A Symmetry Device to Speed Up Circuit Simulation and Stability Tests

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Abstract— **A new simulation device is introduced that employs symmetry considerations in order to speed up network analysis of circuits with parallel branches. Such parallel branches are found e.g. in amplifiers with corporate combiners and push-pull oscillators. The device may be switched between two states, a symmetry and an antisymmetry state. The former is used in normal or even-mode operation and reduces the paralleled branches to a single branch, thus scaling down the time needed for the circuit setup as much as the simulation time. The other state allows for rigorous odd-mode stability analysis when combined with a circulator stability test port. The device is easily implemented in standard circuit simulation programs.**

I. Introduction

HIGH POWER amplifiers require large overall gate-width that is usually obtained by multiple transistors. The transistors are organized in parallel branches with corporate combining networks. Simulation of such structures is often done by setting up each of the branches. While this is cumbersome, work can be reduced using subcircuits. Still the simulation time is the same. As a remedy, we propose a symmetry device that reduces the paralleled branches to a single branch, thus scaling down the time needed for the circuit setup as much as the simulation time. The particular advantage of the proposed device, however, is fully exploited in odd-mode stability investigations.

It is well known that Rollet's k-factor test and mu-factors as defined by Edwards et al. [1] are not enough to ascertain stability of amplifier circuits. The possibility of oscillations in paralleled stages was pointed out by several authors, e.g. [2], [3]. While the excitation of parallel branches in its normal operation is in-phase (push-push), also modes exist that are odd or 180° out-of-phase (push-pull). These modes of operation can only be found by breaking up inner active circuit loops. In [4] these modes of operation are identified by the eigenvalues of the respective impedance-matrix. The author shows that such odd-modes can be suppressed by resistors between paralleled transistors.

Easier ways of ascertaining stability were sought, that do not need access to the system matrix. For a single-loop feedback, the Nyquist criterion was applied to S-parameter simulations using a circulator in [5], [6]. For multiple loops, Ohtomo [7] generalized this approach. While a general method is theoretically appealing, the practical needs favor reduced simulation time, and compact and convenient simulation setups. In this paper, we develop a hierarchical approach that guarantees the completeness of the small-signal stability investigation using Ohtomo's work with respect to a circuit that is reduced to a single branch.

While the symmetry device can be set up for any number of parallel branches, we will limit the discussion to the usual case of binary combined branches. In the following, only small signal stability is investigated, although the proposed symmetry device is equally valid for large-signal simulations, when an imposed modal symmetry is to be maintained.

II. The Symmetry Device

In a common circuit configuration that is found in power amplifiers with corporate combiners, input power is split on two parallel branches where each of them feeds a single transistor (Fig. 1).

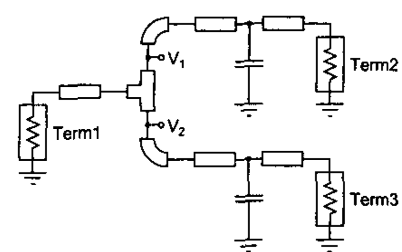

Fig. 1. A typical symmetrical branch.

Using this setup, the even-mode input reflection S_{11}, output reflection S_{22}, and forward transmission S_{21} are correctly modeled. The backward isolation S_{12}, however, does not show the even-mode behavior, but the non-symmetric excitation from Term 2 measured at Term 1 while Term 3 is not excited. In order to get the correct even-mode behavior, it is common practice to combine terminals 2 and 3 into one that operates with half the impedance value of the original terminals. This is correct, since both branches show the same voltage in even-mode operation, while the current is twice the value of a single branch. Hence Term 2 operates at twice the power of a single branch and the parameters S_{21} and S_{12} are wrong by a factor of $\sqrt{2}$.

A more elegant solution can be deduced from Fig. 1. In the case of even mode operation the voltages V_1 and V_2 must be equal. While this condition follows from the equality of the two signal paths, it can also be artificially enforced by a voltage controlled voltage source that transfers the voltage V_1 to the point V_2 without directly influ-

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encing the situation at point V_1. Since the voltage at V_2 is now independent of the circuit that is below of this probe point, it can be removed from the simulation without influencing the result at Term 2 (Fig. 2). Thus the simulation time for the circuit is reduced and the power situation is now correct at the single output terminal.

