From circuit topology to behavioural model of power amplifier dedicated to radar applications

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From circuit topology to behavioural model of power amplifier dedicated to radar applications

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A new behavioural model of a power amplifier (PA) at system level is presented, dedicated to radar applications. This model, which is able to take into account output loading impedance mismatch, is based on a similar topology to the PA's circuit. The model, implemented in Agilent Advanced Design System (ADS), is validated for different loading impedances, until VSWR = 2 (voltage standing wave ratio), on the PA's bandwidth. This approach permits an extraction, resulting from simple CW measurements or simulations, and easy model implementation. This work has been supported by DGA (French Defense and Security Agency).

Introduction: In recent years the development of active electronically scanned array (AESA) radar has been significant. This technology will equip most of next generation military radar systems [1]. In the framework of the development of such systems, an accurate 'system' simulation is needed. Indeed, nowadays, cost reduction of such systems is a key issue for the European defence industry (an AESA is two times more expensive than a passive electronically scanned array) and that implies the use of accurate simulation tools to decrease margins taken on component specifications. Such simulations must be able to optimise the design of the whole radar functional chain by enabling design engineers to predict and analyse the impact of microwave components on 'system' performance. Unfortunately, design models of microwave components cannot be used for such a simulation because it would lead to huge computing time. That is why technical solutions have been explored to reduce complexity of simulation accuracy with radar signals. Today, simulation tools dedicated to AESA radar describe RF systems in only a unilateral way and with insufficient accuracy. Nevertheless, design constraints of AESA lead to significant load mismatch (up to VSWR = 2) with varying phase in microwave chains implying the need for a nonlinear bilateral model. It appears that development of a powerful simulation tool requires an accurate model of the power amplifier (PA) in order to quantify its impact on transmission/reception (T/R) modules and then on emitted signal characteristics. Indeed, the PA undergoes many disturbances in AESA radars, particularly output loading impedance mismatch. In fact, impedance presented to the output port of the PA varies because of AESA controls. The difference between this impedance and PA load required in the case of optimal match condition can be huge. PA behavioural models employed in these simulations, simple gain or AM/AM-AM/PM, are insufficient. Recently, more efficient behavioural models were developed [2–5] but their implementation and their extraction are complex. Therefore, we present the principle of a novel approach, called 'Grey Box', and its results. This approach is particularly useful when the topology of the PA is known at the design level. In order to satisfy AESA radar needs, this model must be compliant with the following specifications: it should be accurate with VSWR up to 2; it should take into account thermal effects; and it should take into account fast and slow memory effects.

Model structure: The Grey Box model is directly derived from the topology of the amplifier. Thus, this model is divided into linear and nonlinear sub-models, respectively associated to passive and active elements. To take into account output impedance mismatch, linear and nonlinear models are described in a bilateral way. Passive elements are described thanks to their linear scattering parameters. Nonlinear scattering functions [3], which are an extension of linear scattering parameters applied to the nonlinear case, permit us to describe the transistors. If the PA has several transistors by the amplification stage, the model topology can be simplified since the impedances presented to active cells at each stage are very close. As a result, passive cells can be reduced to a two-port structure. Therefore, a single nonlinear sub-model is necessary for each stage if input/output currents are divided by the number of transistors for this stage. This model simplification enables us to use a single extraction for all transistors of a same power amplifier stage and to enhance time cost. Fig. 1 shows an example of the model's topology. In the following, the Letter focuses on the modelling of transistors.

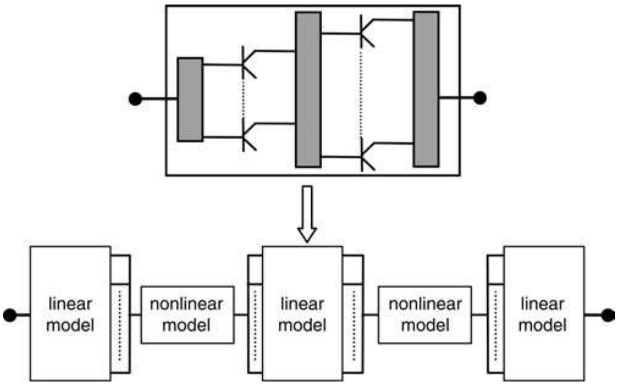

Fig. 1 *Grey Box approach: assembly of linear and nonlinear sub-models, based on same topology of design circuit*

Modelling of nonlinear parts: Transistors are modelised thanks to nonlinear scattering functions. If we make the assumption that a transistor is considered to be a nonlinear two-port circuit at fundamental frequency, without memory effects, it is defined by the following relationship:

$$\tilde{b}_i = f_{NLi}(\tilde{a}_1, \tilde{a}_1^*, \tilde{a}_2, \tilde{a}_2^*) \qquad (1)$$

where $i = 1, 2$, $\tilde{b}_1$, $\tilde{b}_2$ and $\tilde{a}_1$, $\tilde{a}_2$ are, respectively, the reflected and incident power waves at the two ports. In conditions of weak loading impedance mismatch, $\tilde{a}_2$ can be considered weak compared to $\tilde{a}_1$; moreover, if $\tilde{a}_1$ is considered like the reference wave, Taylor series expansions limited to the first order lead to write [3]:

$$\begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} S_{11}(|\tilde{a}_1|) & S_{12}(|\tilde{a}_1|) \\ S_{21}(|\tilde{a}_1|) & S_{22}(|\tilde{a}_1|) \end{pmatrix} \cdot \begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \end{pmatrix} + \begin{pmatrix} 0 & S_{12}^{\Delta}(|\tilde{a}_1|) \\ 0 & S_{22}^{\Delta}(|\tilde{a}_1|) \end{pmatrix} \cdot \begin{pmatrix} \tilde{a}_1^* \\ \tilde{a}_2^* \end{pmatrix} \qquad (2)$$

