Feedforward Reversed Nested Miller Compensation Techniques for Three-Stage Amplifiers

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Abstract—**Two novel reversed nested Miller Compensation (RNMC) techniques for low-voltage three-stage amplifiers are proposed in this contribution: Nested Feedforward RNMC (NFRNMC) and Crossed Feedforward RNMC (CFRNMC). Both techniques employ double feedforward paths to remove the right-half-plane zero. The second architecture generates a left-half-plane zero to further improve the phase margin. To demonstrate advantages of the new RNMC techniques over the traditional RNMC architecture, two three-stage amplifiers are designed employing the proposed techniques in a standard 0.5μm CMOS process. Simulation results show that, with the same gain-bandwidth product, the NFRNMC and CFRNMC amplifiers have improved stabilities over the conventional RNMC amplifiers by more than 15° and 20° in the phase margin, respectively. They both dissipate less than 0.4 mW of power with a ±1 V supply.**

I. Introduction

Supply voltage of integrated circuits continuously scales down with advanced deep sub-micrometer technologies. Amplifiers increasingly demand low voltage, high gain, and wide output voltage swing capabilities. While traditional cascode topologies are not suitable for low voltage operation due to the large headroom requirement. Cascaded multistage amplifiers become a natural option, and attract more and more attentions. These amplifiers can provide high DC gain and large output swing under low-voltage environments, but demand complex frequency compensation techniques [1-11].

The inner stage of a three-stage amplifier is the only inverting stage, the reversed nested Miller compensation (RNMC) becomes the most suitable option [5-8]. A RNMC amplifier usually has a higher bandwidth than an amplifier with traditional nested Miller compensation, because the inner compensation capacitor does not load the output node [10]. Nevertheless, conventional RNMC amplifiers are not suitable for low-power applications due to the existence of the undesired higher order right-half-plane (RHP) zero which may introduce extra power consumption or cause stability problems. Many RNMC techniques have been reported to cancel the RHP zero [5, 8]. RNMC with voltage buffer and nulling resistor is introduced in [8]. RNMC techniques with voltage follower (VF) and current follower (CF) are proposed in [5-7]. RNMC with CF technique removes all RHP zeros at the cost of extra compensation networks with increased power dissipation. Even though RNMC with VF technique reduces power consumption and silicon area, the RHP zero in the open-loop transfer function complicates the stabilization of the amplifier. Moreover, VF technique may limit the output swing of the amplifier.

In this work, we present two new RNMC topologies employing feedforward paths to cancel the RHP zero, with the advantages of simple architecture, small silicon area, and low power consumption.

II. Brief Review of Conventional RNMC

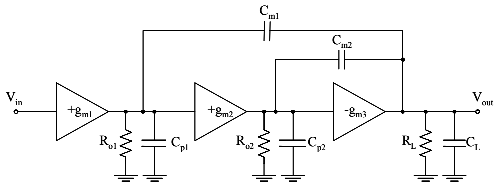
In this section, the conventional RNMC technique is reviewed and compared with the nested Miller compensation (NMC) technique [9,10].

The structures of NMC and RNMC are depicted in Fig. 1. Parameters g_{mi}, R_{oi} and C_{pi} are defined as the transconductance, output resistance, and output parasitic capacitance for the i-th stage, respectively. Moreover, R_L and C_L stand for the equivalent load resistance and capacitance, respectively, and C_{m1} and C_{m2} are the compensation capacitors.

