Non-linear Modelling of Microwave PIN Diode Switches for Harmonic and Intermodulation Distortion Simulation

Vicentiu Cojocaru [1] and Franz Sischka [2]

[1] TDK Electronics Ireland Ltd., Dublin, Ireland [2] Agilent Technologies Deutschland GmbH., Munich, Germany

***Abstract* — The paper presents for the first time a practical and relatively simple non-linear modeling solution for μ-wave PIN diodes for use in HB circuit simulators. It enables very good prediction performance of the very important harmonic and intermodulation characteristics of these devices when used in typical μ-wave switching applications. Accurate harmonic distortion measurements have been performed on a number of commercial surface mount PIN diodes, over a wide range of relevant bias conditions and RF power levels. Parasitic elements are first extracted from microwave S-parameter data. Separate non-linear circuit models are then used for the ON and OFF states of the PIN diodes, and these are directly optimized on the measured harmonic distortion data using a dedicated modeling platform developed within a commercial modeling software tool. The new models have been implemented and tested in a popular harmonic balance circuit simulator with very good results. The modeling solution described here can be also applied to other active devices for similar large-signal modeling problems.**

I. GENERAL INTRODUCTION. PIN MODELLING.

Surface mount PIN diodes are used extensively in the implementation of front-end RF switches in many of the modern, multi-system mobile and wireless designs. This is due to their relative simplicity as a technology, their small size and low cost, their reliability, and not in the least, their excellent power handling and switching performances at microwave frequencies. Indeed, considering the switching performance of a microwave PIN diode in small-signal conditions, it is hard to find many other active electronic components that can present such very distinct behaviour at two different bias conditions (from an almost ideal small capacitive element to an almost ideal small resistive element) [1]. Furthermore, with the latest generations of surface mount PIN diodes, it is becoming possible to achieve a satisfactory OFF condition and performances at 0V bias, which is an obvious significant advantage in many applications (no negative bias is needed).

From a modelling point of view, this rather unique behaviour constitutes on one side a big advantage, because it means that we can imagine some very simple linear equivalent circuits to model each of these two very distinct states (the equivalent circuit shown in Fig. 1 is one of the more complex model solutions proposed in literature [2]). Such models can fit very well the small-signal characteristics over a broad frequency band. However, when it comes to predicting crucial large-signal effects, such as harmonic and intermodulation distortion, a good non-linear model is going to be needed instead. At this point, that beneficial, distinctly different behaviour just mentioned, becomes in a way a problem. Firstly, the main non-linear effects encountered in the ON and OFF states, are principally generated, when a relatively large RF signal is present, by two very different non-linear mechanisms inside the device: *i*) conductivity modulation of the charge within the I-layer in ON state [3] and *ii*) capacitance modulation in the OFF state [4]. Secondly, it is normally difficult enough to find suitable non-linear circuit models that can predict well either of these two effects, so it would be even more difficult to find one single model that can predict both effects. Furthermore, complex non-linear models that may sometimes be imagined for such complex problems end up being of little use in practical terms to designers because their implementation in common commercial circuit simulators is not possible, and/or because the associated model parameter extraction process is too difficult.

So far, apart from the standard SPICE diode model, which is still used despite being quite unacceptable in the case of PIN diodes, there have been a relatively limited number of non-linear circuit models proposed in literature, and their capabilities have been limited in general to predicting some of the small-signal characteristics variations with the bias (such as impedance for example) [5][6]. To our knowledge, until now there has been no non-linear model for PIN diodes implemented in any HB simulator, capable of giving a satisfactory level of HD or IMD predictions. When it comes to optimising these characteristics, the RF engineers have no option available, other than choosing as best as they can the PIN diodes with best HD or IMD characteristics. But even this assessment often has to be based on the very limited HD information available from device manufacturers, or on approximate calculations based on physical parameters from data sheets.

In this paper, we describe a practical solution to this problem, with two simple non-linear models being developed and implemented in a HB circuit simulator, for the ON and OFF states, respectively. Finally, simulations with the optimised new models are compared with the measured HD data for a number of distinct bias conditions (V_d=-3V, V_d=0V and I_d=5mA), with very good agreement being seen in all cases.

