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Overview: Applying Nonlinear RF Device Modeling to Verify S-Parameter Linearity

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Applying Nonlinear RF Device Modeling To Verify S-Parameter Linearity

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Agenda

- RF-IC Modeling: Introducing a New Modeling View
- Introducing Non-Linear RF: Measurements and Harmonic Balance (HB) Simulations
- Modeling Applications for Non-Linear RF
- Examples for S-Parameter Measurement Verification Using HB
- Conclusions

- RF-IC Modeling: Introducing a New Modeling View

With the introduction of the next generation mobile communication systems, modeling engineers are considering to extend existing DC, CV and S-parameter measurements towards nonlinear device characterization. This means that frequency spectra begin to play a more and more important role for modeling.

On the other hand, many modeling engineers still have some problems in understanding the basics of such nonlinear RF modeling. Applying a harmonic balance simulator like Agilent's ADS is a smart way to begin with some studies of the non-linear performance of devices and their corresponding model behavior, even when there are currently no measurement capabilities at hand in the modeling engineer's measurement lab. This presentation is intended to explain the basics of "what's behind S-parameters" from a modeling engineer's standpoint and on how to apply harmonic balance simulators to check the validity of device models.

Usually, modeling engineers use DC analyzers, CV meters and network analyzers to model an electronic device from DC to some Gigahertz.

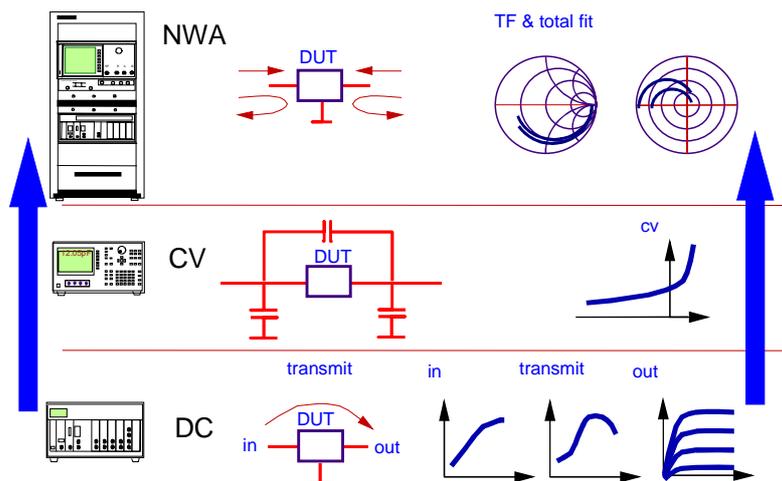


Fig.1: Conventional device modeling from DC -> CV -> S-parameters

However, this kind of device modeling describes the RF performance of components like diodes and transistors in *linear* mode only, because the network analyzer is operated in linear mode. Beyond S-parameters, there is 'the real world', i.e. non-sinusoidal signals, corresponding to nonlinear frequency behavior.

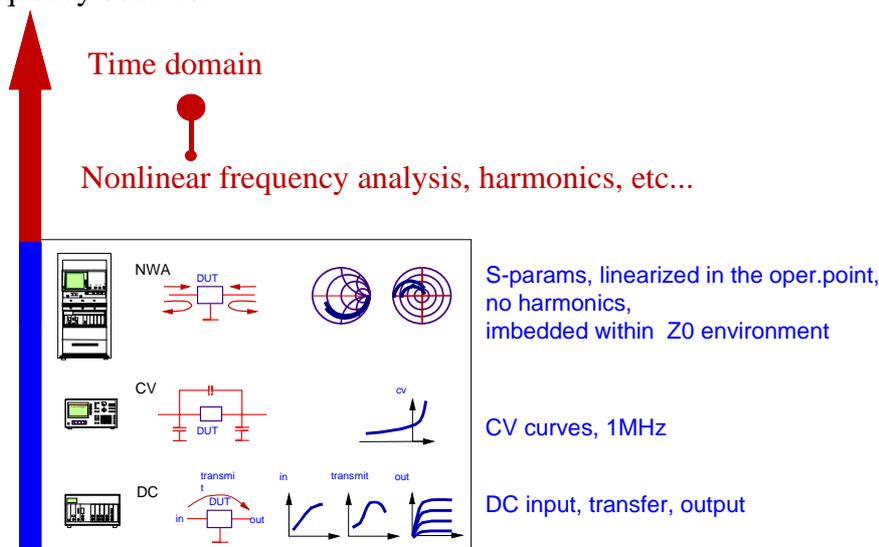


Fig.2: Beyond S-parameters:
Applying harmonic balance simulation allows nonlinear RF modeling

Regarding simulators, this means that a Spice S-parameter simulation is a limitation. It is a *linear* simulation, based on a *small-signal schematic* for a specific operating point, forcing Kirchhoff's law (the sum of currents into a node is Zero) to reflect *a single frequency only* ! The components of this small-signal schematic are linear resistors, inductors and capacitors, and linear dependent sources (e.g. transconductance gm). On the other hand, an Harmonic Balance (HB) simulation is a *non-linear* RF simulation, with no linearization and therefore with Kirchhoff's law reflecting *all possible harmonics frequencies*! Also, for HB simulations, there are no restrictions to having the device imbedded in a uniform characteristic impedance of e.g. 50 Ω.

Fig.3 depicts the difference between a linear, Spice-based, and a non-linear RF simulation. It shows a diode DC characteristic (linear i_D vs. linear v_D) and the locus curve of a certain DC bias point, $v_D=0,9V$, stimulated with an RF signal. Instead of following the previously measured DC traces in a tangent at a certain operating point, the diode 'falls behind' the frequency excitation due to its capacitances and the transit time. The DC tangent changes to an ellipse, and for incrementing RF signal source, this ellipse changes to a more complex trace, due to evolving harmonics (which are a consequence of the nonlinear DC trace!).

Note in fig.3 that due to the linear approach, the Spice curves can only represent a locus curve in circle or ellipse form. They keep the form independent of the applied signal power, and only scale with it. An HB simulation, however, gives realistic locus curves, which traces are a function of the applied RF signal level.

