Three-stage Amplifier Adopting Dual-miller with Nulling-resistor and Dual-feedforward Techniques

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Abstract
A high-gain wide-bandwidth three-stage amplifier, which employs dual-miller compensation with nulling-resistor and dual-feedforward compensation (DMCNR-DFC), is designed and analyzed in this paper. By adopting the technique of DMCNR-DFC, the designed three-stage amplifier achieves well performance including gain-bandwidth product (GBW) and slew rate (SR). The improved DMCNR-DFC three-stage amplifier is designed and simulated in 0.35μm BCD process. Simulation results show that DMCNR-DFC three-stage amplifier achieves a dc gain of about 121.1dB and GBW of about 6.1MHz with 52º phase margin using a 5-V power supply voltage.

Keywords: dual-miller compensation with nulling-resistor, dual-feedforward compensation, three-stage amplifier

1. Introduction
The operational amplifier is a fundamental building block in the analog integrated systems and mixed-signal systems [1-4]. With the development of modern CMOS technology, the channel lengths and supply voltages of MOSFET transistors are scaling down, and conventional single-stage cascode amplifiers are not suitable for obtaining high dc gain and large output-swing simultaneously. In fact, the topology of three-stage amplifier is a good trade off between dc gain, bandwidth and power consumptions. However, three-stage amplifiers suffer from the close-loop stability problem because they have multiple-poles and zeros. Therefore, the frequency compensation technique should be analyzed and discussed to improve the stability of three-stage amplifier system.

In the recent past many years, many frequency compensation techniques of three-stage amplifiers have been reported [5-16]. For the architecture of three-stage amplifier, the nested Miller compensation (NMC), which can provide a well stability, is a well-known compensation technique [9]. However, the NMC three-stage amplifier suffers from enormous power consumption and gain-bandwidth limitation when the number of gain stages increases, and which has a right half plane (RHP) zero. Moreover, the gain-bandwidth production of NMC three-stage amplifier is only one quarter of that of a single-stage amplifier [10]. Based on NMC, many compensation topologies have been reported to improve the bandwidth and the stability of three-stage amplifier, such as nested Gm-C compensation (NGCC) [11], active feedback frequency compensation (AFFC) [12], dual active-capacitor active-feedback compensation (DACFC) [13], impedance adapting compensation (IAC) [14], cross feedforward cascade compensation (CFCC) [7], current buffer Miller compensation (CBMC) [6], AC boosting compensation (ACBC) [15], reverse nested Miller compensation (RNMC) [16], and single-Miller capacitor feedforward frequency compensation (SMFFC) [8], and so on. In general, these compensation techniques based on NMC achieve well performance. However, the frequency compensation technique must still be discussed and analyzed to further improve the performance of three-stage amplifier.

In this paper, a three-stage amplifier, which adopts dual-miller compensation with nulling-resistor and dual-feedforward compensation (DMCNR-DFC), is designed and analyzed.
Section 2 will discuss the conventional NMC three-stage amplifier. The improved DMCNR-DFC three-stage amplifier will be analyzed and designed in Section 3. Section 4 will give the simulation results of three-stage amplifier. Finally, conclusions are given in Section 5.

2. Analysis of Conventional NMC Three-stage Amplifier

Figure 1 shows the topology of NMC three-stage amplifier [10]. \( A_{v1}, A_{v2} \) and \( A_{v3} \) form the basic three-stage amplifier, and their transconductances are expressed by \( g_{m1}, g_{m2} \) and \( g_{m3} \) respectively. \( C_{m1} \) and \( C_{m2} \) are the compensation capacitor, and \( R_{L} \) and \( C_{L} \) are, respectively, load-resistor and load-capacitor. \( r_{o1(2)} \) and \( C_{o1(2)} \) are the equivalent output resistance and the lumped capacitance respectively. Figure 2 is the transistor-level circuit of NMC three-stage amplifier. The first-stage, second-stage and last-stage of NMC three-stage amplifier are made up of transistors \( M_1-M_9, M_{10}-M_{13} \) and \( M_{14}-M_{15} \) respectively.