0-7803-7695-1/03/$17.00 © 2003 IEEE

II. LINEAR MODELING. PARASITICS EXTRACTION

Using a high-performance 50GHz test jig (ICM) with own dedicated TRL calibration procedure, the small-signal S-parameters were measured for all the PIN diodes under investigation over a wide range of relevant bias conditions, from OFF state (V_d=-3V to 0V) to ON state (I_d=0.5mA to 10mA). Although these PIN diodes are intended for use in the lower μ-wave band, these measurements were performed between 0.1GHz and 20GHz. The reason for this was to include in the measurement data the self resonance frequency, which for these types of PIN diodes tends to occur between 15GHz and 20GHz (see Fig. 2). This enables an easier and more precise extraction of the equivalent circuit elements, and especially that of the series parasitic inductance (L_S). A simple equivalent circuit model (Fig. 1), similar to that proposed in [5], have been fitted on the S-parameter data, yielding accurate values for all the parasitic elements (C_{PK}, L_S, R_S). The equivalent μ-wave non-linear capacitance values in the reverse bias region were also determined during these optimizations (Fig. 8.b).

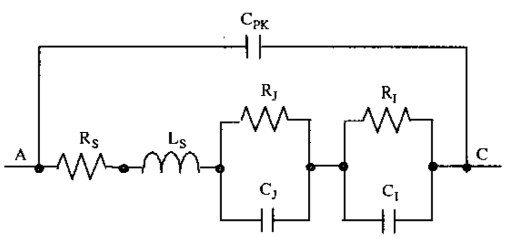

Fig. 1. Simple small-signal equivalent circuit model for a packaged PIN diode. Two parallel R-C circuits are employed to account for the depleted (R_J-C_J) and undepleted (C_I-R_I) regions.

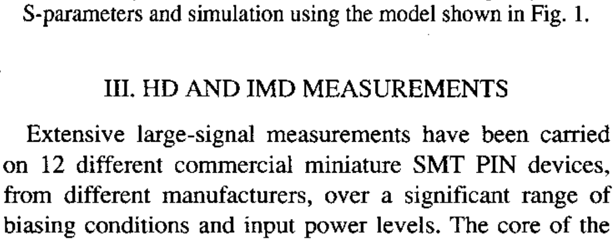

Fig. 2. Comparison between the measured small-signal μ-wave S-parameters and simulation using the model shown in Fig. 1.

III. HD AND IMD MEASUREMENTS

Extensive large-signal measurements have been carried on 12 different commercial miniature SMT PIN devices, from different manufacturers, over a significant range of biasing conditions and input power levels. The core of the tests carried to this point have been single-tone (f_o=1.9GHz) HD measurements, with a limited number of two-tone IMD measurements being also performed. Apart from the non-linear PIN model development, such comprehensive large-signal measurements can be used as a database that could help designers to perform an informed and accurate assessment of the HD and IMD performances of each PIN diode, thus helping them to select the best component in each particular situation. The basic large-signal measurement set-up is shown in Fig. 4. The accuracy and consistency of any HD and IMD measurement is very much dependent on the matching conditions in which the DUT is tested, at the fundamental as well as the harmonic frequencies. These conditions have been always monitored in our case. Fig. 5 shows the typical VSWR characteristics measured at the DUT's input and output ports as well as at the spectrum analyzer. For these large-signal measurements, we have used one of the latest high-performance spectrum analyzers available (E4440 from Agilent Technologies) with a very high dynamic range. An example of the HD characteristics measured for all the 12 PIN diodes in the ON state, for an input power of +35dBm, at different bias current values, is shown in Fig. 6.

Along with the already mentioned small-signal S-parameter, HD and IMD measurements, we have performed also regular DC and low-frequency C-V measurements, as well as less common measurements such as microwave C-V and large-signal I-V measurements on all these diodes. More details, results and analysis of these comprehensive measurements, will be presented in a different article [7].

IV. NON-LINEAR MODELLING SOLUTION

As opposed to trying to find a unique non-linear model for PIN diodes capable to describe the device's HD characteristics in both ON and OFF states, we decided to follow a more practical approach, developing two separate, but relatively simple non-linear models for each of these two fundamentally different conditions. This is not seen as a major disadvantage, since it has become relatively easy in recent versions of commercial simulators to implement local model libraries, from where designers can easily select the appropriate model for each particular situation.