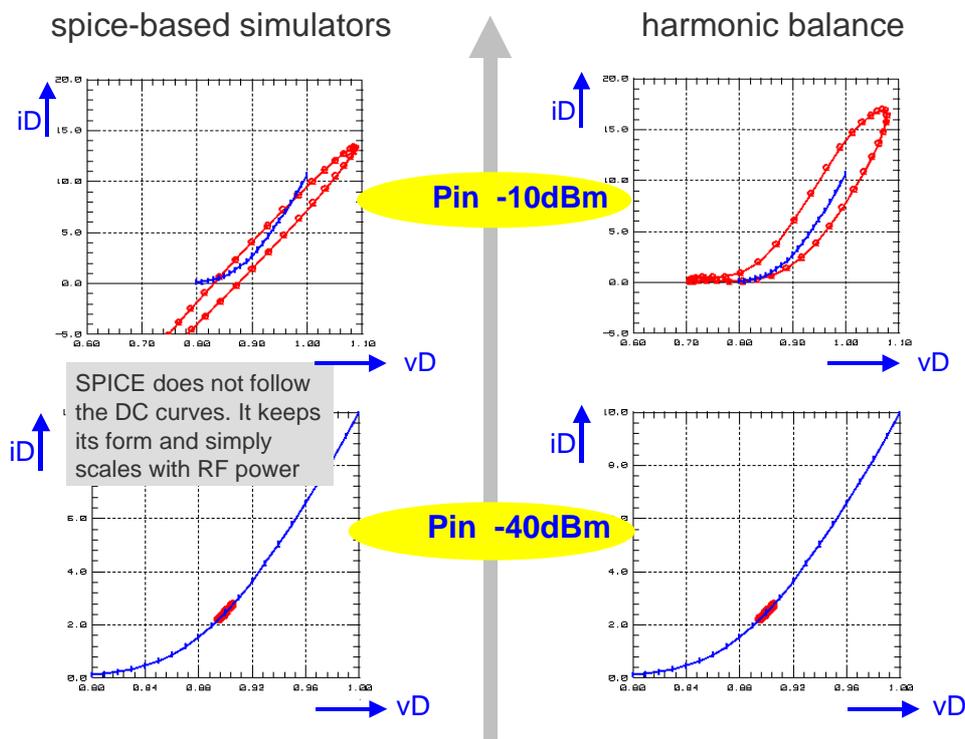


Fig.3: Comparing a spice-based dynamic diode trace (left) to harmonic balance (right)

The conclusion therefore is, that linear S-parameters are a *vehicle* to describe the performance of an electronic device for high frequencies. They are accurate for small-signal modeling of diodes and transistors, but for device modeling at signals higher than $\sim 25\text{dBm}$ (this value varies from device to device), they do not represent the real device performance. At these signal levels, linear S-parameters and characteristics calculated out of them suffer from the underlying linearization in the operating point, not considering harmonics. Also, they are based on a fixed characteristic impedance environment Z_0 .

However, the real world is non-linear currents and voltages, also for RF !
And this means, frequency harmonics need to be taken into account !

- Introducing Non-Linear RF: Measurements and Harmonic Balance (HB) Simulations

A good starting point for understanding RF is the analogy with light. As lenses can be characterized completely by the transmitted and reflected light, so can RF components be characterized by transmitted and reflected RF signals (S-parameters), see fig.4.

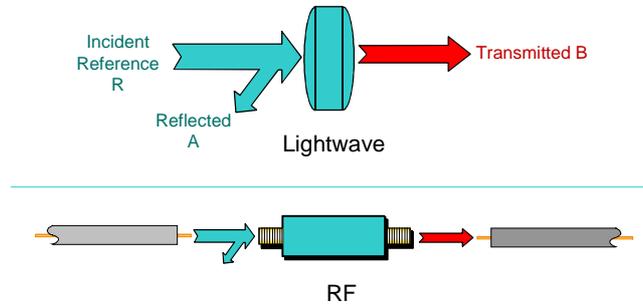


Fig.4: The analogy between light and RF signals

A linear network analyzer (NWA) measures S-Parameters. It switches continuously between forward and reverse data acquisition. In forward, it measures S11 (reflected related to injected signal power), and S21 (transmitted related to injected signal power). In reverse, it measures correspondingly S22 and S12.

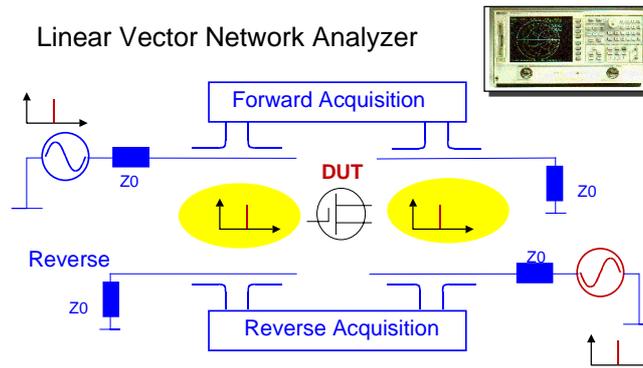


Fig.5: Operating principle of a vector network analyzer

For the measurement results of linear NWAs, *linear* network theory can be applied, and twoport matrix conversions like S2Y, S2Z etc. are possible. As an example, such manipulations are used for the de-embedding of contact pad or package parasitics, which disturb the performance of the inner device.

On the other hand, if we apply RF signals above $\sim 30\text{dBm}$, we have to account for a non-linear behavior of the device. Instead of the stimulating base frequency alone, we end up with many harmonics, see fig.6.

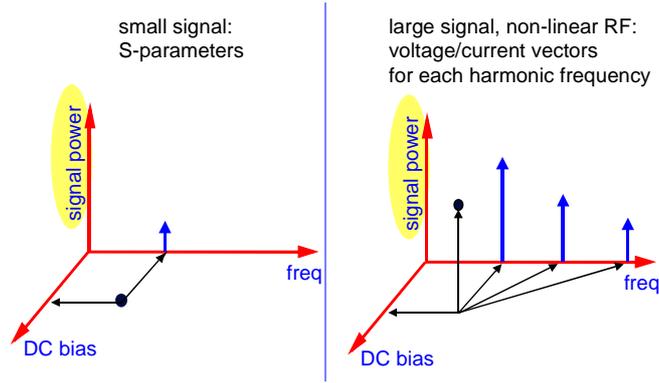


Fig.6: Increasing the applied RF signal level for nonlinear components causes harmonics

This means instead of sine waves at both sides of the device under test, we now have nonlinear time signals related to these frequency harmonics.

