Behavioural Modeling of Microwave Oscillating Amplifiers

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Abstract

The problem of deriving, from experimental data, a behavioral nonlinear model capable of predicting the dynamical response of microwave oscillating amplifiers (either continuous-wave or pulsed) is addressed.

Experimental results are reported, showing that a good simulation accuracy can be combined with an excellent computational efficiency by resorting to a black-box modeling approach in the stroboscopic time-domain, in which the oscillating amplifier is described by an algebraic-differential set of fundamental-frequency phasor equations that can be considered as a "three-port" extended Van der Pol (3P-E-VdP) model of the embedded synchronized oscillator.

An additional advantage of the proposed behavioral approach over standard, detailed, equivalent circuit modeling techniques, is the small number of unknown model parameters that have to be identified, and the fact that their values can be rather straightforwardly extracted from experimental data obtained from conventional microwave measuring apparatuses.

1 Introduction

Since several decades, oscillating amplifiers (also known as "injection-locked" amplifiers) have been widely adopted in the microwave and millimeter-wave frequency range as medium/high power saturated narrow-band amplifiers, exploiting transferred electron devices under continuous-wave/pulsed operation [1, 2], respectively, though microwave transistors have been also adopted when lower power output is required [3].

However, the more complex modulation schemes nowadays adopted in both commercial and military applications, as well as the fact that a number of new solutions imply the combination of several such devices together, make each day more difficult to select and optimize system's operating parameters by adopting conventional modeling and software simulation tools.

This is due to the fact that the standard approach of using, for the computer-aided prediction of relevant figures of merit, a detailed "equivalent circuit" model together with a general-purpose "circuit" simulator has proven to be a difficult and computationally intensive task for micro-wave oscillating amplifiers (MWOA).

Indeed, some peculiar characteristics of this class of circuits, such as their high-selectivity "stiffly" nonlinear nature yet under CW operation, or the intra-pulse time-dependence of active device parameters under pulsed operation, complicate a lot the behavioural features of the embedded synchronized oscillator and thus its modeling, which often requires coupled circuit- and device-level simulation as well as extensive efforts in the identification of the (many) unknown parameters from experimental measurements [4].

Additionally, even if an adequate device/circuit model of the overall MWOA is available, its nonlinear, distributed, and time-varying nature complicates the simulation. In fact, since conventional (Harmonic-Balance based) frequency domain methods are inadequate for this purpose, the most common solution is to rely on time-domain models and/or simulation approaches, which, in this particular case, become extremely time consuming, even if acceleration methods are adopted. This task, already inefficient when continuous-wave/non-modulated operation is concerned, becomes indeed overwhelming under pulsed operation and/or if any sort of modulation scheme is applied either to the input signal (e.g., for frequency/phase coding) or to the pulsed bias supply (e.g. for PCM/PWM coding or chirp/temperature compensation).

In this paper, the results of a rather extensive investigation on the alternative solution of using a compact, behavioural model for the MWOA are presented. As described in next sections, the proposed unified model, which applies to both continuous-wave and pulse-operated MWOA, not only permits to achieve adequate accuracy in the simulation at a fraction of the computation time otherwise required, but also simplifies a lot the model identification from experimental data.

2 Model description

The block-scheme of a reflection-type microwave oscillating amplifier is depicted in Fig. 1. With no loss of generality, in this paper we will refer to this scheme, since the treatment can be applied to transmission-type MWOA as well. In fact, the looked for behavioural model - once verified the applicability conditions for the device under test (DUT) of concern - is independent of the specific structure of MWOA: it is, indeed, a "black-box" nonlinear model.