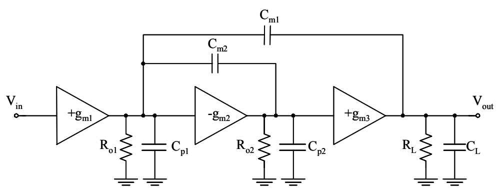
The transfer function for NMC can be expressed as [9]:

$$A_{vNMC}(s)=\frac{g_{m1}g_{m2}g_{m3}R_{o1}R_{o1}R_L}{(1+sC_{m1}g_{m2}g_{m3}R_{o1}R_{o1}R_L)}\cdot \frac{1-s\dfrac{C_{m2}}{g_{m3}}-s^2\dfrac{C_{m1}C_{m2}}{g_{m2}g_{m3}}}{1+s\dfrac{C_{m2}(g_{m3}-g_{m2})}{g_{m2}g_{m3}}+s^2\dfrac{C_LC_{m2}}{g_{m2}g_{m3}}} \approx A_{v0}\frac{1-\dfrac{s}{z_1}-\dfrac{s^2}{z_1z_2}}{1+\dfrac{s}{f_1}+\dfrac{s^2}{f_1f_2}+\dfrac{s^3}{f_1f_2f_3}} \quad (1)$$

Where $f_1 = \frac{g_{m1}}{C_{m1}}, f_2 = \frac{g_{m2}}{C_{m2}}, f_3 = \frac{g_{m3}}{C_L}, z_1 = \frac{g_{m3}}{C_{m2}}$, and $z_2 = \frac{g_{m2}}{C_{m1}}$.



(a)



(b)

Fig. 1. Frequency compensation topologies of (a) NMC, and (b) RNMC.

And the transfer function of RNMC is expressed as [6]:

$$A_{vRNMC}(s) = \frac{g_{m1}g_{m2}g_{m3}R_{o1}R_{o1}R_L}{(1+sC_{m1}g_{m2}g_{m3}R_{o1}R_{o2}R_L)} \cdot \frac{1-s\left(\frac{C_{m2}}{g_{m2}}+\frac{C_{m1}}{g_{m2}g_{m3}R_{o2}}\right)-s^2\frac{C_{m1}C_{m2}}{g_{m2}g_{m3}}}{1+s\left(\frac{C_{m2}C_L}{g_{m3}C_{m1}}-\frac{C_{m2}}{g_{m2}}+\frac{C_{m2}}{g_{m3}}\right)+s^2\frac{C_{m2}C_L}{g_{m2}g_{m3}}} \approx A_{v0}\frac{1-\frac{s}{z_1}-\frac{s^2}{z_1z_2}}{\frac{s}{f_1}+\frac{s^2}{f_1f_2}+\frac{s^3}{f_1f_2f_3}} \tag{2}$$

Where $f_1 = \frac{g_{m1}}{C_{m1}}, f_2 = \frac{g_{m3}}{C_L}\frac{C_{m1}}{C_{m2}}$, and $f_3 = \frac{g_{m2}}{C_{m1}}$.

To stabilize the amplifiers, third-order Butterworth frequency response can be applied to both of NMC and RNMC for arranging the non-dominant poles [10]:

$$f_1 = \frac{1}{2}f_2 = \frac{1}{4}f_3 \tag{3}$$

Then the gain-bandwidth product $GBW = f_1 = \frac{g_{m1}}{C_{m1}}$ and $PM \approx 60^o$.

RNMC is more power efficient than NMC for the same bandwidth. Or in other words, RNMC achieves larger bandwidth than NMC for the same power consumption. In applications with a large capacitive load, C_L>>C_{m1} and C_L>>C_{m2}. In Eq. (1), g_{m3} of NMC should be extremely large for a large enough f_3 to satisfy Eq. (3), thus the third stage will be the dominant factor on power consumption. While g_{m3} in RNMC is reduced by a factor of 2 compared to that in NMC if $C_{m1}=C_{m2}$, and can be further minimized by reducing C_{m1} / C_{m2}. Thus a substantial reduction on the power consumption can be achieved. This advantage comes from the fact that C_{m2} in RNMC does not load the output mode directly.

In the previous discussions, the effects of the zeros are neglected due to the large value of g_{m3}. However, in the low power context, this can not generally be assumed. Extra techniques are necessary to remove the RHP zero(s) in RNMC.