As reported in [10], it is assumed that \( g_{m1}r_{o1(i)}>>1, C_{m1}>>C_{o1}, C_{L}>>C_{m1} \) and \( g_{m3}R_{L}>>1, \) here \( i=1, 2 \). Besides, with an additional condition that \( g_{m3}>>g_{m1(2)} \), the open-loop small-signal transfer function of NMC three-stage amplifier, which is reported in reference [10], can be expressed as:

\[
A_{vNMC}(s) = \frac{g_{m1}g_{m2}g_{m3}r_{o1}r_{o2}R_{L} \left( 1 - \frac{C_{m2}}{g_{m3}} s - \frac{C_{m1}C_{m2}}{g_{m2}g_{m3}} s^2 \right)}{\left( 1 + g_{m2}g_{m3}r_{o1}r_{o2}R_{L}C_{m3}s \right) \left[ 1 + s \frac{C_{m2} \left( g_{m1} - g_{m2} \right)}{g_{m2}g_{m3}} + \frac{C_{m1}C_{m2}}{g_{m2}g_{m3}} s^2 \right]} \quad (1)
\]

As analyzed in reference [10], it is assumed that \( C_{m1}=4(g_{m1}/g_{m3})C_{L} \) and \( C_{m2}=2(g_{m2}/g_{m3})C_{L} \), and the gain-bandwidth product (GBW) of NMC three-stage amplifier can be given by:

\[
GBW = \frac{1}{4} \left( \frac{g_{m3}}{C_{L}} \right) \quad (2)
\]

Equation (1) and Equation (2) indicate that NMC three-stage amplifier has one-fourth GBW of single-stage amplifier and has a RHP zero. The RHP zero degrades the stability significantly. To further improve GBW and stability of three-stage amplifier, an improved topology of three-stage amplifier, which adopts dual-miller compensation with nulling-resistor and dual-feedforward compensation (DMCNR-DFC), is analyzed and designed in section 3.

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**Figure 1. Topology of NMC Three-stage Amplifier**
3. Analysis and Design of Improved DMCNR-DFC Three-stage Amplifier

The topology of improved DMCNR-DFC three-stage amplifier, which adopts dual-miller compensation with nulling-resistor and dual-feedforward compensation, is shown in Figure 3. The dc gain of DMCNR-DFC three-stage amplifier is realized by cascading gain stages $A_v1$, $A_v2$ and $A_v3$. $A_v1$ is a high gain stage, $A_v2$ is high-gain and wide-output-swing second-stage, and $A_v3$ is the last stage with wide-output-swing. $A_vf$ and $A_vf$ form, respectively, a feedforward stage. $R_{m1}$-$C_{m1}$ and $R_{m2}$-$C_{m2}$ form, respectively, miller compensation with nulling-resistor. $A_{vA}$-$A_{vF}$ and $A_{vA}$-$A_{vF}$ form the push-pull second-stage and the push-pull output stage of three-stage amplifier respectively, so DMCNR-DFC three-stage amplifier has an improvement transient response.

3.1 Transfer Function and Stability Analysis of DMCNR-DFC Three-stage Amplifier

As shown in Figure 3, $g_{m1}$, $g_{m2}$ and $g_{m3}$ are, respectively, the transconductances of the first-stage, second-stage and last-stage of DMCNR-DFC three-stage amplifier. $r_{o(1,2)}$ and $C_{o(1,2)}$ are the equivalent output resistances and lumped parasitic capacitance of gain stages respectively, and $R_L$ and $C_L$ are, respectively, the loading resistor and loading capacitor. $g_{mf}$ and $g_{mf}$ are the equivalent transconductances of feedforward stage $A_{vA}$ and $A_{vF}$ respectively. To analyze the stability of DMCNR-DFC three-stage amplifier in this paper, the open-loop transfer function can be obtained by analyzing the equivalent small-signal topology as shown in Figure 3. At the same time, to simplify the transfer function without losing accuracy with the goal of...
providing a clearer insight to the DMCNR-DFC three-stage amplifier, the following assumptions are reasonably made.

1. The loading capacitor $C_L$ is much greater than the compensation capacitors $C_{m(1,2)}$, i.e. $C_L >> C_{m(1,2)}$.
2. The compensation capacitors $C_{m(1,2)}$ and the loading capacitor $C_L$ are much greater than the lumped output capacitors of each stage, i.e. $C_{m(1,2)}$ and $C_L >> C_{o(1,2)}$.
3. The compensation capacitors $C_{m(1,2)}$ have equivalent capacitance, i.e. $C_{m1} = C_{m2}$.
4. The dc gains of all stage are much greater than 1, i.e. $g_{m1}r_{o1}$, $g_{m2}r_{o2}$ and $g_{m3}R_L >> 1$.
5. The output resistance of all stage are much greater than resistors $R_{m(1,2)}$, i.e. $r_{o(1,2)}$ and $R_L >> R_{m(1,2)}$.
6. To have a symmetrical push-pull output stage, the transconductances $g_m$ and $g_{mf}$ are equal, i.e. $g_m = g_{mf}$.

