A UNIFIED ANALYSIS OF MMIC POWER AMPLIFIER STABILITY

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ABSTRACT

High power MMIC amplifiers require large periphery output devices in order to meet their output power goals. Bandwidth and impedance matching considerations typically require that this large output device be subdivided into smaller devices and power combined on-chip. This power combining introduces n possible modes of oscillation when n devices are combined. The usual K,B1-factor stability analysis only addresses one mode (the even mode). This paper presents an analytical approach for predicting and stabilizing oscillations for all n modes. Specific cases for n=2 and 4 are discussed. The approach can be implemented using standard small signal analysis software.

INTRODUCTION

High power MMIC amplifiers require large periphery output devices in order to achieve their power output goals. A 3 watt power MMIC employing FETs, for example, requires approximately 8 mm of output stage periphery in order to operate at maximum power-added efficiency while overcoming output circuit losses [1]. Bandwidth and impedance matching considerations typically require that this large output device be subdivided into smaller devices and power combined on-chip. This subdivision may or may not involve physical separation of the devices [2,3]. Unfortunately, the introduction of on-chip power combining also introduces the possibility of additional modes of oscillation [4]. In general, n orthogonal voltage/current modes, 1 "even" and n-1 "odd", can exist when n devices are combined. The usual amplifier stability analysis involving the K/B1 factors addresses only the even mode. The amplifier can still oscillate in any of the other odd modes even though it has been stabilized in the classical sense (i.e., K>1, B1+).

This paper develops the mathematical framework and techniques for predicting possible oscillations for all n modes in order to ensure MMIC stability. Although the analysis is applicable to any number of combined devices, only the cases for n=2 and 4 will be discussed here. As will be shown, these two cases illustrate the special considerations that apply for small numbers of combined devices (n=2) and the difficulties in analyzing larger numbers of combined devices (n=4).

GENERAL ANALYSIS APPROACH

N=2

The general mathematical technique for predicting mode stability will be developed using the special case of two combined devices (n=2). The network topologies which will be analyzed are shown in Figure 1.

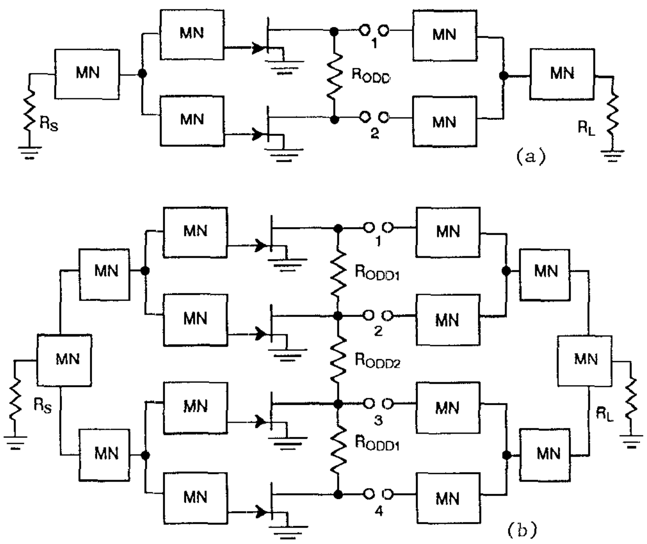

Figure 1. Circuit topologies analyzed in this paper. The division of the circuits into input and output halves for analysis is shown. (a) Two combined devices (n=2). (b) Four combined devices (n=4, corporate combiner).

Although the nonlinear operation of power devices can create various types of instabilities [5], the oscillations analyzed in this paper start from small signal levels and build up until device saturation limits are reached. Small signal parameters (s-,z-,y-, etc.) can therefore be used to predict stability. As will be clear later, z-parameters are the appropriate choice for this type of analysis [6]. Therefore, consider the two-port z-parameters of each half of the amplifier shown in Figure 1(a). Note that the "input" of the input half of the amplifier is terminated in the source resistance R_S and the "output" of the output half of the amplifier is terminated in the load resistance R_L. Ports 1 and 2 of the input half are at the device output terminals. Likewise, ports 1 and 2 of the output half are at the combiner terminals. The form of the z-parameter equation for each half is

$$\begin{bmatrix} z_{11} & z_{12} \\ z_{12} & z_{11} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad (1)$$

i.e, the z-matrix is symmetrical with $z_{22}=z_{11}$ and $z_{21}=z_{12}$. The eigenvalues and eigenvectors of the z-matrix are the scalars, z, and current vectors $|I|$ that are solutions of

$$\begin{bmatrix} Z \end{bmatrix} \begin{bmatrix} I \end{bmatrix} = z \begin{bmatrix} I \end{bmatrix} . \quad (2)$$