III. PROPOSED RNMC STRATEGIES

Adding intended feedforward stages to the amplifiers is a good method to remove the RHP zeros [1-4, 9, 11]. The signals through the feedforward stages and the ones through the Miller capacitors can cancel out each other.

In this section, two new RNMC techniques, Nested Feedforward RNMC (NFRNMC) and Crossed Feedforward RNMC (CFRNMC), will be proposed respectively.

A. Nested Feedforward RNMC (NFRNMC)

The NFRNMC structure is shown in Fig. 2(a). Two nested feedforward paths, g_{mf1} from the input to the output, and g_{mf2} from the output of the first stage to the output, are incorporated into the conventional RNMC. These two paths are nested with each other, and hence the name of the technique.

In order to realize the RHP zero cancellation, the feedforward stages should satisfy $g_{mf1}=g_{m1}$, $g_{mf2}=g_{m3}-g_{m2}$.

Assume parasitic capacitances C_{pi} can be neglected, and the gain of each stage is much larger than unity, the transfer function of NFRNMC can be expressed by:

$$A(s) = \frac{A_{v0}}{\left(1+\frac{s}{p_{-3dB}}\right)\left(1+s\frac{C_{m2}C_L}{C_{m1}g_{m3}}+s^2\frac{C_{m2}C_L}{g_{m2}g_{m3}}\right)} \approx A_{v0}\frac{1}{s\frac{C_{m1}}{g_{m1}}+s^2\frac{C_{m2}C_L}{g_{m1}g_{m3}}+s^3\frac{C_{m1}C_{m2}C_L}{g_{m1}g_{m2}g_{m3}}} = A_{v0}\frac{1}{\frac{s}{f_1}+\frac{s^2}{f_1f_2}+\frac{s^3}{f_1f_2f_3}} \tag{4}$$

where $f_1 = \frac{g_{m1}}{C_{m1}}$, $f_2 = \frac{g_{m3}}{C_L}\frac{C_{m1}}{C_{m2}}$, $f_3 = \frac{g_{m2}}{C_{m1}}$.

The DC gain is $A_{v0} = g_{m1}g_{m2}g_{m3}R_{o1}R_{o2}R_L$, the dominant pole $p_{-3dB} = \dfrac{1}{R_{o1}C_{m1}(g_{m2}g_{m3}R_{o2}R_L)}$, $GBW = A_{dc}\cdot p_{-3dB} = \dfrac{g_{m1}}{C_{m1}}$. The third-order Butterworth function is still effective to arrange the non-dominant poles, so $GBW = f_1 = \dfrac{1}{2}f_2 = \dfrac{1}{4}f_3$. Since there is no RHP zero in (4), the phase margin will be improved compared to the conventional RNMC technique without compromising on power and GBW.

B. Crossed Feedforward RNMC (CFRNMC)

The structure of CFRNMC is shown in Fig. 2(b). The feedforward stage g_{mf1} is connected from the input to the output of the second stage instead of the output of the whole amplifier, and is crossed with feedforward stage g_{mf2} which bypasses the second and third stages. In CFRNMC, a left-half-plane (LHP) zero is generated intently to improve the phase margin further. The two feedforward stages should satisfy $g_{mf1}=g_{m1}$, $g_{mf2}=g_{m3}$. Based on the same assumptions as for the NFRNMC, the transfer function of the CFRNMC is given by:

$$\begin{aligned} A(s) &= \frac{A_{v0}\left(1+s\dfrac{C_{m1}}{g_{m2}}\right)}{\left(1+\dfrac{s}{p_{-3dB}}\right)\left(1+s\dfrac{C_{m2}(C_{m1}+C_L)}{C_{m1}g_{m3}}+s^2\dfrac{C_{m2}C_L}{g_{m2}g_{m3}}\right)} \\ &\approx A_{v0}\frac{1+s\dfrac{C_{m1}}{g_{m2}}}{1+s\dfrac{C_{m1}}{g_{m1}}+s^2\dfrac{C_{m2}(C_{m1}+C_L)}{g_{m1}g_{m3}}+s^3\dfrac{C_{m1}C_{m2}C_L}{g_{m1}g_{m2}g_{m3}}} \\ &= A_{v0}\frac{1+s/z}{1+\dfrac{s}{f_1}+\dfrac{s^2}{f_1f_2}+\dfrac{s^3}{f_1f_2f_3}} \end{aligned} \tag{5}$$