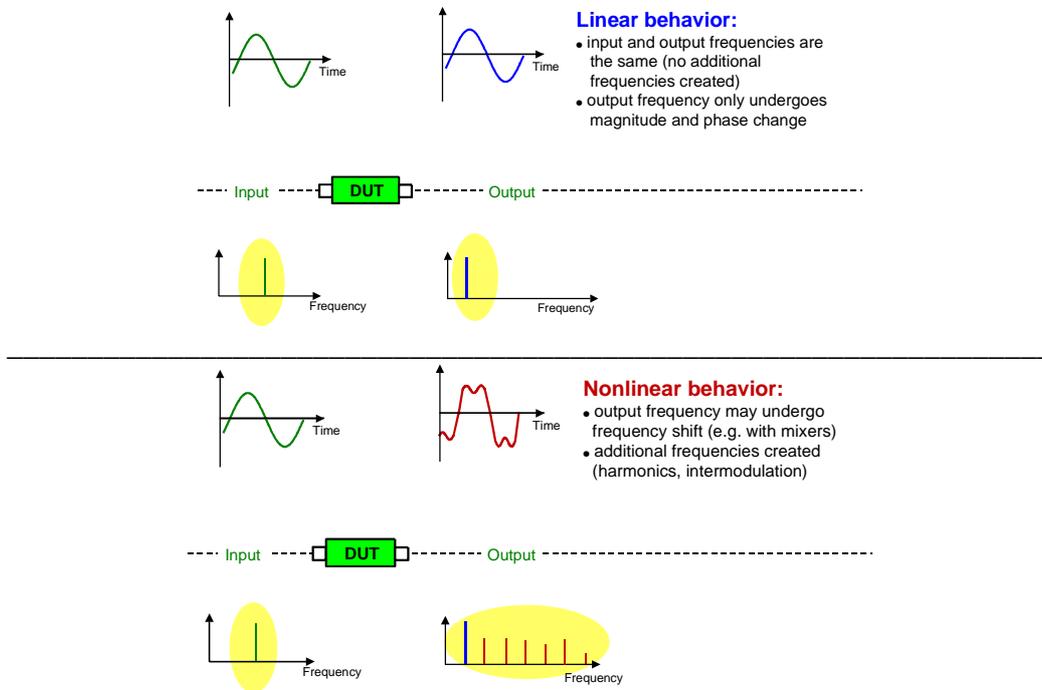


Fig.7: Visualization of linear, small-signal curve traces versus nonlinear

Considering the corresponding measurement equipment, we have to either apply a nonlinear network analyzer (fig.8), or a spectrum analyzer together with a signal source (fig.9).

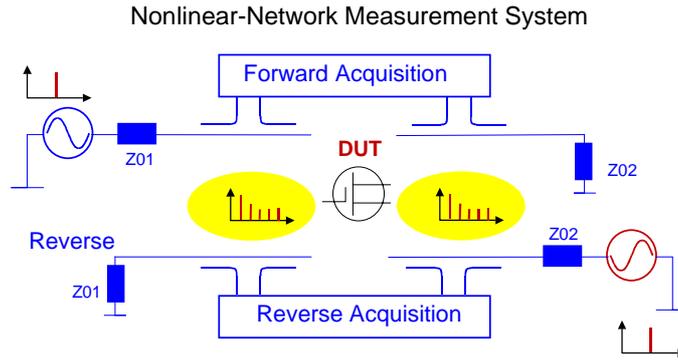


Fig.8: Nonlinear network analyzer scheme

While a nonlinear network analyzer fully describes the device performance by measuring both, magnitude and phase, a spectrum analyzer workbench offers only the magnitudes of the harmonics.

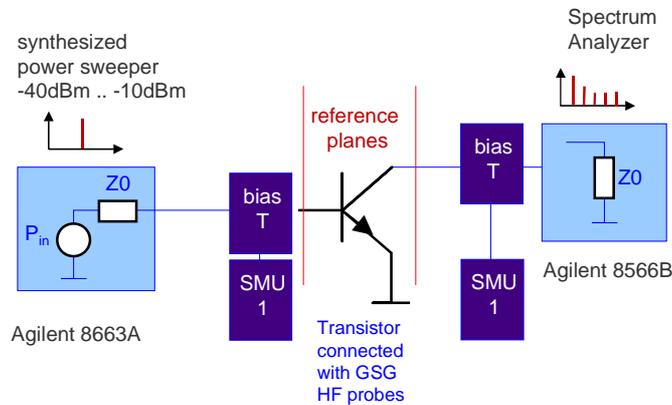


Fig.9: Applying a swept sine generator and a spectrum analyzer, after /Schröter et al./

When signal compression occurs, harmonics will show up. This is sketched below, showing the transmission characteristics of an RF amplifier. Its output can follow the input signal linearly up to a certain stimulus level, and begins then to compress the output signal.

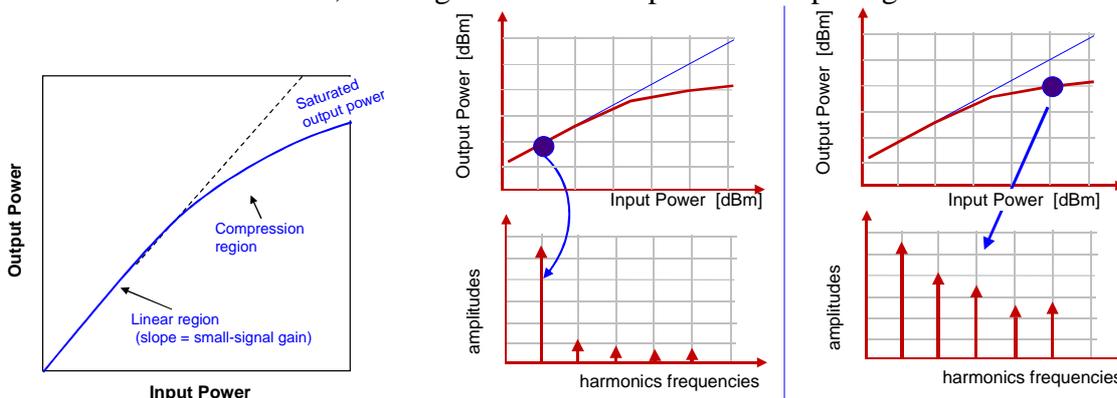


Fig.10: Driving an amplifier into compression causes harmonics

This leads to discussing the harmonic balance (HB) simulation. This kind of simulation corresponds to this effect and the above described nonlinear RF measurement principles. An

harmonic balance simulation satisfies the Kirchoff law for all frequencies, i.e. the sum of currents into a circuit node is zero for *all* frequencies.

Of particular interest is to see how the harmonic balance simulation iterates. Referring to fig.11 below, a HB commences with a first estimate, i.e. a certain signal power at a particular single base frequency, until it hits a nonlinear component, the diode. The diode current exhibits harmonic frequencies. Due to these new frequencies, the sum of currents of all frequencies into the common node cannot be zero. As a consequence, the other currents have to become nonlinear too, in order to make this sum of currents zero for all frequencies. This is depicted in the lower part of this sketch.