For the z-matrix in (1), the two eigenvectors and associated eigenvalues are given by

$$\begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad z_e=z_{11}+z_{12} \quad \text{"even" mode}$$
$$\begin{bmatrix} 1 \\ -1 \end{bmatrix} \quad z_o=z_{11}-z_{12} \quad \text{"odd" mode} \qquad (3)$$

These two eigenvectors are linearly independent or orthogonal and represent the two current/voltage modes, one even and one odd, which can exist in each half of the amplifier. A general current/voltage waveform at the device or output combiner terminals would consist of a linear combination (at small signal levels) of these two fundamental modes. Note that the even mode represents "normal" circuit operation where the currents and voltages at each port are in-phase whereas the odd mode represents circuit operation in which the port currents and voltages are 180° out- of-phase. For n=2, therefore, the odd mode is also known as the "push-pull" mode. The associated eigenvalues for each mode are the impedances seen at each port when excited by each mode, i.e.,

z_e = impedance seen at each port under even mode excitation,
z_o = impedance seen at each port under odd mode excitation.

These interpretations are possible because of the choice of z-parameters to characterize the two amplifier halves. Each half of the amplifier has the same two modes (eigenvectors) but, in general, the values for the associated eigenvalues are quite different. Now, let the second subscript i denote the input half of the amplifier and the second subscript o denote the output half. Then, using the well-known conditions for negative resistance oscillations, the stability conditions for each mode can be stated as

$$\begin{aligned} &\mathrm{Re}\{ z_{ei}+z_{eo} \} < 0 \quad \text{and} \\ &\mathrm{Im}\{ z_{ei}+z_{eo} \} = 0 \quad \text{(even mode)} \\ &\mathrm{Re}\{ z_{oi}+z_{oo} \} < 0 \quad \text{and} \\ &\mathrm{Im}\{ z_{oi}+z_{oo} \} = 0 \quad \text{(odd mode).} \end{aligned} \qquad (4)$$

If these conditions are met for a mode at some frequency, f_0, then oscillations will occur in that mode at f_0.

Verification of Equations Using SPICE (N=2)

The stability equations in (4) were verified by analyzing the sample amplifier network shown in Figure 2. The amplifier was stabilized for even mode operation using the resistors in the input circuit. Subsequent analysis verified that the K-factor was greater than 1 and the B1-factor was positive at all frequencies. With R_{odd} set to ∞ initially, the odd mode eigenvalues for each half of the amplifier, eq. (3), and the eigenvalue sum, eq. (4), were computed vs. frequency using the OUTVAR and OUTEQN blocks in TOUCHSTONE. The same amplifier network was also

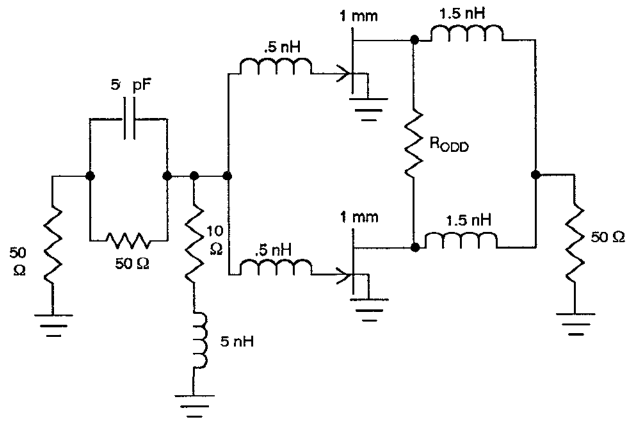

Figure 2. Amplifier network used to verify odd mode stability equations for n=2 case. The K-factor is greater than 1 and the B1-factor is positive for all frequencies indicating unconditional even mode stability.

analyzed using MICROWAVE SPICE in order to verify any predicted oscillations. A Curtice cubic model of a Westinghouse ion-implanted FET was used in the SPICE analysis. In order to keep the two analyses consistent, small-signal s-parameters at the desired bias point were generated for the FET using SPICE and inserted into the TOUCHSTONE analysis.