where $f_1 = \dfrac{g_{m1}}{C_{m1}}$, $f_2 = \dfrac{g_{m3}}{(C_L+C_{m1})}\dfrac{C_{m1}}{C_{m2}}$, $f_3 = \dfrac{g_{m2}}{C_{m1}}\dfrac{C_L+C_{m1}}{C_L}$, and $z = \dfrac{g_{m2}}{C_{m1}}$.

The denominators of (4) and (5) are identical to each other, so NFRNMC and CFRNMC have similar dominant pole, GBW and cut-off frequencies. The difference is on the nominator. The RHP zero in CFRNMC is also removed, and a LHP zero $z_{LHP} = g_{m2}/C_{m3}$ is generated. Since the CFRNMC has larger phase margin than NFRNMC under the same GBW, to achieve the same phase margin as the NFRNMC, CFRNMC can use smaller compensation capacitor and hence achieve a larger bandwidth.

Compared with the SMFFC amplifier in [11], our *CFRNMC* does not have the 2nd order zero in the transfer function, with the cost of a lower f_3.

IV. SIMULATION RESULTS

To verify the proposed compensation techniques, simulations were carried out using a standard 0.5μm CMOS technology. The simplified schematics of the NFRNMC and CFRNMC amplifiers are shown in Fig. 3.

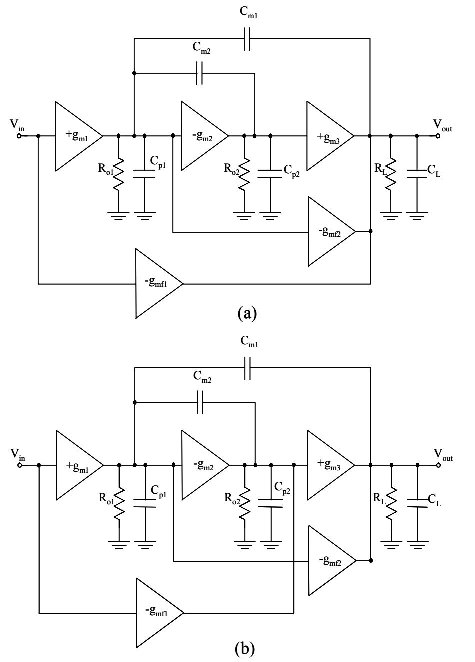


Fig. 2. Structures of (a) NFRNMC, (b) CFRNMC.

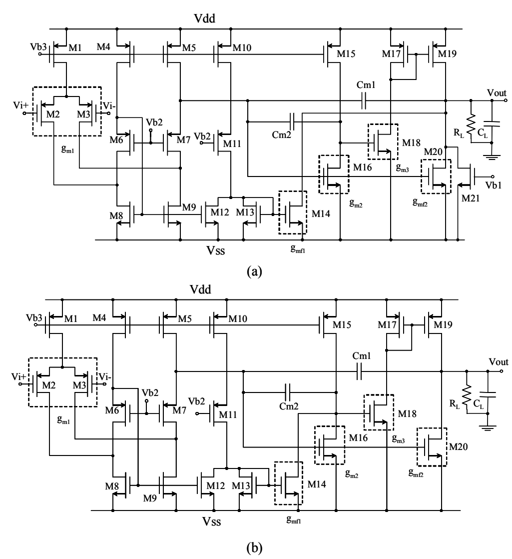


Fig. 3. Simplified schematics of, (a) the NFRNMC amplifier, (b) the CFRNMC amplifier.