The topology of the non-linear circuit model proposed can be summarized by the general schematic presented in Fig. 3. The difference between the two is made by the resistor R_{DCFW}, set to a very low value (1mΩ) for the ON state and to a very high value (1TΩ) for the OFF state.

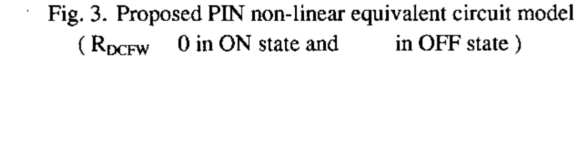

Fig. 3. Proposed PIN non-linear equivalent circuit model (R_{DCFW} 0 in ON state and in OFF state)

A. Non-linear modeling in the OFF state

It is known that the main cause responsible for HD in this region is the high frequency non-linear diode capacitance. An SDD element (SDD_CV) is employed here in order to account for this non-linearity. Initially this is fitted on the low-frequency C-V measurement data. In the presence of even relatively mild large-signal levels when the PIN is switched OFF (the OFF state for these devices means reverse bias voltages not below –3V), the dynamic locus curve will inevitably extend into the forward bias semi-plane. However, this locus curve does not seem to extend into the forward bias region following the actual forward bias DC characteristic of the PIN diode (as it happens in the case of conventional diodes), but rather following an enlarged elliptic curve around the original bias point. Therefore, the SDD_DC_FW has been cut off from model in this case (R_{DCFW}). A third SDD (SDD_DC_RV) is employed to model the reverse I-V characteristic of the PIN. This entire model and its corresponding modeling strategy have been implemented into the combined modeling platform IC-CAP/ADS and then its parameters have been optimized directly on the HD data measured in the OFF state of the PIN diode (V_d = -3V to 0V).

In Fig. 8.a. we present the initial model fit on the low-frequency C-V data, which has been used as a starting point in the optimization. Fig. 8.b shows a comparison between the C-V characteristics measured at low-frequency (1MHz) and those determined at high frequencies (0.1GHz, 1GHz and 2GHz) from the measured S-parameters. In Fig. 8.c. we can see the IC-CAP simulated C-V characteristic resulted at the end of the fitting process on the measured HD data in the OFF region. It is interesting to see how this comes out very close to the 2GHz C-V characteristic determined from the S-parameter measurements. This is an important and very encouraging result, basically proving to a good extent not only the validity of our method, but also proving once more that this particular μ-wave C-V non-linearity is indeed the one responsible for the harmonic distortion generated and measured in the OFF region for such PIN diodes.

B. Non-linear modeling in the ON state

As we mentioned before, for the ON state case, the resistor R_{DCFW} is set to a very low value (1mΩ). This basically means that the SDD element accounting for the I-V non-linearity in the forward region (SDD_DC_FW) becomes now a significant part of the equivalent circuit model. Initially the forward bias DC model is fitted on the regular DC measurement data. Model fit results are shown in Fig. 7 for two PIN diodes with quite different I-V characteristics. The overall model parameters (particularly those related to the transit time) are optimized directly on the measured HD data taken this time in the ON state. Once again, this ON state model and its corresponding extraction and optimization methodologies have been implemented into the same combined modeling platform IC-CAP/ADS.

V. RESULTS

Finally, in Fig. 9 we present three measurement vs simulation HD test results. The first two are in the OFF state (V_d=-3V and V_d=0V) and one is in the ON state (I_d=5mA). Similarly good results have been obtained for all the other bias conditions. To our knowledge, these are the best HD simulation results obtained with a non-linear PIN diode model implemented in a commercial HB simulator.

VI. CONCLUSIONS

We described a practical non-linear modeling solution for the HD and IMD characteristics of PIN diodes used in RF switching applications, suitable for use in HB circuit simulators. Separate non-linear models were proposed for the ON and OFF states. These have been optimized directly on HD measured data from commercial SMT μ-wave PIN diodes. A special modeling platform has been developed within the IC-CAP modeling tool for this purpose. The resulting models have been implemented in the ADS simulator using symbolically defined device elements (SDD). The test results show very good predictions of the harmonic distortion characteristics of the PINs measured. The modeling strategy described could be extended to other active devices for similar large-signal modeling problems.