Figure 3(a) shows the odd mode eigenvalue sum generated by TOUCHSTONE. At 5 GHz, a net negative real part (negative resistance) was computed with a net reactance equal to zero. The oscillation condition of eq. (4) was therefore satisfied. Figure 3(b) shows the corresponding SPICE analysis where the instantaneous drain voltages of the two FETs are plotted vs. time. As can be seen, push-pull oscillations are indeed occurring at 5 GHz.

The same analysis can be used to stabilize the amplifier in the odd mode. Although several resistive stabilization schemes are possible [4], only the approach shown in Figures 1 and 2 will be analyzed here. This approach consists of straddling a resistor (R_{odd}) between the drains of the two FETs. Odd mode current, being 180° out-of-phase between the two FETs, must flow through this resistor. A suitable choice for the value of this resistor will dampen out the oscillations. Figure 4(a) plots the odd mode eigenvalue sum for the amplifier with R_{odd}=400 ohms. Note that now the sum of the real parts is > 0 so that oscillations are impossible. A SPICE verification of this result is shown in Figure 4(b) where an initial transient in the drain voltages is dampened out by the odd mode resistor (the transient is caused by an initial current pulse used to initiate possible oscillations). As it turns out, any value of R_{odd} < 400 ohms (including a short circuit) will work as well.

N=4

The amplifier topology to be analyzed for the case of n=4 is shown in Figures 1(b). The symmetric z-matrix of each amplifier half is given by

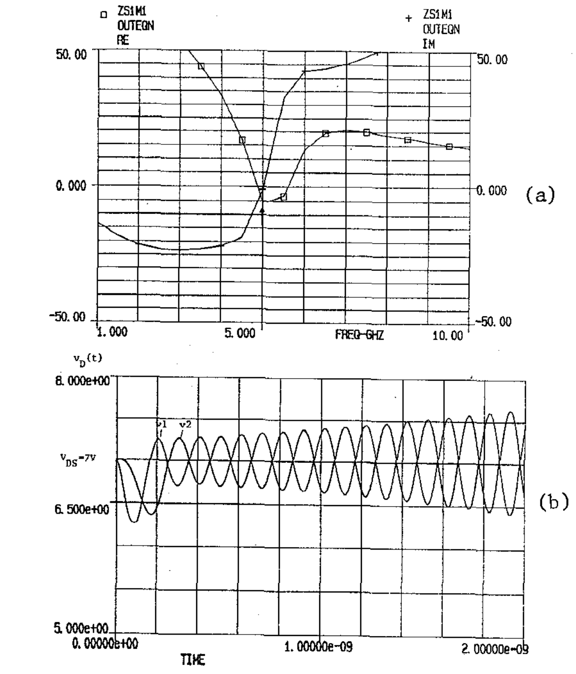

Figure 3. (a) Odd mode eigenvalue sum for the amplifier in Figure 2 (Rodd=∞). The conditions for oscillation are satisfied at 5 GHz. (b) SPICE analysis of the same amplifier verifying the odd mode oscillation at 5 GHz.

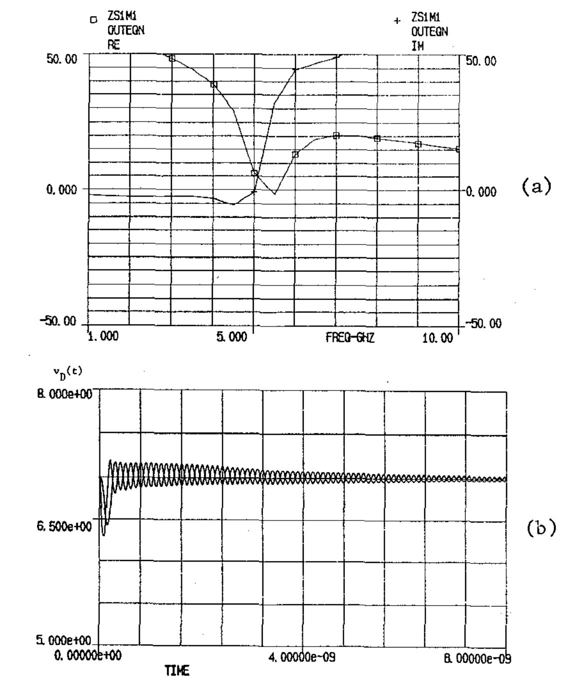

Figure 4. (a) Odd mode eigenvalue sum for the amplifier in Figure 2 with Rodd = 400 ohms. The oscillation conditions are no longer satisfied giving a stable amplifier. (b) SPICE analysis of the amplifier with Rodd = 400 ohms showing a decaying transient and odd mode stability. The transient was caused by a current pulse purposely applied to initiate any possible oscillations.

