BRIEF PAPER

A New Common-Mode Stabilization Method for a CMOS Cascode Class-E Power Amplifier with Driver Stage

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SUMMARY This paper presents a new common-mode stabilization method for a CMOS differential cascode Class-E power amplifier with LC-tank based driver stage. The stabilization method is based on the identification of the poles and zeros of the closed-loop transfer function at a critical node. By adding a series resistor at the common-gate node of the cascode transistor, the right-half-plane poles are moved to the left half plane, improving the common-mode stability. The simulation results show that the new method is an effective way to stabilize the PA.

key words: CMOS, Class-E power amplifiers, common mode, stability, closed-loop transfer function, pole, zero, right half plane

1. Introduction

In the lower GHz range, more and more low output power power amplifiers (PAs) are implemented in CMOS for cost reduction or for promoting monolithic integration. Stability is an important design goal in the design of PAs. Many papers [1]–[4] have been published to analyze the large-signal stability problem. The differential cascode topology is widely used in deep sub-micron CMOS PAs due to the low breakdown voltage of the CMOS technology. However, a differential circuit can run into the common-mode stability problem. [5] analyzes the common-mode stability of a single stage PA, but without driver stage nor cascode transistors. In this paper, we will show that the cascode transistors provide a new means to stabilize common-mode instabilities by adding a common-gate resistor. This paper presents a common-mode stability analysis of a CMOS differential cascode Class-E PA [6] with LC tank-load driver stage based on the analysis of poles and zeros of the closed-loop transfer function at a critical node.

This paper is organized as follows. Section 2 introduces the theoretical background and models used for the analysis of the common-mode stability. Section 3 presents numerical results of a PA, followed by a discussion of a new stabilization method. Section 4 gives simulation results to verify the stabilization method. Finally, conclusions are drawn in Sect. 5.

2. Common-Mode Stability Analysis

A simplified topology of the differential cascode Class-E

Fig. 1 Topology of the differential cascode Class-E PA with output impedance of the driver.

Fig. 2 Common-mode small signal circuit of half the circuit.

PA including the output impedance of the driver is shown in Fig. 1, in which R_L is the effective load resistance, and L_{bs} and L_{bg} are the bondwire inductances of the supply and ground respectively. C_d is the on-chip decoupling capacitance. The output impedance of the driver includes the drain inductances (L_{drv1} and L_{drv2}) with parasitic resistances R_{ldrv1} and R_{ldrv2} respectively, and the output capacitances (C_{drv1} and C_{drv2}) of the driver. Other parts of the driver are not shown for simplicity. Figure 2 shows the common-mode equivalent small-signal circuit. The common-mode stability has been analyzed in [5], but without taking into account the cascode transistors or a driver stage. The common-mode equivalent circuit is without the output series resonant paths, as both outputs carry identical signals in common mode. In common mode, the bond-wire inductances L_{bg} and L_{bs} and the decoupling capacitance C_d must be considered.

As proposed in [7], except for exact pole-zero cancellations, all the closed-loop transfer functions at different nodes share the same characteristic equation, which means they have the same poles. So, the need for initial consideration of different observation nodes arises. In this paper, the closed-loop transfer function at node IN is used to an-

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alyze the stability, starting from the matrix equations based on Kirchhoff's current and voltage Laws:

$$Y_{cm} \times V_{cm} = I_{cm} \quad (1)$$

in which, Y_{cm} is the common-mode admittance matrix and V_{cm} represents the common-mode network voltages (at nodes IN, D1, D2, G2, VDD and VSS) corresponding to the common-mode currents injected at the same nodes, defined in I_{cm} . The Y_{cm} is given in (2), in which

$$Y_d = sC_{shunt1} + 1/(sL_{d1}) \quad (3)$$

Consider a unit current entering node IN, I_{cm} and the corresponding V_{cm} can be written as:

$$I_{cm} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad (4)$$

$$V_{cm} = \begin{bmatrix} IN & D1 & D2 & G2 & VDD & VSS \end{bmatrix}^T \quad (5)$$

By solving (1) for I_{cm} and V_{cm} defined in (4) and (5), the common-mode closed-loop transfer function $H_{cl,cm}(s)$ at IN is found as IN (divided by 1A) in V_{cm} , which can be calculated numerically. With the obtained $H_{cl,cm}(s)$, the respective poles and zeros can be easily extracted using math tools, e.g. Matlab in our case. No analytical expressions of poles or zeros are required in this way. The root locus can be simply obtained by sweeping the parameters we want to track.

3. Stabilization Methodology

A typical pole-zero map of the common-mode closed-loop transfer function $H_{cl,cm}$ at IN is shown in Fig. 3 for a typical system. A pair of right-half-plane (RHP) complex-conjugate poles is not shown in Fig. 3 because the absolute value of their imaginary parts is much higher than the characteristic frequency of CMOS (more than 10^{16} Hz in our case). Thus the modeling of these two poles is not accurate, and the poles are neglected. However, there exists another pair of RHP complex-conjugate poles in Fig. 3, which implies common-mode instability. This pair must be moved to the left half plane (LHP).