ACKNOWLEDGEMENTS

The authors would like to thank Chris Gibby for his contribution to the automation of the HD measurements.

REFERENCES

[1] J. F. White, *Microwave Semiconductor Engineering*, J.F. White Publications Ltd., Massachusetts, 1995.

[2] L. Drozdovskaia, "RF frequency properties of a reverse biased thick switching PIN diode", *Proc. Of IEEE Radio and Wireless Conf.*, Denver, September 2000.

[3] R. Caverly, G. Hiller, "Distortion in PIN Diode Control Circuits", *IEEE Trans. on Microwave Theory and Tech.*, vol. MTT-35, no. 5, pp. 492-500, May 1987.

[4] R. Caverly, G. Hiller, "Distortion in Microwave and RF Switches by Reverse Biased PIN Diodes", *IEEE MTT-S Int. Microwave Symposium Digest*, pp. 1073-1076, May 1989.

[5] R. Caverly, N. Drozdovski, L. Drozdovskaia, M. Quinn, "SPICE modelling of microwave and RF control diodes", *IEEE Midwest Symp. On Circuits & Systems*, August 2000.

[6] J. Walston, SPICE circuit yields recipe for PIN diode", Microwaves and RF, pp. 78-89, November 1992.

[7] V. Cojocaru, C. Gibby, "Comprehensive characterization of μ-wave PIN diodes for modern communication systems", to be submitted to the *2003 EuMC Conference*.

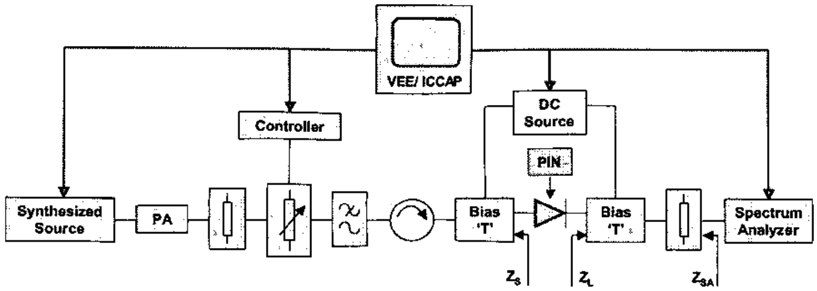

Fig. 4. The large-signal measurement set-up used for the HD (and IMD) tests (SMT PIN diodes were placed in an ICM μ-wave test-jig).

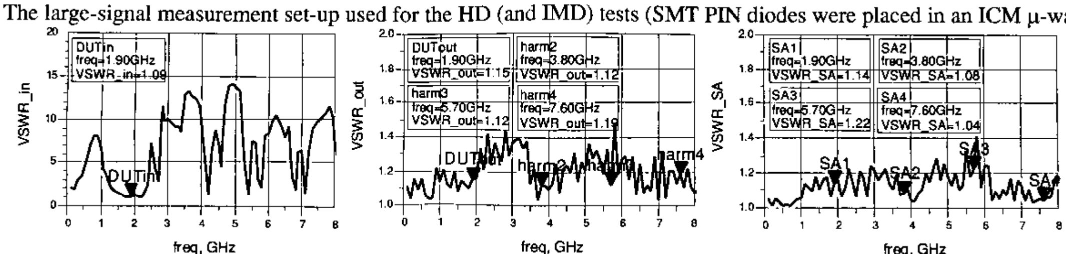

Fig. 5. Measurement results verifying the relevant impedance matching conditions required at the input and output DUT ports (Z_S, Z_L) and at the spectrum analyzer (Z_{SA}), at fundamental frequency (f_o=1.9 GHz) and up to the 4[th] harmonic.