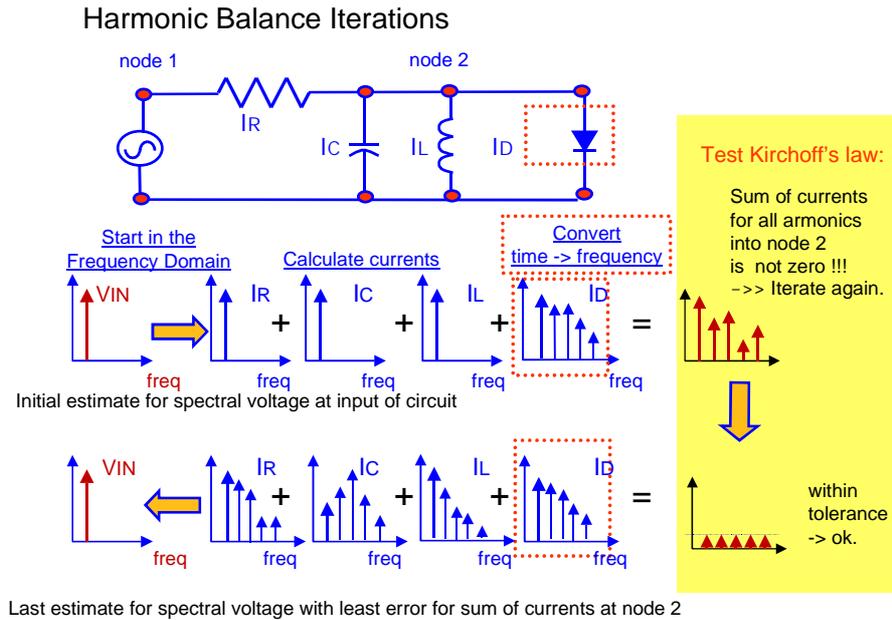


Fig.11: The harmonic balance simulation principle

Since most nonlinear device models are described in the time domain, an HB simulation of a nonlinear circuit has to switch permanently between frequency and time domain, see fig.12.

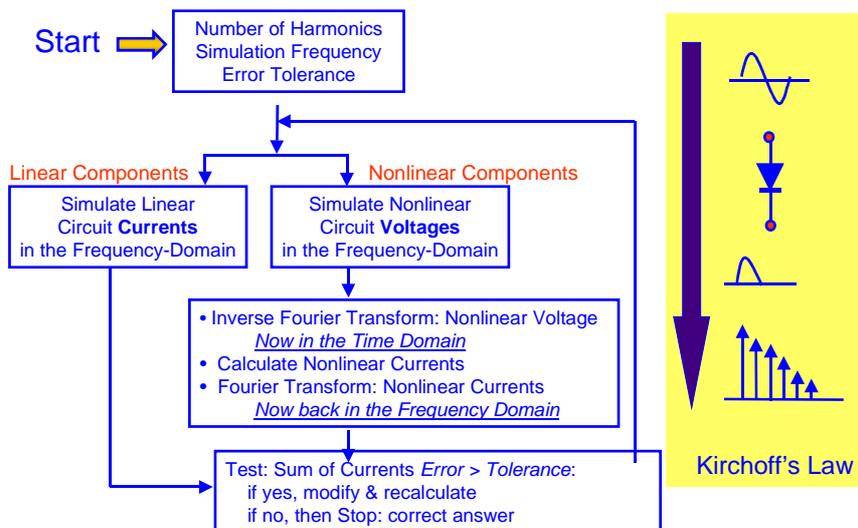


Fig.12: Flow chart of a harmonic balance simulation

Besides the so far discussed HB simulations, ADS of Agilent-EEsof features a whole family of simulators to satisfy RF simulation and modeling requirements. From linear frequency-domain simulations to nonlinear harmonic balance, and in the time domain from a HF-wise enhanced Spice to convolution simulation. Both domains can be combined by applying the envelope simulator. These kinds of simulators are automatically invoked by ADS, depending on the simulation request of the user.

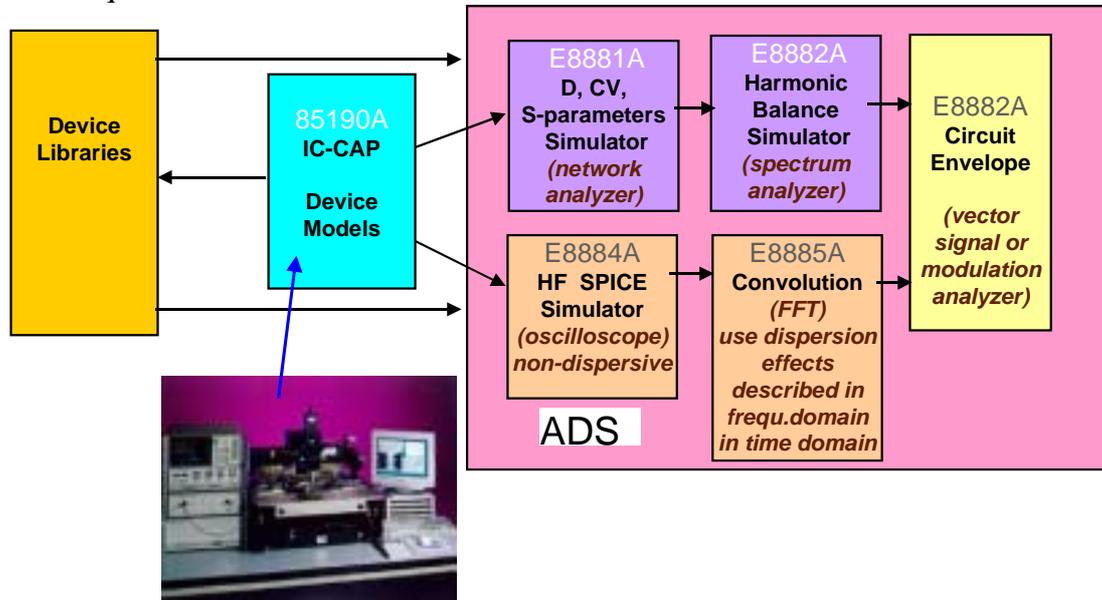


Fig.13: Modeling and simulation tools from Agilent-EEsof

- Modeling Applications for Non-Linear RF

There are two applications of HB for device modeling:

- Related to device characterization, i.e. measurements, the usage of a nonlinear network analyzer, or a frequency generator together with a spectrum analyzer demands for nonlinear HB simulations. The modeling is first done conventionally (DC- \rightarrow CV- \rightarrow S-parameter), and the obtained model parameters are fine-tuned. In other words, an HB simulation is compared to a nonlinear NWA measurements and the model parameters are fine-tuned to fit the traces of all RF signal levels. See publication /Vandamme/ for details.
- Another important application of HB is related to model verification. It can be applied to test if the device behaved linear during the conventional linear network analyzer measurements. And such kind of tests can even be performed after a state-of-the-art DC- \rightarrow CV- \rightarrow S-parameter modeling, without nonlinear NWA measurement data available.