Based on those assumptions, the open-loop small-signal transfer function of DMCNR-DFC three-stage amplifier can be given as:

\[
A_c(s) = \frac{A_{dc}}{1 + \frac{s}{z_{LHP1}} \left( 1 + \frac{s}{z_{LHP2}} \left( 1 + \frac{s}{z_{LHP3}} \right) \right) \left( 1 + \frac{s}{p_{-3dB}} \right) \left( 1 + \frac{s}{p_{nd1}} \right) \left( 1 + \frac{s}{p_{nd2}} \right) \left( 1 + \frac{s}{p_{nd3}} \right) \left( 1 + \frac{s}{p_{nd4}} \right)}
\]  
(3)

\[
A_{dc} = g_{m1}g_{m2}g_{m3}r_{o1}r_{o2}R_L
\]  
(4)

\[
z_{LHP1} = \frac{1}{C_{m2} \left( R_{m2} + R_{m1} \right) - 1/g_{m3}}
\]  
(5)

\[
z_{LHP2} = \frac{g_{m3} \left( R_{m2} + R_{m1} \right) - 1}{R_{m1}C_{m1} \left( g_{m3}R_{m2} - 1 \right)}
\]  
(6)

\[
z_{LHP3} \approx \frac{g_{m1}g_{m2} \left( R_{m2} - 1/g_{m3} \right)}{R_{m2} \left( g_{m2}C_{o2} + g_{m1}C_{o2} \right)}
\]  
(7)

\[
p_{-3dB} = \frac{1}{g_{m3}g_{m2}r_{o2}r_{o1}R_mC_{m1}}
\]  
(8)

\[
p_{nd1} = \frac{1}{R_{m2}C_{m2}}
\]  
(9)

\[
p_{nd2} = \frac{g_{m2}R_{m2}}{R_{m2}C_{o2} + R_{m1}C_{o1}}
\]  
(10)

\[
p_{nd3} = \frac{g_{m1}}{C_L}
\]  
(11)

\[
p_{nd4} = \frac{1}{(R_{m1}C_{o1})/\left( R_{m2}C_{o2} \right)}
\]  
(12)

\[
GBW = A_{dc} \times p_{-3dB} = \frac{g_{m1}}{C_{m1}}
\]  
(13)
In this topology as shown in Figure 3, $R_{m1} \gg 1/gm3$, so it is concluded that $z_{LHP1} < p_{nd1}$. The zero $z_{LHP1}$ can cancel the pole $p_{nd1}$. $R_{m1}$ and $R_{m2}$ are in an order of magnitude, and $C_{m(1,2)}$ and $C_{m(1,2)}$ are the lumped capacitance and compensation capacitance respectively. Based on the above assumption, the relation of zero $z_{LHP2}$ and pole $p_{nd2}$ can be obtained as:

$$z_{LHP2} = \frac{gm3 (R_{m2} + R_{m1}) - 1}{R_{m1}C_{m1} (gm3R_{m2} - 1)} < p_{nd2} = \frac{gm3R_{m2}}{R_{m2}C_{o2} + R_{m1}C_{m1}} \quad (14)$$

Equation (14) shows that the zero $z_{LHP2}$ can cancel the pole $p_{nd2}$. At the same time, $C_{m(1,2)}$ are the lumped capacitance, so the zero $z_{LHP3}$ and the pole $p_{nd4}$ can be pushed to a frequency that are higher than the unity-gain frequency (UGF). So, Equation (3) can be approximated as:

$$A_v(s) \approx \frac{A_{dc}}{1 + \frac{s}{p_{3db}}} \left(1 + \frac{s}{p_{nd3}}\right) \quad (15)$$

Equation (15) indicates that DMCNR-DFC three-stage amplifier is approximated to a system with two poles. Therefore, phase margin (PM) of DMCNR-DFC three-stage amplifier can be approximately written as:

$$PM \approx 90 - \arctan\left(\frac{GBW}{p_{nd3}}\right) \quad (16)$$

To ensure the stability of a unity-gain feedback system, three-stage amplifier should have a phase margin of at least 45º and 60º preferable in most situations. Therefore, pole $p_{nd3}$ should be larger than GBW, and GBW of DMCNR-DFC three-stage amplifier can be written as:

$$GBW = \frac{gm1}{C_{m1}} \leq p_{nd3} = \frac{gm3}{C_L} \quad (17)$$

According to the above analysis, by adopting the DMCNR-DFC technique, the designed DMCNR-DFC three-stage amplifier achieves wider GBW than the conventional NMC three-stage amplifier for a given load capacitance $C_L$.