$S_{ij}(|\tilde{a}_1|)$ represent nonlinear scattering functions, as a function of the incident wave's magnitude. To extend the capabilities of prediction to the PA's bandwidth, the frequency dispersion of the transistor must be considered. An efficient solution consists of parameterising $S_{ij}(|\tilde{a}_1|)$ with appropriate coefficients. Thus (2) becomes:

$$\begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} S_{11}(|\tilde{a}_1|) \cdot c_{11}(\Omega) & S_{12}(|\tilde{a}_1|) \cdot c_{12}(\Omega) \\ S_{21}(|\tilde{a}_1|) \cdot c_{21}(\Omega) & S_{22}(|\tilde{a}_1|) \cdot c_{22}(\Omega) \end{pmatrix} \cdot \begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \end{pmatrix} + \begin{pmatrix} 0 & S_{12}^{\Delta}(|\tilde{a}_1|) \cdot c_{12}^{\Delta}(\Omega) \\ 0 & S_{22}^{\Delta}(|\tilde{a}_1|) \cdot c_{22}^{\Delta}(\Omega) \end{pmatrix} \cdot \begin{pmatrix} \tilde{a}_1^* \\ \tilde{a}_2^* \end{pmatrix} \qquad (3)$$

$c_{ij}(\Omega)$ is frequency function, normalised to one, where $\Omega = \omega - \omega_0$. The identification of nonlinear scattering functions and coefficients are obvious because it requires a simple extraction. In order to solve (2) nonlinear scattering functions are extracted, at the PA's operating frequency, from three different loading impedance CW measurements, with a vectorial network analyser (VNA) [6], or CW harmonic balance simulations. Coefficients are extracted, for low level signal excitation, thanks to the same method as nonlinear scattering functions for several frequency points on the PA's bandwidth.

Model implementation: The Grey Box model has been implemented in Agilent ADS, likewise in [5]. Data files from S-parameters passive element's simulation describe linear parts. Frequency device domain (FDD) is used in order to modelise transistors, where (3) defines the relationships between the input/output ports.

Results: To validate the proposed modelling approach, it was applied to a PA design project in Agilent ADS. It is an X-band, 18 dB gain amplifier, which contains four GaAs HBTs in the driver's stage and eight in power's stage. Fig. 2 shows an example of comparison between circuit-level simulation and the Grey Box model at operating frequency, the PA was terminated with different loads far beyond its optimum load (VSWR = 2). At different input levels, Fig. 3 shows a comparison of output power response of the circuit level and behavioural model against the PA's bandwidth.

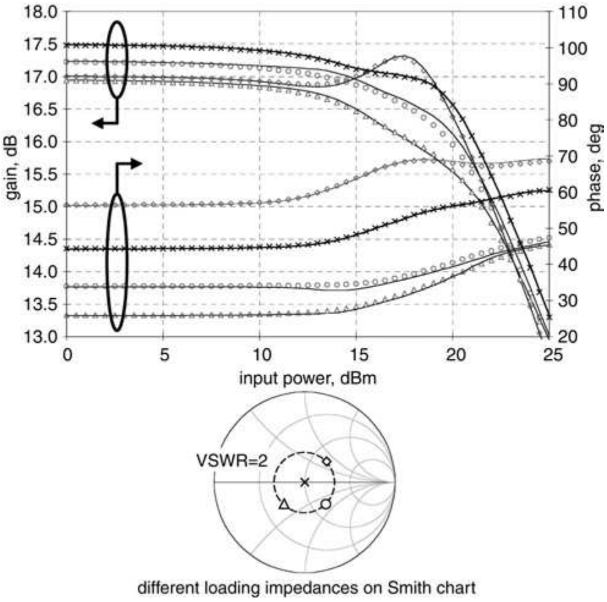

Fig. 2 *Simulation-based Grey Box model (solid lines) compared to circuit (circles, cross, rhombus triangles)*

Gain in decibels and AM-PM in degrees against input power in dBm for the two-stage amplifier of Fig. 1 terminated with different loads at PA's operating frequency

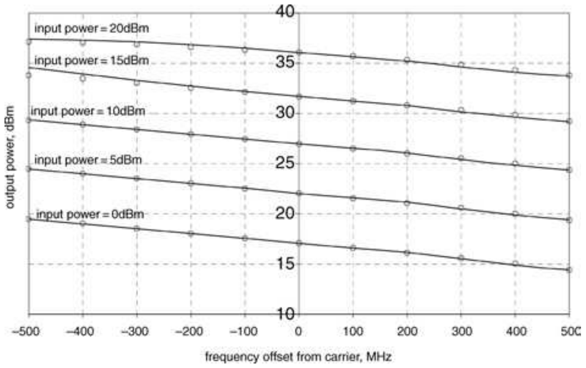

Fig. 3 *Simulation-based Grey Box model (solid lines) compared to circuit (circles)*

At different input levels, output power in dBm against frequency offset from carrier in MHz for PA's nominal load

Conclusion: We have presented a novel behavioural model based on an actual PA design. It is divided into several simple sub-models corresponding to linear and nonlinear parts of this PA. The tests, carried out on a two-stage PA, have been validated in frequency domain. This new approach has several advantages: it enables a good prediction of the PA's behaviour in the case of strong output loading impedances mismatch (until VSWR = 2), it is extracted from simple CW measurements or simulations, and its implementation in a simulator is obvious. This model should be used in the time domain environment in order to evaluate the PA's behaviour submitted to pulse signal excitations for radar applications and finally it should be integrated in the DGA/CELAR AESA radar simulation tool.

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