Focussing on model verification for the rest of this presentation, two main questions can be answered when using HB simulations after or during modeling:

- Were the measurement conditions ok. for the particular diode or transistor during the linear NWA characterization?
- and up to which RF power level is it ok to simulate linear S-parameters with SPICE?

- Examples for S-Parameter Measurement Verification Using HB

Like already sketched in figure 13, it is of particular interest that Agilent-EEsof's IC-CAP modeling software can be linked to nonlinear RF simulations, i.e. to ADS. Just a few steps have to be followed in order to define a harmonic balance simulation in IC-CAP:

- In the corresponding Modeling Setup Input, the SWEEP TYPE is selected as 'HB'.
- Then, the number of harmonics is entered and the RF signal magnitude is specified.
- The Setup Outputs (voltage/current) now include the DC bias conditions plus the voltages and currents of the harmonics with magnitude and phase.

See fig. 14.

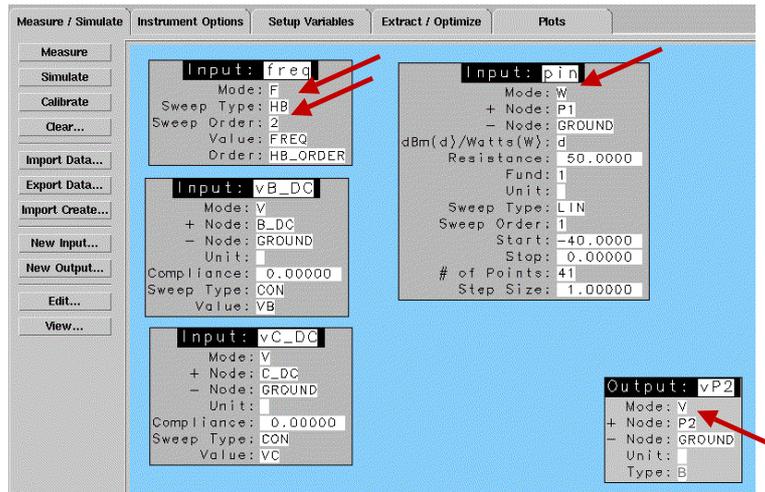


Fig.14: Setting up an HB simulation in IC-CAP

After these definitions, the data behind the stimulating 'Inputs' and the measurement 'Output' entries look like given in fig.15.

INPUT	OUTPUT
sweep type: HB	mode: v
sweep order: 1	
value: 100MHz	
HB order: 5	
data:	data:
0Hz=DC	3V
100MHz	97mV + j*30mV
200MHz	9mV + j*1.1mV
300MHz	-4mV - j*2mV
400MHz	1mV - j*3mV
500MHz	-2mV + j*2mV

Fig.15: Structure of data behind the stimulus (Input) and measurement/simulation (Output) fields

In the following examples, a bipolar transistor is considered. Its dynamic nonlinear RF performance is analyzed using a HB simulation. This can be done after the modeling has been performed and the parameter list has been obtained. Such kind of inspections are very useful to identify problems when no good fitting was obtainable in both, DC and S-parameter domain, together, or when problems persists in the modeling of a transit time modeling (fT).

In order to introduce to the modeling verification examples, we commence with considering

- How do the Gummel-Poon curves look like dynamically

Static DC curves become dynamic, when the transistor can no longer follow the frequency excitation due to the transistor capacitances and the transit time. This means, that the device cannot follow the DC transfer curves any more. Fig.16 depicts this case for a bipolar transistor and its Gummel-Poon curves. Considering a certain RF frequency, and with increasing RF signal level, these curves will first become 'elliptic' (Spice small signal), and will then change to pretty complex traces (large signal harmonics, HB) for further increased RF power.

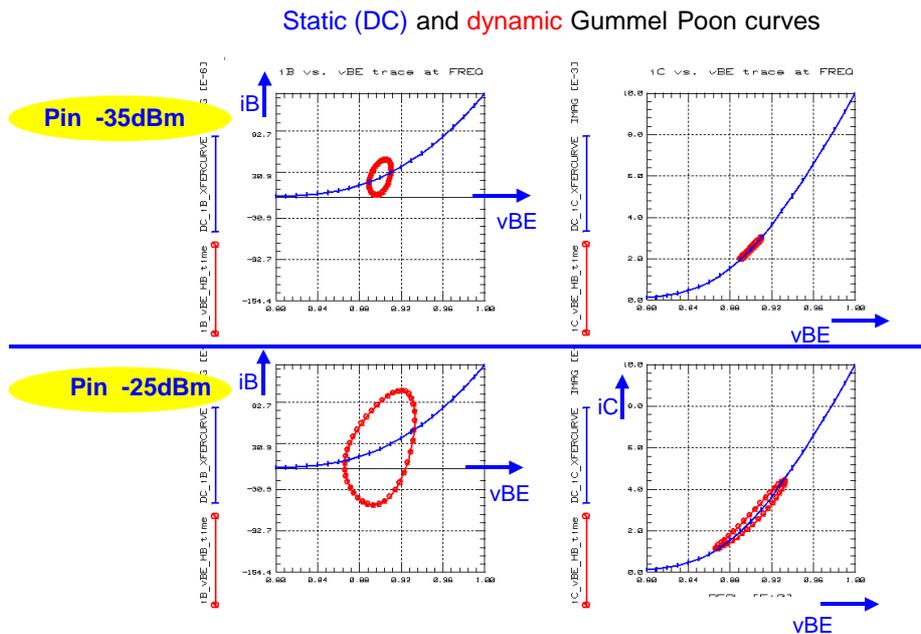


Fig.16: Dynamical performance of bipolar Gummel-Poon traces

Such simulation experiments of a new developed diode or transistor model give the modeling engineer valuable feedback on the applied measurement conditions and a possibility to check for valid small-signal performance during the previous S-parameter measurements. When this non-linear HB simulation gives linear device performance, it assures that the network analyzer measurement conditions, on which the model development had been based, were correct !

