Modified Current-reuse OTA to Achieve High CMRR by utilizing Cross-coupled Load

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***Abstract*—Since biomedical signals have very low amplitude and high common-mode like environmental noise, the amplifiers used with these signals should have high CMRR. The cross-coupled amplifier attenuates common-mode signal strongly because of its load behavior for differential and common-mode signal which leads to high CMRR. Since cross-coupled amplifier differential gain is low, its load is combined with current-reuse operational amplifier. The final CMRR of a fully differential current-reuse OTA with conventional common-mode feedback and modified load is simulated and compared in a 0.18 μm CMOS technology. Their CMRR is simulated for mismatch and process variation. According to the simulation, for the same power consumption, W and L, the modified current-reuse with cross-coupled load has the best performance. Its CMRR in the worst case was about 90 dB while the total power consumption was 18 μW at 1.8 V supply voltage. The Bandwidth is 4.8 kHz and the total input referred noise in this bandwidth is $1.04\ \mu V_{rms}$ and $0.43\ \mu V_{rms}$ from 0.5 to 100 Hz which is acceptable noise and bandwidth for the EEG application considered in this study.**

***Index Terms*—Instrumentation amplifier, High CMRR, Cross-coupled OTA, Current-reuse OTA.**

I. INTRODUCTION

Operational amplifiers (OPAMPs) are designed to achieve high CMRR (common mode rejection ratio) while mismatch limits their performance. Specially for CMOS operational amplifier this restriction will be seen easier in comparison with bipolar operational amplifier [1]. As most of the conventional amplifiers utilize CMOS technologies, they have lower CMRR than bipolar ones. The necessity of high CMRR amplifier becomes more stringent when the input signal is much smaller than common-mode signal like power line noise.

In the recent decades, the importance of EEG (Electroencephalography) signals has increased significantly due to their use in different fields [2], [3]. While wet electrodes don't work well for prolonged time monitoring, dry electrodes offer a promising alternative [4]. Although dry electrodes brings higher user comfort, they have higher skin-to-electrode impedance. In conjunction with this and in order to achieve lower signal attenuation, it will be beneficial to have a higher input impedance value in the amplifiers. This means that the input node of the amplifier will have very high impedance (about $1M\Omega$ [5] in low frequencies). High impedance node will behave like an antenna and absorb power line noise. This signal is a common-mode signal. Biomedical signals, particularly brain signals, have typically very low amplitude, that will need high CMRR amplifiers to amplify the signals accurately [6].

Normally, the gain of the amplifier is considerably high. Thus, circuit designers use feedback to control the gain which consequently destroys the CMRR due to the unbalanced feedback network. Therefore, they use instrumentation amplifiers to achieve both accurate gain and CMRR [7]. But in comparison with a single operational amplifiers, they are difficult to design and implement.

The three-OPAMP instrumentation amplifier is one of the structures which is used to achieve high CMRR. In this structure, three OPAMPs are used with seven resistors. The final CMRR will be depended on resistors value accuracies. Most of the resistors of typical integrated circuits technologies are not very accurate. The more accurate resistors consume considerably high area in comparison with single transistors. Another disadvantage of this technique is that their common-mode range does not include neither positive supply nor negative supply. In addition, they should have three amplifiers which means they consume much power.

The current-feedback instrumentation amplifier is another structure which is used to achieve high CMRR. Like the three-OPAMP instrumentation amplifier, it has three operational amplifiers and a feedback network which consists of two resistors. The output voltage is being converted to current which is insensitive to the common-mode voltage. Then, it will be fed back to the input. In this situation the CMRR does not depend on the matching of the main elements and it's related to the matching of G_m and some parasitic conductances. That's why, this structure has relatively high CMRR. But the input noise will be increased because of the feedback network. Furthermore, the power consumption is still high due to the use of three amplifiers.