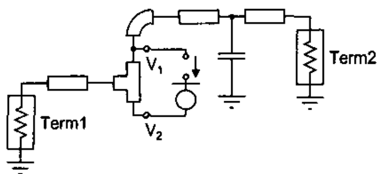

Fig. 2. A symmetry device replaces the second branch.

The voltage controlled voltage source that transfers the voltage V_1 of the complete circuit branch to the point V_2 of the truncated branch is the first part of what we call a symmetry device in the following. Since the impedance between point V_1 and the branch point, and point V_2 and the branch point is the same, also the currents are equal in size flowing into the branch point. It is obvious from Kirchoff's Laws that the complete branch behaves in the same way as before the truncation. Note, that with respect to a power wave representation the wave coming from Term 2 is equally supplied to the lower branch by the controlled voltage source. For the application of this device, no change of the power divider is needed. While we used a voltage controlled voltage source, one could use a current controlled current source instead. This configuration may be employed directly to the branch node, if accessible.

From the preceeding paragraphs the analogy to symmetry boundary conditions in electro-magnetic simulations might have become obvious. When we think of the schematic translated into a circuit layout, it is exactly such a symmetry boundary condition that can be imposed at the plane of symmetry. The voltage controlled voltage source thus is equivalent to the effects of a perfect magnetic conductor (PMC).

III. Stability Mode

So far we discussed the normal state or even-mode excitation of parallel branches. For oscillators and in order to guarantee stability of an amplifier circuit, the odd-mode excitation is important. While the even-mode excitation is in phase, the odd-mode operation is 180° out-of-phase, and the voltage at node V_2 becomes $-V_1$. This situation is easily achieved with the voltage controlled voltage source as above by negating the measured voltage. As pointed out in [4] the branch node hereby becomes a virtual ground. Again an analogous electro-magnetic symmetry boundary condition is found with the perfect electric conductor (PEC).

Here, too, the voltage controlled voltage source can be replaced by a current controlled current source at the branch node. The odd-mode current flows from point V_1 into the branch point and continues from the branch point to the point V_2. No current leaves the two branches and the closed loop is independent of the rest of the circuit.

The odd-mode setup constitutes the second purpose of the symmetry device as shown in Fig. 3. The device is switched from the even to the odd-mode state when the two variables *Num* and *Mode* are equal.

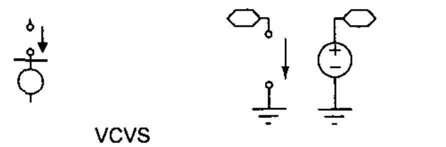

Fig. 3. The symmetry device implemented as a voltage controlled voltage source.

An alternative implementation of the symmetry device uses an S-parameter two-port that is placed at the branch point. It divides the transmitted power by two and represents half the input impedance at the output in the even-mode. The S-parameter matrix and the port impedances can be implemented as

$$S = \begin{pmatrix} 0 & \sqrt{2} \\ 1/\sqrt{2} & 0 \end{pmatrix} \qquad Z = \begin{pmatrix} 50/\sqrt{2} \\ 50\sqrt{2} \end{pmatrix} \tag{1}$$

which in a 50 Ohm system is equivalent to

$$S = \begin{pmatrix} -1/3 & 4/3 \\ 2/3 & 1/3 \end{pmatrix} \qquad Z = \begin{pmatrix} 50 \\ 50 \end{pmatrix} \tag{2}$$

This matrix is neither symmetric nor unitary and thus represents a circuit that is neither reciprocal nor loss-less.

In the odd-mode case the S-parameter two-port is independent of the port impedances

$$S = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \tag{3}$$

Note that the input reflection S_{11} and one transmission parameter S_{12} or S_{21} can be chosen freely but are set symmetric here.

IV. Stability Analysis

So far we dealt with the correct setup of the circuit for even-mode and odd-mode operation. In order to investigate the stability of a closed-loop circuit, we follow the rigorous approach of Ohtomo [7]. In order to be able to find an instability in the circuit, it is a necessary condition that this instability involves an interface port. In this approach, the circuit is thus partitioned into two S-parameter matrices connected by ports that can be checked by the Nyquist criterion.