### 3.2. Transistor-level Circuit of DMCNR-DFC Three-stage Amplifier

![Figure 4. Transistor-level Circuit of DMCNR-DFC Three-stage Amplifier](image-url)
The transistor-level circuit of DMCNR-DFC three-stage amplifier is shown in Figure 4. Transistors M₁~M₉ form the first gain stage Aᵥ₁, and transistors M₁₀~M₁₃ form the second gain stage Aᵥ₂. Aᵥ₃ is made up of transistor M₁₄. M₁₅ forms the feedforward stage Aᵥ₃. and Aᵥ₃ and Aᵥf form the push-pull output-stage. Feedforward stage Aᵥ₃ is made up of transistors M₁~M₉ and transistor M₁₃. At the same time, Aᵥ₃ and Aᵥ₃ form the push-pull stage at the output of the second gain stage Aᵥ₂. Those two push-pull output stages can effectively improve the slew-rate of DMCNR-DFC three-stage amplifier. Rₘ₁•Cₘ₁ and Rₘ₂•Cₘ₂ form the compensation network respectively.

4. Simulation Results
To verify the circuit of DMCNR-DFC three-stage amplifier shown in Figure 4, NMC and DMCNR-DFC three-stage amplifier are both designed and simulated in 0.35μm BCD technology with a 5-V power supply voltage.

The simulated open-loop frequency response of NMC three-stage amplifier and DMCNR-DFC three-stage amplifier are, respectively, shown in Figure 5 and Figure 6 under 100-pF load capacitor and 25-kΩ load resistor. The NMC three-stage amplifier achieves the dc gain of 121.2dB, phase margin of 54.4º and GBW of about 1.84MHz, but DMCNR-DFC three-stage amplifier achieves the dc gain of 121.2dB, phase margin of 52º and GBW of about 6.1MHz. Simulation results show that DMCNR-DFC three-stage amplifier achieves wider GBW than NMC three-stage amplifier.

![Figure 5. Open-loop Frequency Response of NMC Three-stage Amplifier](image)

![Figure 6. Open-loop Frequency Response of DMCNR-DFC Three-stage Amplifier](image)

![Figure 7. Transient response of NMC three-stage amplifier](image)

![Figure 8. Transient response of DMCNR-DFC three-stage amplifier](image)
Figure 7 and Figure 8 show, respectively, the simulated transient response of NMC three-stage amplifier and DMCNR-DFC three-stage amplifier in a unity-gain negative feedback configuration to a 125-kHz 1-Vpp pulsing input signal. NMC three-stage amplifier achieves positive slew rate (SR\(^+\)) of 1.43 V/\(\mu\)s and negative slew rate (SR\(^-\)) of 1.39 V/\(\mu\)s. And DMCNR-DFC three-stage amplifier achieves SR\(^+\) of 6.3V/\(\mu\)s and SR\(^-\) of 6.32V/\(\mu\)s. Simulation results show that DMCNR-DFC three-stage amplifier achieves well SR than NMC three-stage amplifier. Finally, performance summary of NMC three-stage amplifier and DMCNR-DFC three-stage amplifier are given in Table 1. From Table 1, the DMCNR-DFC three-stage amplifier achieves a well performance.

<table>
<thead>
<tr>
<th>Table 1. Performance Summary of Three-stage Amplifier</th>
</tr>
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<tbody>
<tr>
<td>Ref. [8] Ref. [14] NMC three-stage amplifier in this paper DMCNR-DFC three-stage amplifier in this paper</td>
</tr>
<tr>
<td>Process</td>
</tr>
<tr>
<td>Supply voltage (V)</td>
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<tr>
<td>Loading Capacitive (pF)</td>
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<tr>
<td>(I_{dd}) (mA)</td>
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<tr>
<td>(A_{in}) (dB)</td>
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<tr>
<td>GBW (MHz)</td>
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<tr>
<td>Phase margin</td>
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<tr>
<td>Average SR (V/(\mu)s)</td>
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</tbody>
</table>

5. Conclusion

A DMCNR-DFC three-stage amplifier, which adopts dual-miller compensation with nulling-resistor and dual-feedforward technique, has been designed and analyzed in this paper. By adopting the dual-miller compensation with nulling-resistor and dual-feedforward technique, the RHP zero can be removed, and the designed DMCNR-DFC three-stage amplifier achieves wider GBW and well SR than NMC three-stage amplifier. Simulation results show that DMCNR-DFC three-stage amplifier achieves well small-signal and large-signal performances.

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