This was graphically evidenced in Fig. 1, where the two input and output ports are evidenced, while the rest of the MWOA (input-output separation circulator + embedded oscillator) has been encapsulated into a single box. On the other hand, it has to be pointed out that such a nonlinear two-port structure (considered either as a black-box or not) is still too much general for the purposes of our analysis. Some class defining rules must be set before going on further. Such rules can be summarized very concisely, simply by stating that the DUT must be a correctly designed and operated MWOA. This circumstance alone, implies - in practice - all others - more technical - conditions, which can be detailed as follows:

1) the oscillator embedded in the MWOA must be a reasonably high-selectivity one, to guarantee quasi-sinusoidal operation under both transient and steady-state operation;

2) the input signal amplitude and frequency are compatible with correct fundamental mode of operation of the MWOA (without limiting, however, the signal amplitude to be a "small" one, as in other treatments);

3) if the MWOA of concern is a pulse-operated one, it is assumed that the bias voltage supply has been properly designed to guarantee a correct build-up of the oscillations, with no initial spurious "moding". It is also assumed here that the input signal is applied before the bias pulse, as it is convenient in practical use, though a slight modification of the theory can cover different cases too.

Under these, rather mild and usually verified, assumptions, we can express our final goal as the derivation of a nonlinear mathematical model of the MWOA directly in terms of the fundamental-frequency complex envelope components (amplitude and phase) of the voltage at the input and output reference planes ($\{V_1,\phi_1\}$and $\{V_2,\phi_2\}$), since the higher-order harmonics can be safely neglected owing to the quasi-sinusoidal quasi-static hypotheses embedded by the above cited "regularity" assumptions.

Such behavioural model can then be developed by properly extending, to the two-port case of concern, the work done by Calandra and Maniscalco for the one-port case [5]. In analogy to what shown there, where a two-port extended Van der Pol (2P-E-VdP) model was found necessary to adequately describing the behaviour of a one-port quasi-sinusoidal driven-oscillator, an analogous mathematical derivation (which uses a stroboscopic-time perturbation-refined approach, as described in [6]) can be demonstrated to provide, in this two-port case, a three-port extended Van der Pol (3P-E-VdP) model, defined by the algebraic-differential set of equations:

$$\frac{dX}{dt} = \alpha\left(X^2 - 1\right)X + \beta I_S \cos\left(\vartheta - \phi_S\right)$$
$$\frac{d\vartheta}{dt} = 2\pi(f_0 - f_S) - \gamma\left(X^2 - 1\right) - \frac{\beta I_S}{X}\sin\left(\vartheta - \phi_S\right)$$
$$V_1 \exp\{j\phi_1\} = V_{10} X \exp\{j(\vartheta + \xi_1)\} + Z_1 I_S \exp\{j(\psi_1 + \phi_S)\}$$
$$V_2 \exp\{j\phi_2\} = V_{20} X \exp\{j(\vartheta + \xi_2)\} + Z_2 I_S \exp\{j(\psi_2 + \phi_S)\}$$

in which in the state-variable $X\bullet\exp(j\theta)$ represents an "internal" scaled voltage (see [5]), while the twelve parameters α, β, γ, Z_1, ψ_1, V_{10}, ξ_1, Z_2, ψ_2,V_{20}, ξ_2 and f_0 characterize the overall oscillating amplifier block (including also the source and the load), and I_S, ϕ_S characterize the driving signal current (amplitude and phase).

Although, in principle, all twelve above said model parameters - constant in case of CW operation - should be taken as "intra-pulse" time varying - in case of pulsed operation - the experimental campaign made on several different X-band oscillators has shown that only the time dependence of V_{10}, V_{20} and f_0 (input and output port free-running oscillation amplitudes and frequency) needs to be taken into consideration by necessity. This fact means, in practice, that only rather straightforward measurements (on vector network analyzer - VANA -

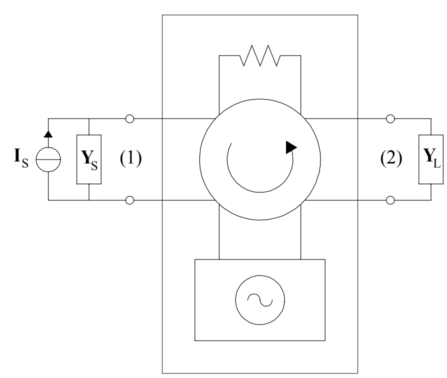

Fig.1: Block diagram of a circulator-coupled reflection-type oscillating amplifier.

and on amplitude/frequency profiling apparatuses) are required to extract all above parameters from experimental data, even when pulsed operation is concerned.