Auto-zero and chopping techniques are other techniques which will lead to a high CMRR [7], [8] because they reduce offset of the main amplifier. In addition, they will help to reduce flicker noise which is dominant for biomedical amplifiers. All of these techniques are complex and thereby difficult to implement.

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In the next section, first the definition of CMRR and the most important parameters which impact on CMRR will be presented and discussed. Then, according to the detailed equation of CMRR, the CMRR of a cross-coupled amplifier is investigated and it is tested in a CMOS $0.18\mu m$ CMOS technology. It will be shown that the different behavior of the load of cross-coupled amplifier causes different impedance in common-mode and differential mode. Since the impedance in common-mode is considerably lower than in differential mode, the final common-mode signal attenuation will be much greater than in conventional structures. It is shown that this different behavior might lead to an increased CMRR of different fully differential structures. To demonstrate this, a fully differential current-reuse amplifier with modified load is designed which leads to higher CMRR than conventional one with common-mode feedback. The current-reuse is chosen to achieve lower thermal noise [9] and it will have high CMRR. This highly precise operational amplifier will be suitable for biomedical applications particularly for EEG amplifiers.

II. CMRR AND AFFECTING PARAMETERS

The gain of the amplifier is being calculated according to (1), where differential-to-differential gain A_{dd} and differential-to-common-mode gain A_{dc} are defined as (2) and (3), respectively. v_{id} and v_{ic} are differential mode and common-mode input, respectively and v_{od} is shown in Fig. 1. Finally, the CMRR is ideally equal to infinite and is calculated according to (4).

$$v_{od} = A_{dd}\, v_{id} + A_{dc} v_{ic} \tag{1}$$

$$A_{dd} = \left.\frac{v_{od}}{v_{id}}\right|_{v_{ic}=0} = g_m R_L \tag{2}$$

$$A_{dc} = \left.\frac{v_{od}}{v_{ic}}\right|_{v_{id}=0} \approx 0 \tag{3}$$

$$CMRR = \frac{A_{dd}}{A_{dc}} = A_{dd}(dB) - A_{dc}(dB) \tag{4}$$

Due to the mismatch the output voltages are not ideally same which means their A_{dc} is not zero anymore and is equal to (5). Therefore, the CMRR will be limited to a specific value. For example for Fig. 2 if there is just a mismatch between resistor loads, the CMRR is given by (6). It means in order to achieve high CMRR, one should have high R_L for differential mode, high R_B , high g_m and low ΔR_L for common-mode.

$$A_{dc} = \frac{\Delta R_L}{2R_B} \tag{5}$$

$$CMRR = \frac{A_{dd}}{A_{dc}} = \frac{g_m R_L}{\Delta R_L / 2R_B} = \frac{2 g_m R_B}{\Delta R_L / R_L} \tag{6}$$

The parameters which might have mismatch are not only limited to the load. Threshold voltage, $\mu_{n,p} C_{ox}$ and even W/L will have mismatch in implementation. By considering the mismatch of all these parameters, the CMRR equation should be modified as (7) [1].

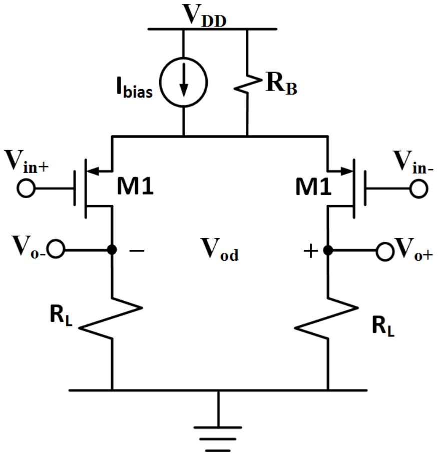

Fig. 1. A typical operational amplifier

$$CMRR = \frac{2 g_m R_B}{\frac{2\Delta V_T}{V_{GS}-V_T} + \frac{\Delta R_L}{R_L} + \frac{\Delta \mu_{n,p} C_{ox}}{\mu_{n,p} C_{ox}} + \frac{\Delta W/L}{W/L}} \tag{7}$$

Although $\mu_{n,p} C_{ox}$ variation is undeniable, the threshold voltage effect can be reduced by biasing the transistors in the sub-threshold region. In addition, the W/L variation effect can be minimized by choosing large W and L (not W/L) which are essential in order to have minimum flicker noise in biomedical amplifiers [10]. In this article, we have focused on how to reduce the effect of $\Delta R_L / R_L$.