$$\begin{bmatrix} z_{11} & z_{12} & z_{13} & z_{14} \\ z_{12} & z_{22} & z_{23} & z_{13} \\ z_{13} & z_{23} & z_{22} & z_{12} \\ z_{14} & z_{13} & z_{12} & z_{11} \end{bmatrix} . \quad (6)$$

The eigenvectors (modes) and associated eigenvalues for this matrix are

$$\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \quad z_e = z_{11}+z_{12}+z_{13}+z_{14} \quad \text{even mode}$$

$$\begin{bmatrix} 1 \\ -1 \\ -1 \\ 1 \end{bmatrix} \quad z_{o1} = z_{11}+z_{14}-z_{12}-z_{13} \quad \text{odd mode \#1}$$

$$\begin{bmatrix} 1 \\ b1 \\ -b1 \\ -1 \end{bmatrix} \quad z_{o2} = z_{11}-z_{14}+b1(z_{12}-z_{13}) \quad \text{odd mode \#2}$$

$$\begin{bmatrix} 1 \\ b2 \\ -b2 \\ -1 \end{bmatrix} \quad z_{o3} = z_{11}-z_{14}+b2(z_{12}-z_{13}) \quad \text{odd mode \#3}$$

where $b1=((-\beta/\alpha)+((\beta/\alpha)^2+4)^{1/2})/2$
$b2=((-\beta/\alpha)-((\beta/\alpha)^2+4)^{1/2})/2$

$\beta = 2(z_{23}-z_{14})$ and
$\alpha = z_{12}-z_{13}$.

When R_{odd2} equals ∞, $z_{23}=z_{14}$, $\beta=0$, b1=1 and b2=-1. In this case the stability of the amplifier can be checked by adding the eigenvalues for each half of the circuit as before. However, the case in which n=4 differs from the n=2 case when both odd mode resistors are finite. In this situation, the even mode eigenvector and the first odd mode eigenvector will be identical for both halves of the amplifier circuit, but the second and third odd modes will no longer possess this symmetry (e.g., the odd mode #2 eigenvector for the input half of the amplifier will have the voltage/current form [1 b1 -b1 -1] whereas the output half where no symmetry destroying odd mode resistors are present will still have the [1 1 -1 -1] form). Oscillation possibilities cannot be checked by adding the eigenvalues for these modes because the current and voltage waveforms are no longer identical for both halves of the amplifier. Stability can still be ensured for these modes by looking at the eigenvalues for the input half (where the active devices are located and where, hence, the negative resistances are generated) and varying the odd mode resistor values until any negative resistances are removed.

Verification of Equations Using SPICE (N=4)

Shown in Figure 5 is the sample amplifier network used to check the n=4 odd mode stability equations. Again, with the R_{odd} resistors set to ∞, the eigenvalue sums for the odd modes were computed. Two of the odd modes, the 1 -1 -1 1 and the 1 -1 1 -1 mode, meet the oscillation conditions at 3.5 GHz (Figure 6). The other odd mode, the 1 1 -1 -1 mode, meets the oscillation conditions at 2.05 GHz. Figure 7 plots the 1-1-11 mode oscillation. One mode at a time was observed by suppressing the other two modes with appropriate resistor combinations. The 1 -1 -1 1 mode, for example, was brought out by shorting the drains of the two outer and the two inner devices together. All three modes can be suppressed by using low values for R_{odd1} and R_{odd2}.

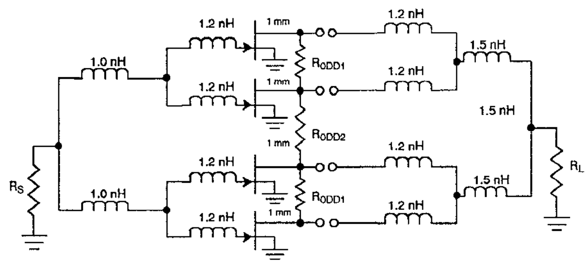

Figure 5. Amplifier network used to verify the odd mode equations for the n=4 case (corporate combiner).