For the common-mode stability analysis, all the design parameters in the core circuit are not altered because these should be optimized for the differential-mode operation, so only L_{bg} , L_{bs} and C_d are considered here as degrees of freedom. To make the results more clear, only the evolution of

Fig. 3 Pole-zero map of $H_{cl,cm}$ at IN in common mode.

the real part of the RHP poles as a function of L_{bg} , L_{bs} and C_d is shown in Fig. 4(a). As shown in Fig. 4(a), the effect of L_{bg} and L_{bs} on the RHP poles of $H_{cl,cm}$ can be neglected. As C_d increases, the RHP conjugate poles are moving towards the LHP but are still in the RHP. A resistor can be added in series with C_d to move the RHP poles to the LHP. This has been analyzed in detail in [5], and won't be analyzed here. However, adding a resistor in series with C_d degrades the decoupling performance. Here a new method to stabilize the circuit in common mode is proposed, which doesn't degrade the circuit performance. This new method is based on adding a series resistor R_{g2} at the gates of the cascode transistors (M2, M4 in Fig. 1).

Due to the existence of multiple feed-back loops in common mode, it is very difficult to get a simple expression to describe why R_{g2} improves the stability. However, we can simply consider two extreme conditions: R_{g2} being 0 or infinite. Figure 4(b) shows the real part of the RHP poles as a function of L_{drv1} when R_{g2} is 0 and infinite. When R_{g2} is 0, both C_{gs2} and C_{gd2} are shorted to VDD. As shown in Fig. 4(b), the RHP poles always exist. However, when R_{g2} is infinite, the RHP poles are moved to the LHP if L_{drv1} is less than a threshold inductance (0.6 nH in our case). Hence, there is a threshold resistance for R_{g2} that can stabilize the PA if L_{drv1} is small enough.

The evolutions of the RHP pole with positive imaginary part as a function of R_{g2} is shown in Fig. 5 for different L_{drv1} values. The other conjugate pole with negative imag-

Fig. 4 (a) Evolution of the real parts of the RHP poles in $H_{cl,cm}$ as a function of L_{bg} , L_{bs} and C_d ; (b) The real part of the RHP poles as a function of L_{drv1} when R_{g2} is 0 and infinite.

Fig. 5 Evolutions of the RHP pole with positive imaginary part in $H_{cl,cm}$ against R_{g2} for different L_{drv1} values.

$$Y_{cm} = \begin{bmatrix} s(C_{drv1} + C_{gs1}) + sC_{gd1} + \frac{1}{sL_{drv1}} & -sC_{gd1} & 0 & 0 & -\frac{1}{sL_{drv1}} & -s(C_{drv1} + C_{gs1}) \\ g_{m1} - sC_{gd1} & s(C_{gd1} + C_{ds1} + C_{gs2}) + sC_{ds2} + g_{m2} & -sC_{ds2} & -g_{m2} - sC_{gs2} & 0 & -g_{m1} - sC_{ds1} \\ 0 & -g_{m2} - sC_{ds2} & s(C_{ds2} + C_{gd2}) + Y_d & g_{m2} - sC_{gd2} & -Y_d & 0 \\ 0 & -sC_{gs2} & -sC_{gd2} & s(C_{gs2} + C_{gd2}) + \frac{1}{2R_{g2}} & -\frac{1}{2R_{g2}} & 0 \\ -\frac{1}{sL_{drv1}} & 0 & -Y_d & -\frac{1}{2R_{g2}} & \frac{1}{2R_{g2}} + Y_d + \frac{1}{sL_{drv1}} & -\frac{1}{2} sC_d \\ -s(C_{drv1} + C_{gs1}) - g_{m1} & -sC_{ds1} & 0 & 0 & -\frac{1}{2} sC_d & \frac{1}{2} sC_d + g_{m1} + \frac{1}{2sL_{bg}} + s(C_{gs1} + C_{drv1} + C_{ds1}) \end{bmatrix} \quad (2)$$

inary part moves in the same direction. Other poles stay in the LHP when R_{g2} and L_{drv1} are changing. As shown in Fig. 5, the RHP pole moves towards the LHP as R_{g2} increases. The minimum R_{g2} needed to move the RHP pole to the LHP increases as L_{drv1} increases. When L_{drv1} exceeds some threshold, the use of R_{g2} can not move the RHP poles to the LHP anymore. A small L_{drv1} can easily be implemented by using a differential inductor. This will not affect the performance in differential mode while the differential inductance can be set to what is needed. So the use of R_{g2} is quite efficient to stabilize the circuit in common mode when a differential inductor is used in the driver stage. The K factor of a differential inductor can be more than 0.8, which means that the common-mode inductance can be very small. The K factor of the differential inductor in our case is about 0.83. The common-mode inductance is 0.25 nH, while the differential inductance is 2.7 nH. This means the common-mode stability problem can be solved by R_{g2} .

4. Simulation Results

Verification of the stability method was performed on a 2.45 GHz Class-E PA designed in a Silterra 0.18 μm RF CMOS process. Figure 6 shows the simulated and calculated minimum R_{g2} to stabilize the circuit as a function of L_{drv1} for different C_d values. As shown in Fig. 6, the calculation results correspond to the simulation results very well. With increasing C_d , the maximum allowable L_{drv1} that can

be stabilized by R_{g2} is increasing. In our case, when C_d is 100 pF, the maximum L_{drv1} is around 0.4 nH for both simulation and calculation results. This value becomes 0.6 nH for simulation results and 0.75 nH for calculation results when C_d is infinite.

5. Conclusion

This paper proposes a new and practical common-mode stabilization method for a CMOS cascode Class-E PA with driver stage. By adding a resistor at the common-gate node of the cascode transistor, the PA is stabilized in common mode. The simulation results confirm the proposed stabilization method, showing that the proposed method is an effective way for the common-mode stabilization.

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Fig. 6 Simulation and calculation results of the minimum R_{g2} to stabilize the PA as a function of L_{drv1} for different C_d values.