The Nyquist criterion is an exact graphical method that determines stability of a closed-loop transfer function $H(s)$ from its open-loop transfer function $G(s)$ that is found from the relation

$$H(s) = \frac{G(s)}{1 - G(s)} \tag{4}$$

according to the signal-graph in Fig. 4. For stability, $H(s)$ must not have poles in the right half-plane correspondent to growing oscillations. Poles of $H(s)$ are equivalent to zeros of $1 - G(s)$. The Nyquist criterion investigates the number of clockwise revolutions N_r of $G(j\omega)$ in the complex plane around the point $1 + 0j$ for ω from $-\infty$ to $+\infty$ given by

$$N_r = z - p \qquad (5)$$

with z and p the right half-plane zeros and poles of $G(s)$. In order to determine z not only N_r but also p is needed. The complete number of zeros N_z of $1 - G(s)$, however, can be determined by summing up the number of clockwise revolutions in Nyquist plots of all subgraphs. Subgraphs are defined by employing isolators in the ports. For more information including a proof we refer the reader to [7].

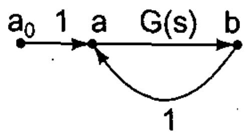

Fig. 4. Signal-flow graph of a feedback loop.

For the practical application of this method an implementation of a switched circulator is shown in Fig. 5. In order to check all loops, this device is put at every interface port between active and passive devices.

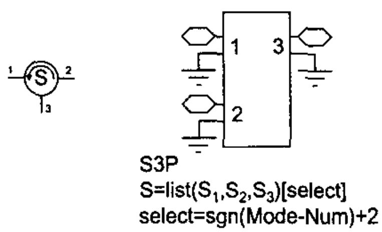

Fig. 5. The switched stability test device.

The circulator device has three modes. In the first mode, ports 1 and 2 operate as thru, while port 3 is isolated. In the stability test mode the device operates as ideal circulator. The third mode realizes an ideal isolator to create subgraphs. The corresponding S-parameter matrices are

$$S_{1,2,3} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (6)$$

All the circulator devices must be numbered by the parameter *Num* without any specific order. The *Mode* parameter of the device is used to select the specific mode of operation (1 to 3) depending on *Mode* being smaller, equal, or greater than *Num* respectively. Since the test port is switched to an open in non-operating mode, all the test devices can be connected to a single port.

V. Hierarchy

In order to check all possible loops of a multi-stage multi-branch power amplifier for stability, a hierarchical approach is needed. As shown in Fig. 6 the branch points are numbered from the outermost loop inwards analogous to brackets. Branch points that are on the same hierarchical level get the same number. Employing the symmetry device

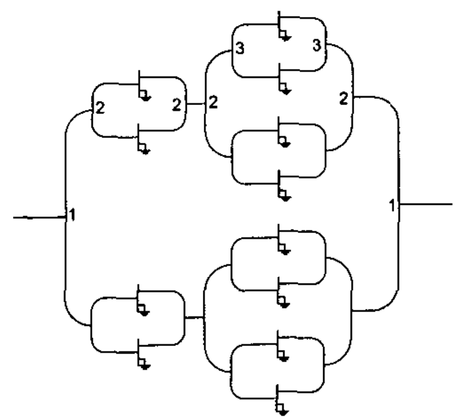

Fig. 6. A typical hierarchy of a high power amplifier.

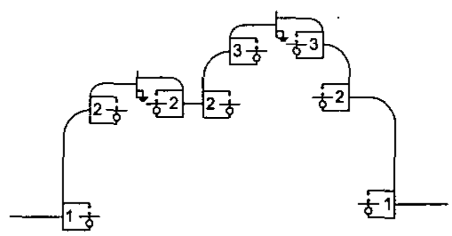

Fig. 7. The symmetry device reduces the simulation setup.

with the number of the branch point entered as *Num*, the circuit reduces to a single branch shown in Fig. 7

Now the loop number *Mode* of the symmetry device can be swept from zero to the maximum branch point number. By this means, the even-mode configuration and all possible odd-mode configurations are created. For each loop sweep, a sweep of the stability devices is done such that all stages are checked. Since the test port of the stability device isolates when switched off, all devices can be connected to a single S-parameter terminal (Fig. 8). For each stability and symmetry mode an S-parameter simulation is triggered. The resulting S-parameters are displayed in a Nyquist plot. Any curve that encircles the point $1 + 0j$ indicates an instability. The number of the circulator tap and the symmetry mode indicate the instable loop.