In fact, the model parameter identification phase can be accomplished by appropriate curve-fitting of the amplitude and phase MWOA's *steady-state* response curves under sinusoidal, swept-frequency, operation, for a set of different input signal amplitudes, once the (bias- and time-dependent, if applicable) values of V_{10}, V_{20} and f_0 have been obtained by direct measurement.

3 Experimental results

The above described modeling approach has been already successfully applied to several different devices.

We will report here results pertaining to a purposely constructed (9.75GHz, +10dBm) MWOA, comprising a three-stage circulator and a dielectric-resonator FET oscillator, capable of operating under both continuous and pulsed operation.

Such circumstance has permitted to perform the characterization phase under CW/non-pulsed operation, thus permitting to use quite accurate, conventional, instrumentation (an automatic vector network analyzer, a frequency counter, and a two-channel power meter). From this experimental data base, by means of a purposely developed measurement error correction and identification software, the numerical values of the model parameters $\{\alpha, \beta, \gamma, Z_1, \psi_1, V_{10}, \xi_1, Z_2, \psi_2, V_{20}, \xi_2$ and $f_0\}$ have been extracted.

The typical outcome of the comparison between (raw) measured and reconstructed (simulated) values of MWOA's scattering parameters $S_{11}(\omega)$ and $S_{21}(\omega)$, for a constant V_{DC} bias of 2.6V and three different input signal amplitudes, is illustrated in Fig. 2a and 2b, which demonstrate the typical, good, quality of the agreement achievable in practice. As far as the CW/non-pulsed operation of this MWOA is concerned, it has also to be pointed out that a low sensitivity of all parameters (except, of course, V_{10}, V_{20} and f_0) with respect to V_{DC} was observed, which allowed to neglect their intra-pulse variation under pulsed operation (where the bias voltage top pulse is not always exactly constant, sometimes also intentionally).

For the measurement of the intra-pulse time-evolution of $V_{10}(t)$, $V_{20}(t)$ and $f_0(t)$ under (CW injection-primed) pulsed operation, two - custom - amplitude and frequency pulse profiling measuring systems were adopted, and the experimental outcomes have been curve-fitted to three (multiple time constant) exponential type functions, for the sake of simplicity (and for smoothing).

With no further "tuning" of the extracted parameter values or time-dependencies, the model has then been validated, by adopting it in the simulation of the MWOA response under various input and bias (pulsed and non-pulsed) conditions, whose comparison with measured data has always provided quite satisfactory results.

As an example, the response of the MWOA under pulsed-bias operation (50 µs pulse-width, 1kHz PRF, $2.6V_{DC}$) to a BPSK (0-180°, nominal) modulated input signal of various carrier amplitudes and frequencies is reported in Fig. 3.

As it can be observed from the comparison among measured and simulated data pertaining to the amplitude and phase transients, quite good simulation accuracy was achieved with a CPU time consumption of only a few seconds (on a low-cost personal computer) for all the three reported simulations.

It can also be observed that, notwithstanding the simplifying assumptions intrinsic to the proposed approach, all behavioural characteristics of the oscillating amplifier response have been reproduced, including initial unlock or phase-transient uncertainties (due to trajectory bifurcations in presence of phase-noise) when the injection signal strength is inadequate or the injection frequency not optimally chosen (Fig. 3a), which can instead easily be done (see Fig. 3c) with the help of the modeling and simulation tool here proposed.

4 Concluding remarks

A behavioural modeling and simulation approach has been proposed, to predict the dynamical response of microwave oscillating amplifiers (either pulsed or not) under both continuous-wave and modulated input signal drive, directly in terms of the complex envelope components (amplitude an phase) of the voltage at the input and output reference planes.

The reported experimental results have shown that a good simulation accuracy can be achieved, together with an excellent computational efficiency, by adopting a "three-port" extended Van der Pol (3P-E-VdP) model of the MWOA, which includes nonlinear susceptance effects typical of solid-state active devices, as well as the presence of a general (linear) coupling structure between the synchronized oscillator and the input and output ports. When pulsed operation is involved, the intra-pulse time-variations of amplitude and frequency of the free-running oscillation are also accounted for.

