STABILITY ANALYSIS OF MULTI-TRANSISTOR MICROWAVE POWER AMPLIFIERS

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ABSTRACT

Stability analysis of structures composed of transistors "paralleled" by means of power dividers/combiners is a key point in the design of MMIC power amplifiers. However, techniques to cope with this problem are quite rare in the literature and standard, straightforward tools are usually not available in CAD programs. A new simplified approach, which can be applied using conventional linear tools for microwave circuit analysis, is proposed in this paper.

INTRODUCTION

Stability analysis is one of the most common problems circuit designers must face off, particularly at microwave frequencies where the risk of unstable behavior is not negligible even with a single transistor amplifier.

Most common approaches to stability analysis, widely used by microwave circuit designers, are based on the Nyquist criterion and other tools which have been derived under simplified assumptions (e.g., Bode criterion, stability circles, Rollet factor, etc..) [1,2]. These approaches have the advantage of being based on the "$j\omega$" domain which is strictly related to the type of data available from network analyzer measurements, electromagnetic simulations or frequency-domain dispersive models.

In order to correctly apply the above mentioned techniques, attention must be paid to the condition for the validity of the Nyquist criterion [3..6] which, in its more useful form, is valid for systems having a stable loop gain. Otherwise, the right application to systems having an unstable loop gain requires the knowledge of the number of right-half-plane poles in order to analyze the stability [5..8].

In any case, the Nyquist-based approaches have been mainly applied to determine the instability conditions for oscillators and for the stability study of single-stage or cascaded amplifiers. Only a few works [7..10] have been dedicated to (or have partly dealt with) the more complex stability analysis of circuits composed of paralleled stages. This is a particularly important aspect in MMIC power amplifier design where, in order to obtain the required load power, several transistors are "paralleled" by means of power combining/dividing microstrip structures.

In this paper, a new simplified approach to the small-perturbation stability analysis of MMIC power amplifiers is proposed which can be applied to the most common case of symmetrical circuit structures. With respect to other techniques outlined in the literature [7..10], the analysis technique proposed here is mathematically sound, simple, straightforward, and gives useful information to outline possible strategies for circuit stabilization. Moreover, the new approach is based on conventional scattering parameter analyses and can be easily applied using conventional CAD tools for microwave linear circuits. Simulation results confirming the validity of the method are provided in the paper.

THE NEW APPROACH TO STABILITY ANALYSIS OF SYMMETRICAL STRUCTURES

To describe the new approach the structure in Fig.1a will be considered. It represents a common way of paralleling a suitable, even number of identical transistors in order to reach, in the last stage of the amplifier, the power level required by the load. For simplicity a structure having the same topology has been chosen both for the output combiner and input divider; the method, however, can be applied to any kind of coupling structure under the only constraints of a symmetric topology and of a number of paralleled devices which is power of two. In particular, the same approach can easily be applied to the quite common circuit topology which employs a driver for each couple of power transistors.

As it will be shown, the symmetry of the coupling structures can be exploited in order to perform the stability analysis in terms of a limited number of conventional stability analyses involving single-device amplifiers with suitable equivalent load and source terminations.

Let us consider, for instance, the four-port combining structure **O** in Fig.1; for symmetry reasons, it holds:

$$\begin{aligned} S_{11} = S_{22} = S_{33} = S_{44} = S_R \\ S_{12} = S_{21} = S_{34} = S_{43} = S_{MN} \\ S_{13} = S_{14} = S_{23} = S_{24} = S_{31} = S_{32} = S_{41} = S_{42} = S_{MF} \end{aligned} \qquad (1)$$

so that the scattering matrix of the coupling structure can be written as:

$$\begin{aligned} b_1 &= S_R a_1 + S_{MN} a_2 + S_{MF} a_3 + S_{MF} a_4 \\ b_2 &= S_{MN} a_1 + S_R a_2 + S_{MF} a_3 + S_{MF} a_4 \\ b_3 &= S_{MF} a_1 + S_{MF} a_2 + S_R a_3 + S_{MN} a_4 \\ b_4 &= S_{MF} a_1 + S_{MF} a_2 + S_{MN} a_3 + S_R a_4 \end{aligned} \tag{2}$$