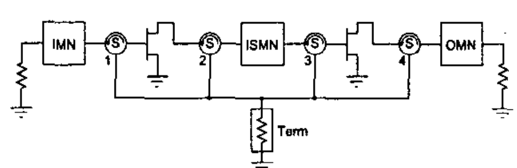

Fig. 8. Setup of a two-stage multi-branch amplifier for a complete odd-mode stability test.

Mathematically the full solution for power waves in any branch is found as the superposition of all eigen-modes. Since all symmetries and all non-linear devices are checked, this approach is complete. This general approach is also valid with transistor feedback loops. For straight branches, as shown here, a single stability device per transistor would be sufficient for a complete stability test.

VI. Examples

An X-band amplifier with a hierarchy as shown in Fig. 6 was tested for odd-mode stability. Fig. 9 shows the even and the two or three odd modes at each stability port. The amplifier is stable.

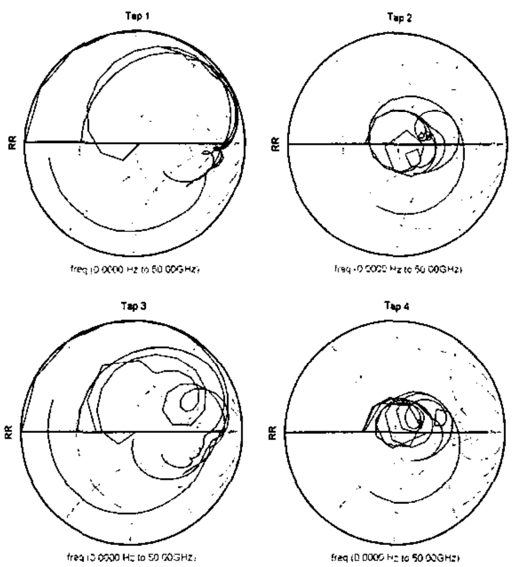

Fig. 9. Nyquist plots of a 10 GHz amplifier.

As a second example, a first version of a 60 GHz amplifier was found to be prone to oscillation depending on process variations. Fig. 10 shows the Nyquist plot for the second paralleled stage in dependence on the odd-mode resistors. The curve without odd-mode suppression cuts the real axis with an absolute value $|S| > 1$ at the resonance frequency of about 18.6 GHz.

When this mode can oscillate, the transistors involved reach the saturation limit and therefore operate in a non-linear regime. While the push-pull oscillation mode cannot be seen at the amplifier output terminal, since a virtual ground exists at the combining point, the even harmonics created by the non-linear operation are detected in a measurement. The S-parameter S_{21} of a non-oscillating and an oscillating amplifier are compared in Fig. 11. Peaks at 36.5 GHz and 73 GHz show the second and fourth harmonic.

VII. Conclusions

The introduction of a symmetry device in combination with a circulator test port and the setup of a hierarchical simulation was shown to be an effective means of reducing simulation and setup time for amplifier development and

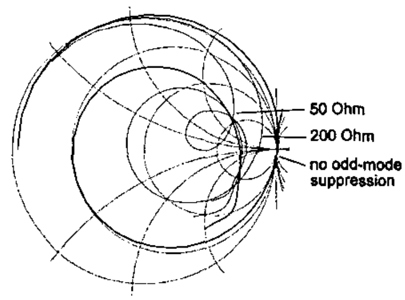

Fig. 10. Nyquist plot of the second stage of a 60 GHz amplifier with different odd-mode suppressions.

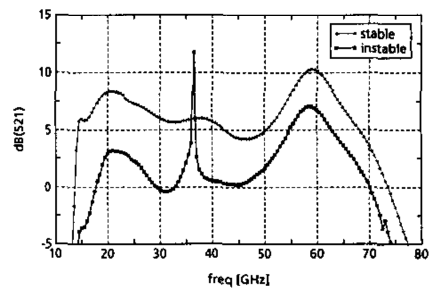

Fig. 11. Measured S-parameter S_{21} of a stable and an instable 60 GHz amplifier.

rigorous odd-mode stability tests. The proposed method gives specific information on potential instabilities and the involved signal path. The effects of a modification of the circuit can be readily analyzed.

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