot, due to the dependency in conversion loss. Therefore, the best drive level has to be determined iteratively.

A breadboard mixer for 14 GHz operation with an applied LO at 13 GHz was assembled to verify the performance of three different diode models and compare them with simulations carried out with the circuit of figure 4. All models use the conventional exponential law to describe the diode DC current and different capacitance versus voltage descriptions. Model 1 uses the capacitance of a junction diode which is essentially exponential (conventional), model 2 uses a hyperbolic tangent description [Eq. 1 without exponential term], and model 3 uses the capacitance equation of Eq. 1. The results of table I were obtained for a down-converter mixer driven by a LO power of 10 dBm. The experimental single ended diode mixer was carefully matched to represent the ideal circuit as close as possible. Observe that all models are capable of representing the small signal conversion performance with a reasonable accuracy at 14 GHz. The differences resulting from the different capacitance equations become more crucial at higher frequencies, where model 1 predicts an optimistic power compression performance. Another distinction between these models can be found from third order intermodulation product suppression at 14 GHz, shown in figure 6. Observe that suppression is modeled within a reasonable range by model 1 and model 2 gives a poor prediction at low signal levels. However, model 3 presents a better overall prediction.

	conventional (1)	tanh (2)	new model (3)	Measured
Conversion loss [dB] (14 GHz)	5.5	5.5	5.5	5.8
P_{1dB} at input [dBm]	8.5	8.3	8.1	7.7
Conversion loss [dB] (30 GHz)	5.9	5.5	5.8	not possible
P_{1dB} at input [dBm]	9.1	7.47	7.7	with setup

Table I: Comparison of performance of different diode models with experimental results

Based on this investigation one concludes that model 3 is better than the previous to predict linearity and high frequency performance. However, when comparing convergence efficiency, model 1 was faster than model 2 or model 3 including user defined equations. In particular, the simulation of IM3 for a single ended diode mixer required a long time due to the need of a higher number of harmonics. That can be prohibitive in the design of a circuit with a large number of diodes. Therefore, model 1 is indicated for initial stages of design, and after the final topology is reached, model 3 should be employed for fine adjustments.

Conclusion

We have presented an approach to optimize the dimensions of PHEMT diodes for mixer applications. Accurate prediction can be made about mixer conversion and compression behavior. The verification between the measured results of a single ended diode mixer and the simulation for three different diode models confirm that the suggested diode model delivers the best results. The capacitance equation of this diode model uses a tanh function for the reverse bias region and an exponential increase in the forward bias region.

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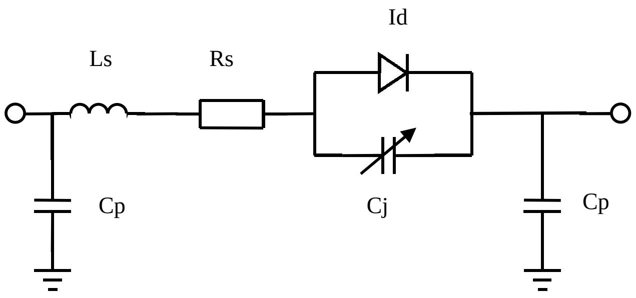

Fig. 1: Schematic of the diode model

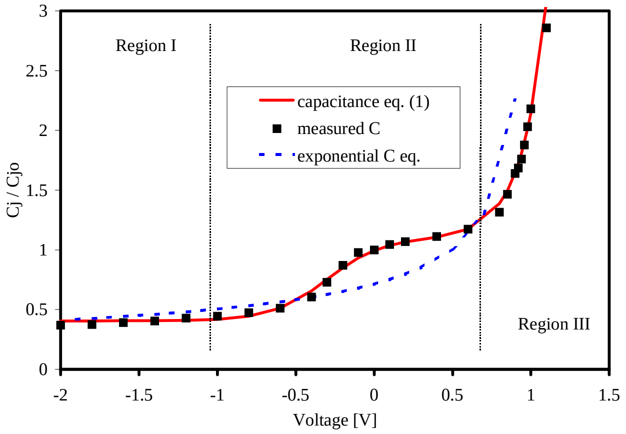

Fig. 3: Normalized non-linear capacitance obtained from measured S-parameters and calculated with the analytical capacitance equation (1) and the conventional, in most simulators implemented exponential capacitance equation