Moreover, it is convenient to define the vector **a**=[a_1 a_2 a_3 a_4]^T of incident waves in the following way:

$$\mathbf{a} = \alpha\,\mathbf{m_1} + \beta\,\mathbf{m_2} + \gamma\,\mathbf{m_3} + \delta\,\mathbf{m_4} \tag{3}$$

$$\text{with} \quad \mathbf{m_1} = [1, 1, 1, 1]^T \quad \mathbf{m_2} = [1, -1, 1, -1]^T \quad \mathbf{m_3} = [1, 1, -1, -1]^T \quad \mathbf{m_4} = [1, -1, -1, 1]^T$$

α, β, γ, δ being suitable scalar quantities.

Equation (3) simply states that any possible vector **a** of incident waves can be expressed through a linear combination of the linearly independent vectors $\mathbf{m_1}$, $\mathbf{m_2}$, $\mathbf{m_3}$, $\mathbf{m_4}$ which represents a *“base”* in the space of the incident waves. Obviously, it would be possible to choose other vector bases, but the choice in (3) allows for the simplification of the stability analysis since it takes advantage of the structural symmetry of the circuit. More precisely, the vector base in (3) is associated to “signal loops” in the amplifier topology which may be responsible for unstable behavior and can be thought as related to *“fundamental oscillation modes”* [9,10] of the amplifier.

According to the previous definitions, since under small perturbations we can apply the superposition of effects, the stability analysis problem can be reduced to four independent stability analyses carried out by considering separately the *“fundamental modes”* $\mathbf{m_1}$, $\mathbf{m_2}$, $\mathbf{m_3}$, $\mathbf{m_4}$. For instance, by considering the fundamental mode $\mathbf{m_3}$ defined in (3), equations (2) lead to:

$$b_1 = b_2 = -b_3 = -b_4 = b = (S_R + S_{MN} - 2\,S_{MF})\,a \quad \text{with} \quad a = a_1 = a_2 = -a_3 = -a_4 = \alpha \tag{4}$$

The latter equation shows that the stability analysis for the fundamental mode $\mathbf{m_3}$ simply requires to study a circuit where the output port of the transistor is terminated on an equivalent load reflection coefficient given by:

$$\rho_{L3} = b/a = S_R + S_{MN} - 2\,S_{MF} \tag{5}$$

The same method can be applied to the input combining structure leading to an equivalent source reflection coefficient ρ_{S3} which, for the structure in Fig.1a, clearly has the same expression of ρ_{L3} once we replace in (5) the scattering parameters of the output coupler with those of the input combiner. The reflection coefficients ρ_{S3} and ρ_{L3} are easily computed through conventional S-parameter analyses of the coupling structures.

Thus, for each mode of the circuit structure, the single-transistor equivalent structure in Fig.1b must be analyzed for stability. This task can be performed using conventional and well-known techniques usually available as standard tools in CAD programs. Clearly, in order to have a stable power amplifier, the equivalent circuit associated to each mode must result stable. It is interesting to note that this kind of analysis, as will be discussed in the following, also gives useful information to circuit designers on “signal paths” that may be critical for stability.

VALIDATION AND SIMULATION RESULTS

The technique for stability analysis described above was adopted in the design of a 20GHz, 1W MMIC quasi-linear power amplifier based on GaAs HFETs manufactured by Alenia Marconi Systems, Italy. In particular, a final stage was designed composed of four $0.25\times600\mu\text{m}^2$ HFETs “paralleled” by means of microstrip power combiners/dividers having a topology of the kind in Fig.1a.

The stability analysis of the circuit was performed in the Hewlett-Packard Microwave Design System environment, according to the proposed procedure. For the initial design, the equivalent circuit associated to the fundamental “differential” mode $\mathbf{m_3}$ ([1, 1, -1, -1]) was unstable as shown by the Bode plots in Fig.2 where amplitude and phase of the loop gain $\rho_{IN3}\cdot\rho_{S3}$ are plotted; more precisely, at a frequency of about 10 GHz the loop gain has a phase of 0° with a magnitude equal to 0.4 dB.