Fig. 4 shows the magnitudes and phases of the proposed NFRNMC and CFRNMC amplifiers along with a conventional RNMC amplifier. As can be seen from the figure, the NFRNMC and CFRNMC amplifiers achieve a phase margin (PM) of 66° and 71°, respectively. In order to appreciate the effects of the proposed compensation techniques on the PM, we also simulate the same GBW by removing the feedforward paths. It is obvious that the phase margin is greatly reduced

Transistor (s)	NFRNMC	CFRNMC
M1	2×(12u/1.8u)	2×(12u/1.8u)
M2 M3	8×(12u/0.6u)	8×(12u/0.6u)
M4 M5	1×(16.8u/1.8u)	1×(16.8u/1.8u)
M6 M7	4×(7.5u/1.2u)	4×(7.5u/1.2u)
M8 M9 M12 M13	1×(10.5u/1.2u)	1×(10.5u/1.2u)
M10	4×(14.4u/1.8u)	4×(14.4u/1.8u)
M11	10×(16.05u/1.2u)	10×(16.05u/1.2u)
M14	2×(10.5u/1.2u)	2×(10.5u/1.2u)
M15	10×(9.3u/1.8u)	10×(14.7u/1.8u)
M16	4×(9u/1.2u)	4×(9u/1.2u)
M17 M18	1×(9u/0.9u)	1×(9u/0.9u)
M19 M20	3×(9u/0.9u)	3×(9u/0.9u)
M21	-	3×(9u/0.9u)

Table I. Transistor aspect ratios of NFRNMC amplifier and CFRNMC amplifier.

Specification	RNMC	NFRNMC	CFRNMC
Loading capacitance (pF)	120		
Loading resistance (kΩ)	25		
DC power consumption (mW)	0.33	0.36	0.40
Gain-bandwidth product (MHz)	2.5		
Phase margin (degree)	<50	66	71
DC gain (dB)	>100	>100	>100
C_{m1} (pF)	7		
C_{m2} (pF)	1		

Table II. Comparison of simulated performance for RNMC, NFRNMC and CFRNMC amplifiers.

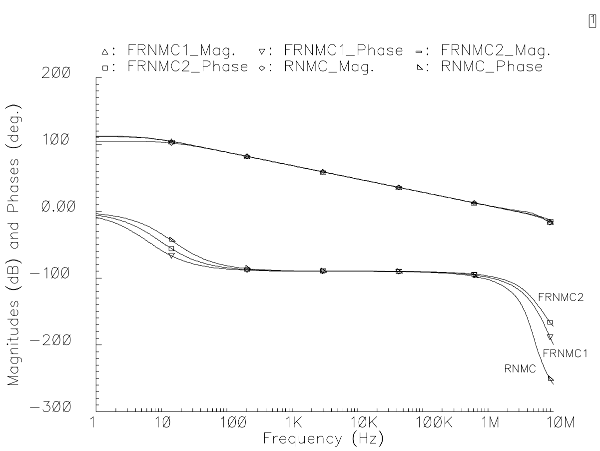


Fig. 4. Comparison of frequency responses (Here FRNMC1 and FRNMC2 stand for NFRNMC and CFRNMC, respectively).

Finally, in Table II, we give a brief simulated results comparison of the conventional and proposed RNMC mplifiers (Fig. 3). We can conclude, from the table, that the proposed RNMC techniques lead to larger phase margin and hence better stability of the amplifiers than the conventional RNMC under the same GBW without much sacrifice on the power consumption. The proposed amplifiers are currently being fabricated and we will present measurement results in the future.

V. CONCLUSION

Feedforward paths are used in the proposed NFRNMC and CFRNMC techniques to realize the RHP zero cancellation. Simulation results are given to confirm the advantages of the proposed RNMC techniques. The use of the new techniques preserves the amplifier's output swing and allows higher phase margin.

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