One of the main advantages of the proposed behavioural approach over standard detailed circuit-modeling techniques, is the small number of unknown model parameters that have to be identified, and the fact that their values can be rather straightforwardly extracted from experimental data obtained from conventional scattering-parameter and power/frequency profiling automated measuring apparatuses.

Finally, it can be noticed that the proposed model equations can be easily integrated into any general purpose software simulation tool, still guaranteeing quite reduced simulation times even under complex operating conditions (pulsed operation or elaborate modulation schemes), thus lending themselves as an effective computer-assisted tool for system-level performance evaluation and operating parameters optimization.

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(a)

(b)

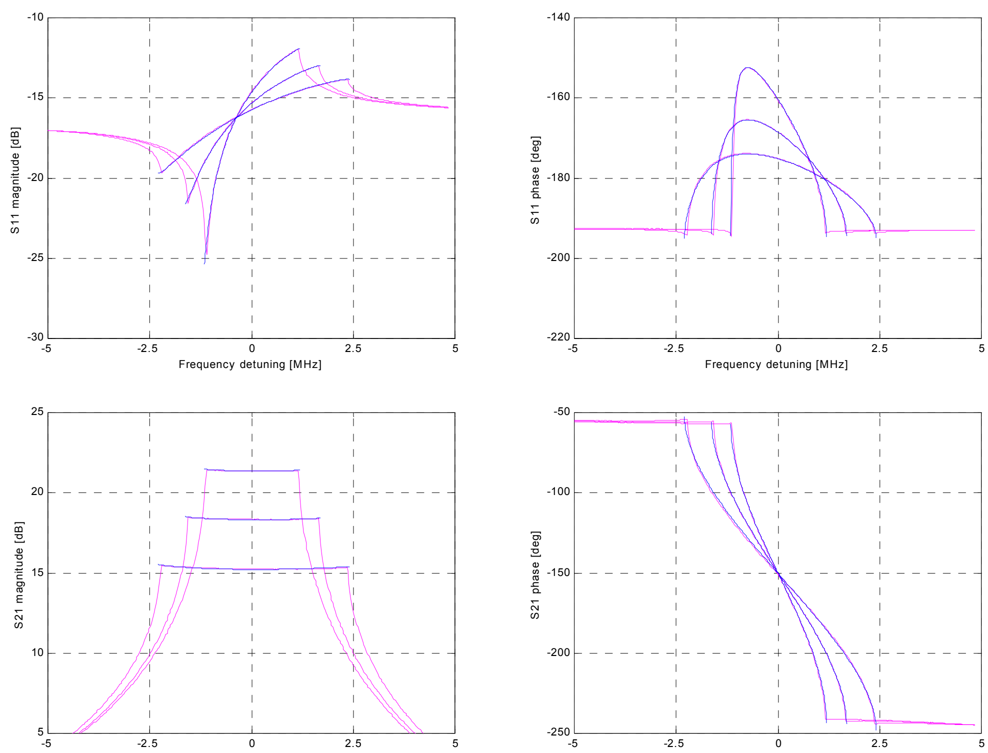
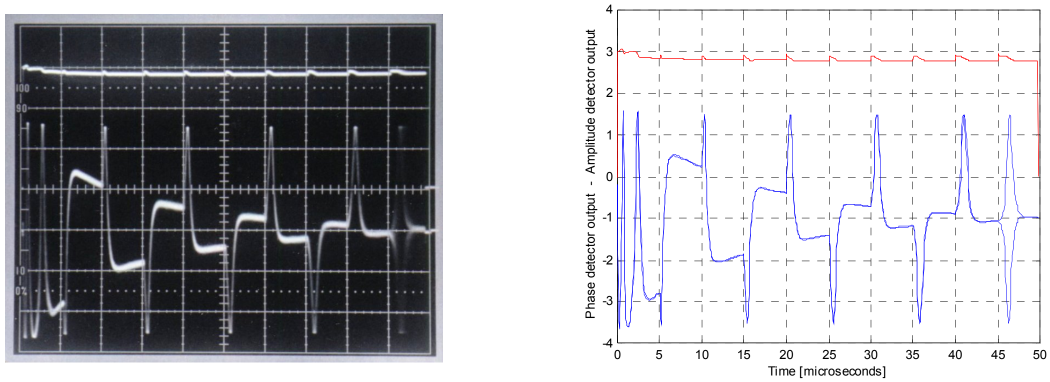