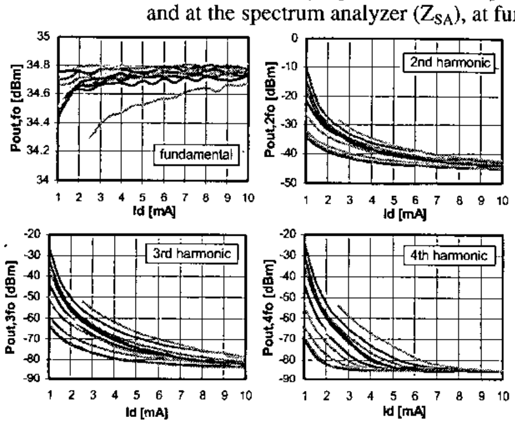

Fig. 6. Measured HD characteristics at +35dBm input power level for 12 commercial SMT PIN diodes

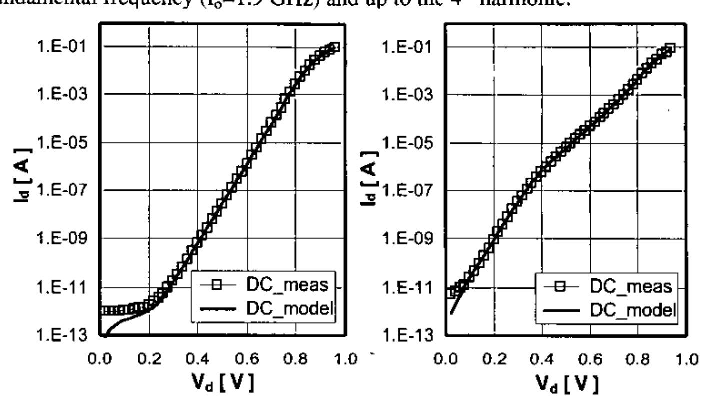

Fig. 7. DC modeling test results for two of the SMT PIN diodes with significantly different DC characteristics

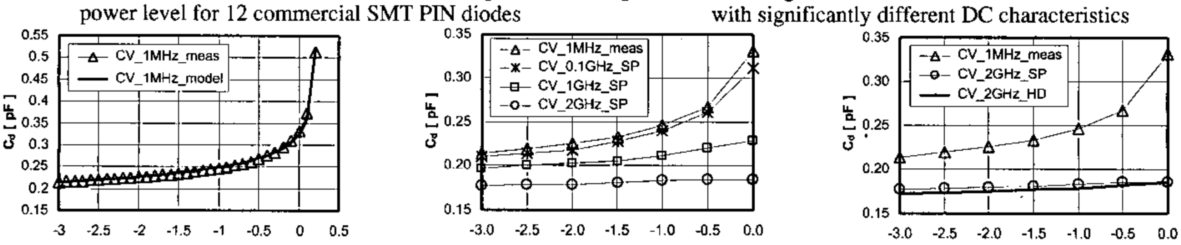

Fig. 8. a) Modeling of the low-frequency C-V characteristics; b) C-V characteristics of a typical PIN diode at low and high-frequencies; c) C-V model fit achieved (thick continuous line) after model optimization on the HD characteristics in the OFF region, using ICCAP.

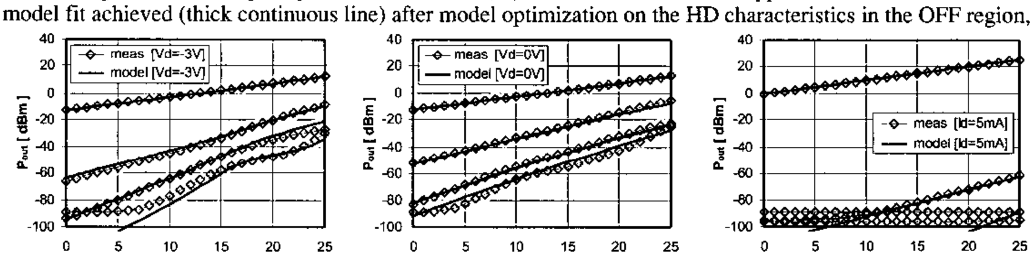

Fig. 9. Measurement vs simulation HD test results (up to 4[th] harmonic) with the new non-linear PIN models (V_d=-3V; V_d=0V; I_d=5mA).