Another issue is to check the question:

Was the transistor DC bias sufficiently high ?

In this case, an harmonic balance simulation can easily detect if the DC bias was sufficiently high in order to operate the transistor in a proper amplification mode. As can be seen from figure 17, a too low v_{BE} leads to a passive behavior of the transistor in the $50\ \Omega$ network analyzer environment. It becomes clear that for the specific transistor, a minimum v_{BE} of $0,75\text{V}$ is required for a proper phase shift between v_{CE} and v_{BE} , while an even higher v_{BE} is required to have linear signals measured. Conventional device modeling is therefore only possible for these linear operating conditions.

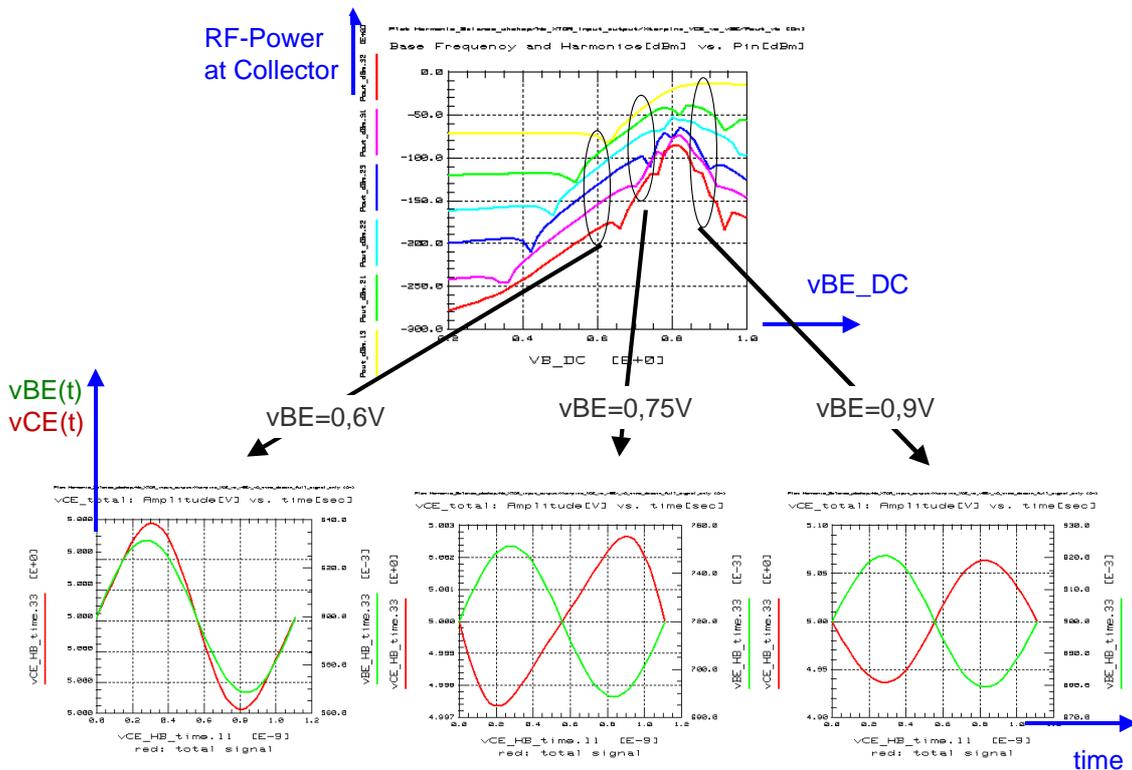


Fig.17: Nonlinear transistor performance for incrementing v_{BE} DC bias conditions

For example, after much questioning about poor S-parameter fit, this kind of simulation results gave the ultimate hint why it was impossible to model the measured S-parameters below a certain DC bias level!

And, at the end, it was a fabrication failure, detected with HB simulations!

Did the RF signal shift the DC operating point ?

In the case that the RF signal is no longer small compared to the DC bias power, it can shift the DC operating point. A Spice-like simulation would not reflect that ! This signal level mismatch can be one of the reasons why a specific model parameter set cannot fit both, the DC domain and the S21 curves in the low-frequency range.

The effect of a DC bias shift can best be seen in the output resistance plot of transistors, because such a plot has the highest sensitivity to too high RF signal levels. To check the signal powers, the DC output resistance of a transistor is simulated under different RF power levels, using harmonic balance, and then compared to the previously measured DC curves.

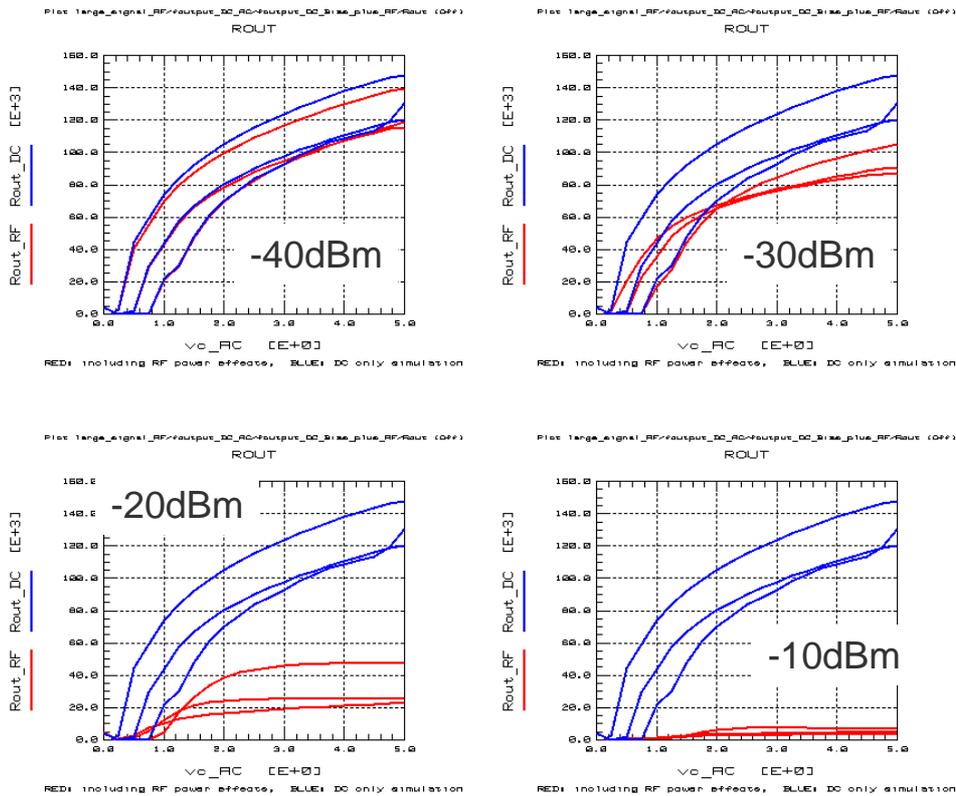


Fig.18: Output resistance of a bipolar transistor as a function of the RF signal level at the Base, compared to the DC traces

Note that the transistor RF model parameters do only affect the S-parameter traces in the upper frequency range. The low frequency fitting of the S-parameters is 100% determined by the DC and CV parameters! Therefore, this simulation result of fig. 18 is particularly important to identify S21 modeling problems at low S-parameter frequencies.