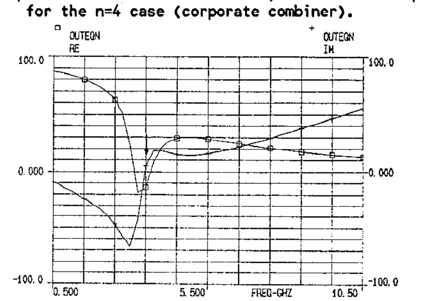

Figure 6. The 1-1-11 mode and 1-1 1-1 mode eigenvalue sums for the amplifier in Figure 5 (Rodd = ∞). Oscillation conditions are satisfied at 3.5 GHz. Oscillation conditions for the 11-1-1 mode were satisfied at 2.05 GHz.

ADDITIONAL CONSIDERATIONS AND PROPERTIES OF THE MODES

Several points will be discussed here concerning the analysis technique and the properties of the modes in general. This will give some additional insight into power amplifier stability.

First, it is interesting and important to note that the values of the odd mode eigenvalues (and, hence, the stability conditions) do not depend on the values of the terminating source and load impedances whereas the values of the even mode eigenvalues are terminating impedance dependent. Therefore, odd mode oscillations, unlike even mode oscillations, are a go or no-go proposition depending only on the devices and the combining networks and not on the values of

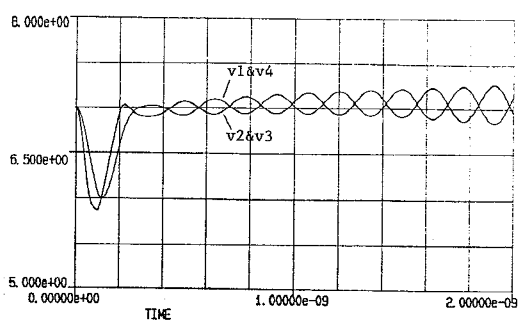

Figure 7. SPICE analysis of the amplifier in Figure 5 showing the individual odd mode oscillations of the 1-1-1 1 mode (11-1-1 and 1-1 1-1 mode stabilized).

the terminating impedances. The technique presented here can be used to check for "unconditional" odd mode stability without regard for the infinite combinations of source and load impedances. Unconditional even mode stability should be checked using the usual K/B1 factor analysis.

Second, it should be noted that the reason odd mode oscillations occur is because the amplifier is potentially unstable (i.e., K<1) between the various combining points. In particular, the amplifier will oscillate if it is unstable to short circuits placed at the combining points. The sum of the odd mode eigenvector components (which represent voltages or currents) always add up to zero. The odd mode will therefore create a virtual ground at all combining points. If the amplifier is not stable with a short circuit at these points, the odd mode will "generate" the short and initiate oscillations (see ref. [4]). The amplifier in Figure 2, for example, has a K-factor < 1 between the two combining points and is unstable to a short circuit placed at either point at 5 GHz. This gave rise to the push-pull oscillations shown in Figures 3(a) and 3(b). As discussed, the overall amplifier K-factor is greater than 1 and unconditional even mode stability is assured.

Third, the technique presented here could be applied to amplifier partitioning at the input side of the active devices. The eigenvalue sums computed using this partitioning would still show a net negative resistance with zero net reactance at those frequencies where oscillations occur. That is, the stability conditions of equation (4) still apply. Multi-stage amps may be handled by performing multiple partitions.

Finally, it should be mentioned that, in general, a short circuit placed between the input or output terminals of the combined devices(i.e., R_{odd}=0 ohms) will usually stabilize the amplifier against odd mode oscillations. However, in instances where the devices are widely separated, the "short circuit" will really be a length of transmission line. The inductance of this line may cause problems by introducing an additional "combining point".

SUMMARY

A technique for predicting power amplifier stability has been presented. Cases for two and four combined devices have been analyzed. It was shown that the stability of the amplifier for all modes (even and odd) can be checked using small signal analysis software. Methods for stabilizing the amplifier were also discussed. The technique should prove useful to designers of power MMICs.

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