In order to verify the validity of the stability analysis technique, the complete circuit was analyzed using a transient simulator[1] which confirmed the results predicted by the new stability analysis procedure. In particular, Fig. 4a shows

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[1] Obviously, time-domain analysis was carried out by means of a non-linear dynamic HFET model.

the amplifier response to a short input voltage pulse; as expected the output voltage is characterized by a rising oscillation.

The stability analysis performed gave also useful information on the kind of instability. In fact, while the stability of the mode $\mathbf{m_1}$, $\mathbf{m_2}$ and $\mathbf{m_4}$ suggests that the two "inner loops" (see Fig.1a) composed of the transistors T_1, T_2 and T_3, T_4, respectively, are stable, the instability of $\mathbf{m_3}$ points out the presence of an "unstable signal path" composed by the "outer loop". This information is particularly useful since immediately suggests that a possible solution to stabilize the amplifier could be based on the introduction of suitable resistors between the points A and B in Fig.1a, so that losses are introduced only for the unstable differential mode[2]. It can be observed that the introduction of resistors in a different position, such as between the nodes C and D, E and F in Fig.1a, would not have given the same results since, in such condition, the mode $\mathbf{m_3}$ would be unaffected.

The stabilization procedure was carried out by inserting the above mentioned AB resistors and using the stability analysis procedure to find a suitable resistance value. In Fig.3, the Bode plots corresponding to those in Fig.2, but for the "compensated" circuit are plotted showing stable behavior. Finally, the time domain analysis performed again for the complete power amplifier excited by a short voltage pulse, showed, as expected, decaying behavior denoting stability (see Fig.4b).

CONCLUSION

A new approach has been proposed and validated for the stability analysis of MMIC power amplifiers. The new analysis technique, which can be efficiently applied to the most common case of symmetrical circuit structures, can easily be carried out using conventional tools for linear microwave circuit analysis. Moreover, it provides an insight on the kind of instability which would arise in the circuit, thus giving useful information in order to introduce suitable stabilization components. The simplicity and solidity of this approach, with respect to other techniques outlined in the literature [7..10], makes it a valuable tool for MMIC power amplifier design.

ACKNOWLEDGMENT

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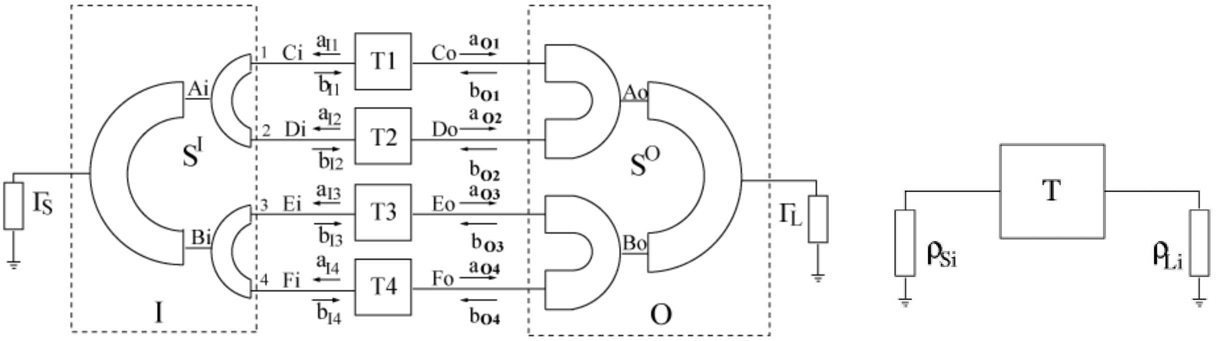
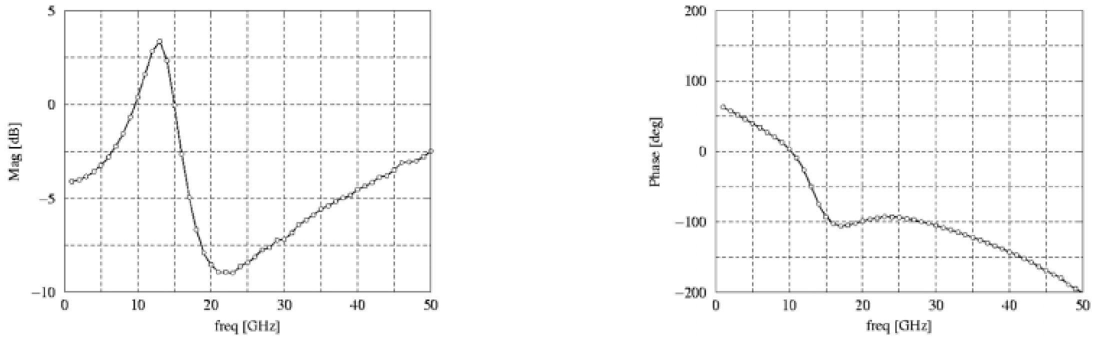
[2] The stabilization resistors can be introduced in the input divider and/or output combiner depending on stability and other design constraints.