And this is especially true for small MOS transistors with small i_D currents. They can be affected by even small RF signals in the -30dBm range. In this case, the starting points of the measured S21 curves cannot be fitted by the model, although it fits accurately the DC curves!

As an example, regarding the specific BSIM3 parameters for modeling the DC output resistance, i.e.

- PCLM (Fitting for low v_D , i.e. channel length modulation),
- PDIBLC1, PDIBLC2 (Fitting for medium v_D , i.e. drain induced barrier lowering)
- PSCBE1, PSCBE2 (Fitting for high v_D , i.e. substrate current induced body effect)

it becomes clear that when the underlying curves change (what happens when the transistor is stimulated with a too high RF signal), the effective values of these parameters change as well, and no S21 modeling can be achieved!

Were the S-parameter measurements disturbed by the RF signal

Fig.19 recapitulates the problem when using linear network analyzers and a too big RF signal: harmonics occur, but only the base frequency is cut out of the full frequency spectrum, i.e. the measurement result is a violation of Kirchhoff's law. In such a situation, using a Spice-like simulator introduces then a second problem, because such S-parameter simulations refer to a linearized device performance in the operating point! If such power levels need to be applied to a given modeling problem (e.g. RF power transistors, accurate diode models for demodulation circuits etc.), it is therefore recommended to replace a Spice-like S-parameter simulation by a harmonic balance simulation, out of which S-parameters are calculated ! Only in this case, the measurement principle with its limitations is taken into account by the simulations. The models based on such measurements and simulations are therefore much more reliable. See publication /S.Hamilton/ for more details.

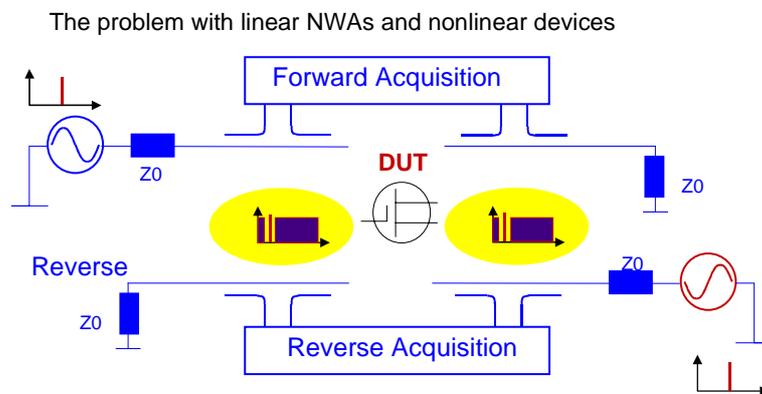
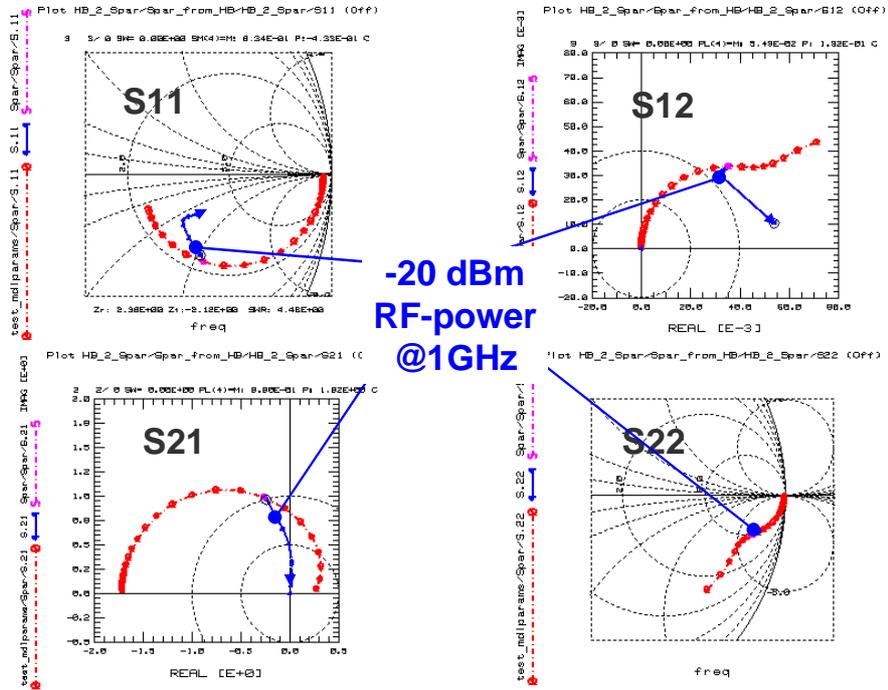
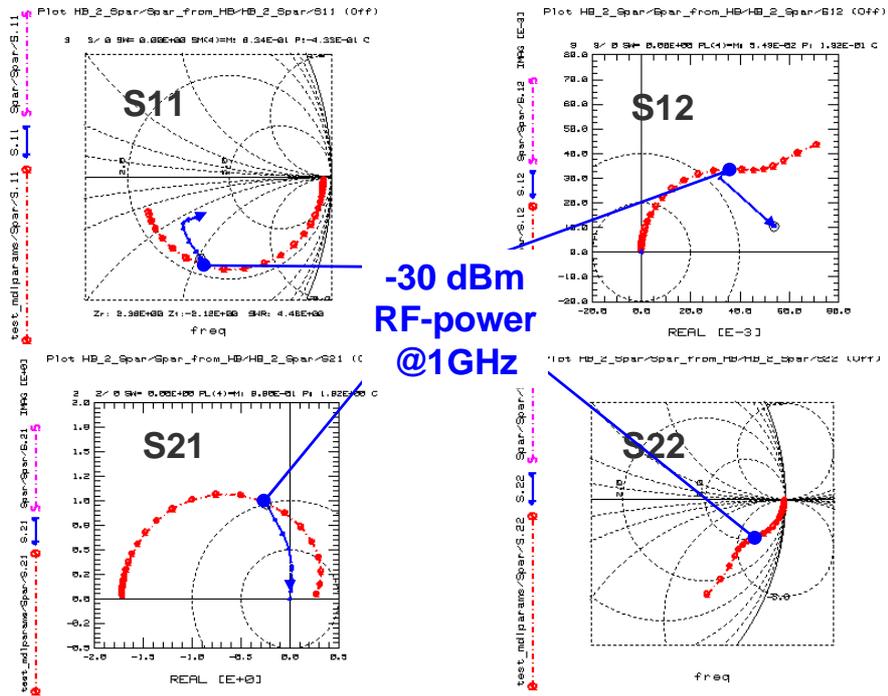