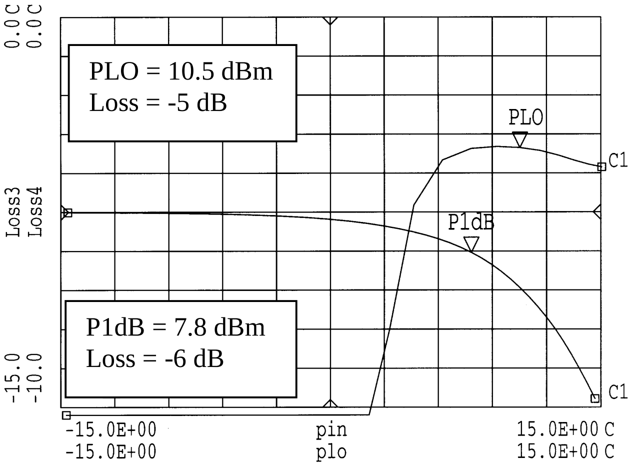

Fig. 5: Simulated example of conversion loss as a function of LO and RF power. The circuit used is shown in figure 4 (RF = 14 GHz; LO = 13 GHz)

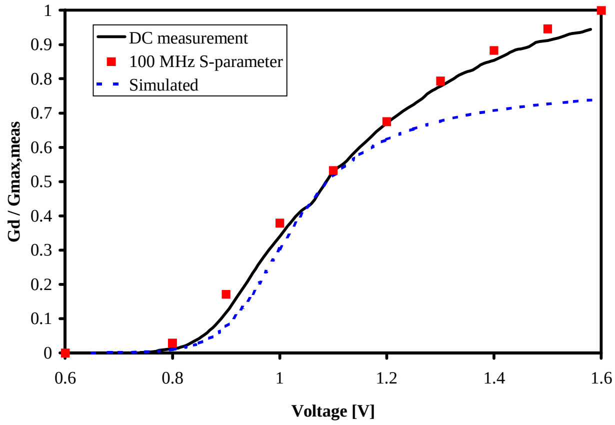

Fig. 2: Plot of normalized diode conductance obtained from DC and S-parameter measurements and the calculated deviation of a conventional diode current equation with constant series resisitance

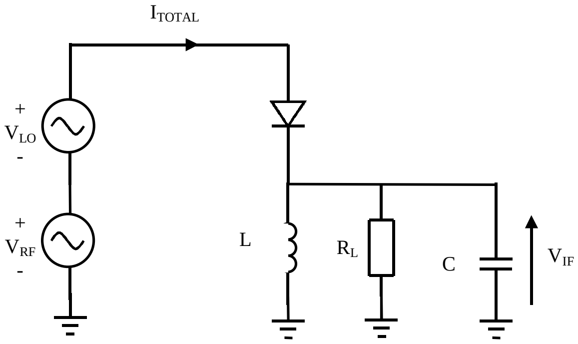

Fig.: 4: Ideal mixer prototype applying voltage generators

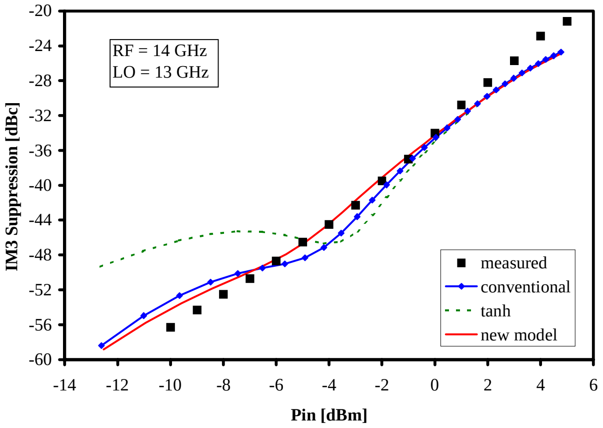

Fig. 6: Measured and modeled third order intermodulation suppression (P_{LO} = 10 dBm)