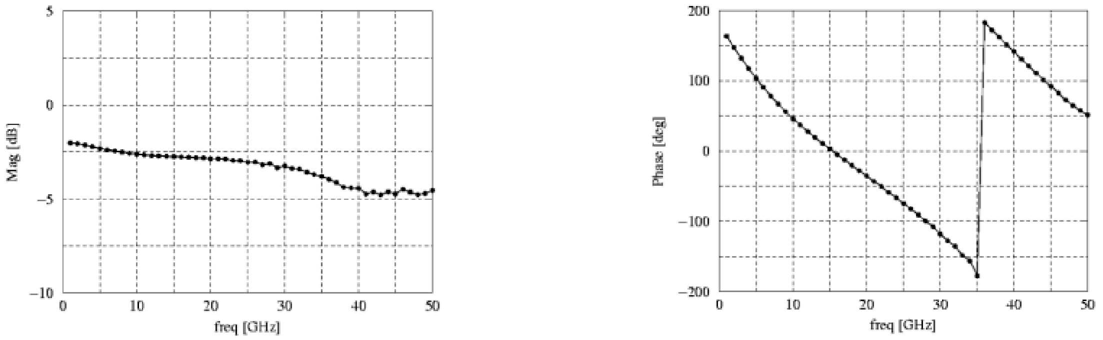
a) **b)**

Fig.1:a) Schematic of a power amplifier based on input dividing and output combining networks **b)** equivalent circuit for the stability analysis associated to the fundamental i^th mode of the structure.



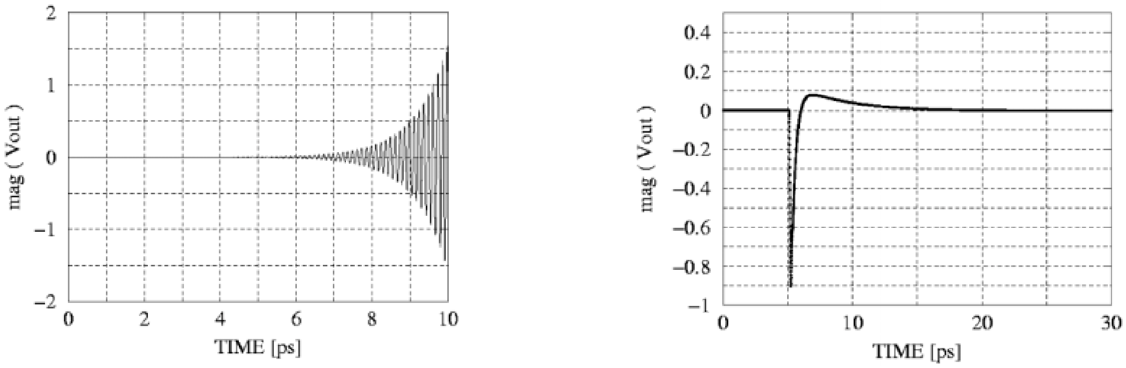
a) **b)**

Fig.2: Bode plots for the fundamental mode $\mathbf{m_3}$ of the amplifier structure.



a) **b)**

Fig.3: Bode plots for the fundamental mode $\mathbf{m_3}$ after the introduction of a stabilizing resistor.



a) **b)**

Fig.4: **a)** Time-domain response of the power amplifier to a voltage pulse: the rising, oscillating output voltage confirms the unstable behavior. **b)** Pulse response of the amplifier after the "compensation" procedure.