Fig.19: Linear network analyzer 'cut' the base frequency S-parameters out of the real harmonic frequency spectrum of nonlinear devices

Like already discussed, the S-parameter traces are depending on the applied RF signal level. The plots in figure 20 visualize the change of the location of a certain frequency point related to increasing RF power. It is important to note that depending on the device, i.e. the model parameters, signal levels of -30dBm can already change the locus of an S-parameter point.

Note: Generally, increasing RF signals turn S-parameters towards zero.



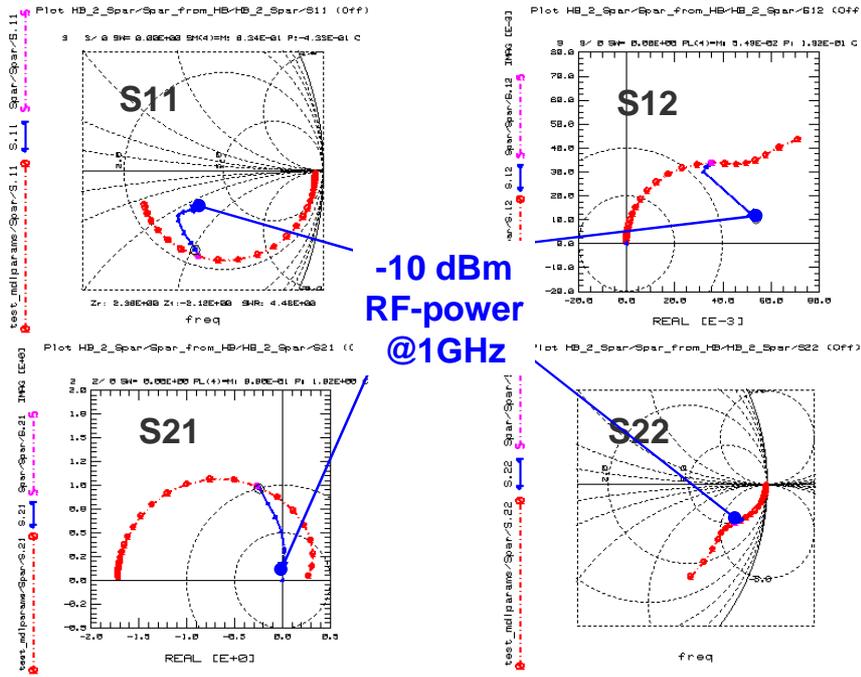


Fig.20: Change of S-parameter locus for increasing RF signal

Since it is so important to not overdrive the transistor with the RF signal level, the following practical method can be applied.

When measuring a DC output characteristics and calculating R_{out} out of it, the resulting curve is very sensitive. Therefore, we can use this plot to identify possible effects of a too big an AC power applied to the transistor. This means, we measure the DC output characteristics through the NWA S-parameter testset, and let the NWA operate in continuous mode, i.e. unsynchronized to the DC measurement. Then, we increase the RF signal power (decrease port attenuation) until we see an effect on the R_{out} . We now know the maximum allowed RF power for the NWA S-parameter measurements!

The following plot reflects such a test. The disturbed curve happens when there is too much RF power applied to the transistor.

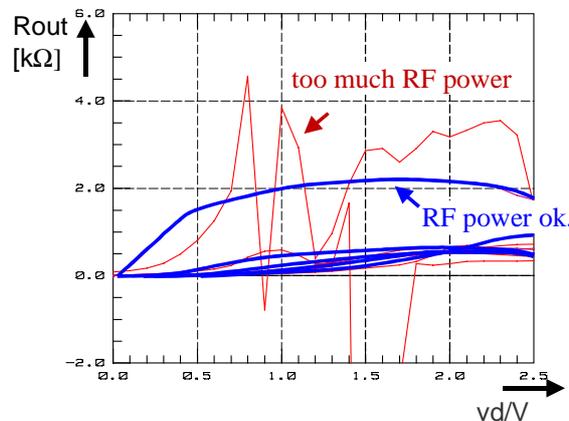


Fig.21: Transistor output resistance measurement with sufficiently low RF signal excitation and a too big one

- Conclusions

With the link of IC-CAP to ADS, modeling engineers can extend their characterization strategy from existing DC -> CV -> S-parameter modeling into the real RF application of the device. They can verify S-parameter measurements for possible linear NWA measurement limitations. Last not least, with nonlinear RF experience, they are in a much better shape to discuss RF-IC design goals with design engineers and find out the best solution *together*.

Note:

a special ADS-lite version for IC-CAP users is available:
Agilent product number E8882A #K02

Publications

For modeling engineers, a special 'Characterization and Modeling Handbook' is available.
Contact the author, franz_sischka@agilent.com, for a pdf copy.

M.Schröter, D.R.Pehlke, T.-Y. Lee, Compact Modeling of High-Frequency Distortion in Bipolar Transistors, ESSDERC 1999, Leuven, Belgium, Sept.13.-15, pp476-479, ISBN 2.86332.245.1

E.P.Vandamme, NNMS measurement data in ICCAP - Data import and subsequent model verification/tuning, European Microwave Conference 2001, London, September 2001

S.Hamilton, RF Circuit and Component Modeling, International Courses for Telecom Professionals, CEI-Europe, Finspong, Sweden, www.cei.se

Info available on the web:

A very good Application Note on S-parameters is:

Agilent Technologies Interactive Application Note 95-1,
S-Parameter Techniques for Faster, More Accurate Network Designs.

<http://www.tm.agilent.com/data/static/eng/tmo/Notes/interactive/an-95-1>

Related to nonlinear NWA measurements, many publications are located at

<http://users.skynet.be/jan.verspecht/>

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