Fig. 2: Measured and simulated (raw) scattering parameters S_{11} (a) and S_{21} (b) of the DUT under sinusoidal non-pulsed operation, for three different values of input signal amplitude (Pin/Pout=-24 dB, -21dB, -18dB).

(a)



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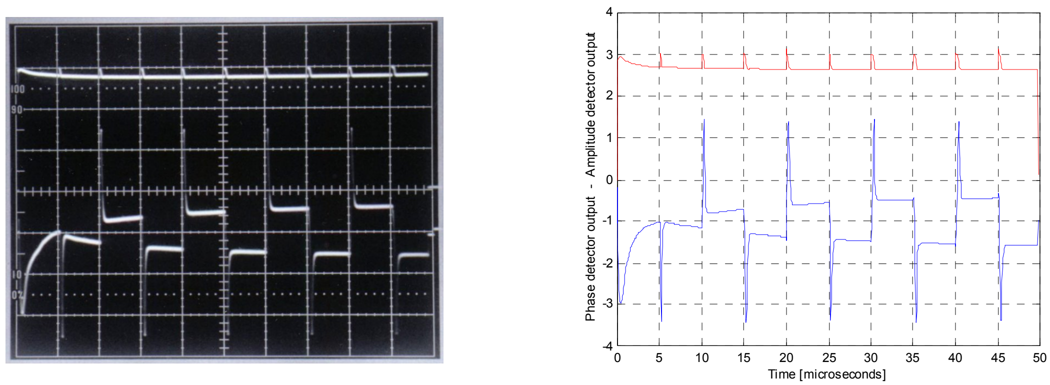

(c)

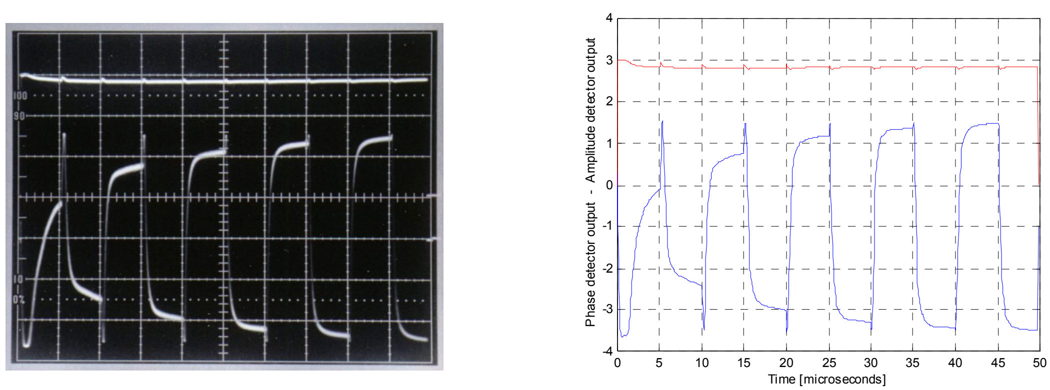

Fig. 3: Measured (left) and simulated (right) response of the oscillating amplifier under pulsed operation [50 µs pulse-width, 1kHz PRF, 2.6Vdc pulsed bias] for a BPSK modulated [10 µs period square-wave] input signal with the following injection parameter values:
(a) f_s=9.756916 GHz, Pin/Pout=-30 dB;
(b) f_s=9.756916 GHz, Pin/Pout=-20 dB;
(c) f_s=9.756362 GHz, Pin/Pout=-30 dB.
Top trace is the amplitude detector output; Bottom trace is the phase detector output.