III. CROSS-COUPLED AMPLIFIER LOAD ANALYSIS

The differential gain of the cross-coupled amplifier is very sensitive to device mismatch. This sensitivity can be seen in the output impedance. The differential gain and the output impedance can be written as (8) and (9):

$$A_{dd} = -g_{m1} R_{out,d} \tag{8}$$

$$R_{out,\ d,\ max} = r_{o1} \parallel r_{o2} \parallel r_{o3} \parallel 1/g_{m3} \parallel -1/g_{m2} \tag{9}$$

Ideally, by choosing equal $(W/L)_2$ and $(W/L)_3$, the gain will have its maximum value which is because of maximum output impedance. The maximum achievable output impedance is shown in (10). Considering the mismatch, the gain will be controlled with mismatch between g_{m3} and g_{m2} and this mismatch will lead to a change in the positive and negative output nodes which can destroy circuit operation when used in a feedback configuration. In order to have fixed positive and negative output nodes, the $(W/L)_2$ and $(W/L)_3$ should be different. In this case, assume that $1/g_{m2} - 1/g_{m3}$ is dominant in (9). Then, the output impedance and gain will be according to (11) and (12), respectively. In order to minimize the g_m variation, the output transistors should be

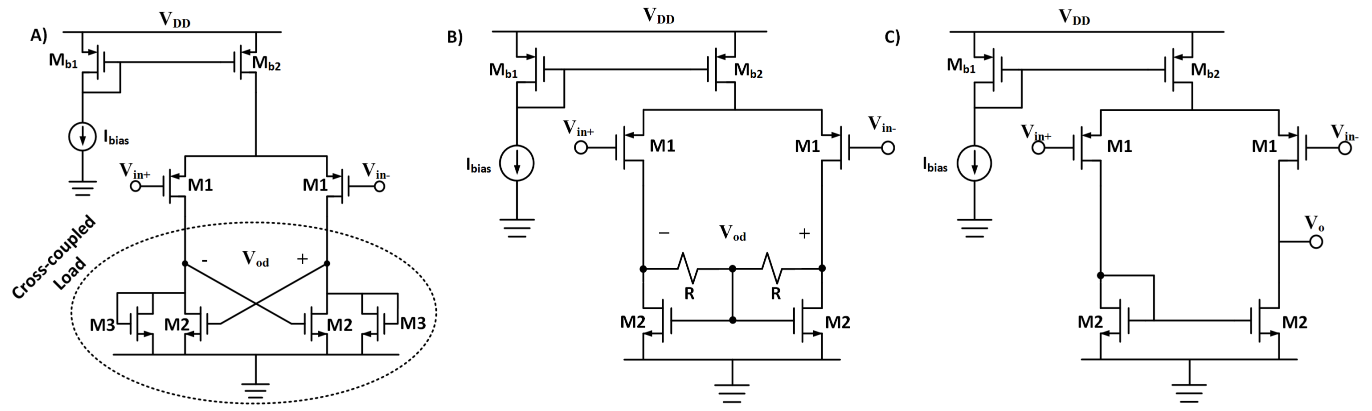

Fig. 2. A) The cross-coupled operational amplifier B) A fully differential amplifier with active load and resistive common-mode feedback C) a single ended operational amplifier with active load

biased in the sub-threshold region. As a result, this structure has a fixed positive and negative output even if the circuit has large mismatch.

$$R_{out,max} = r_{o1} \parallel r_{o2} \parallel r_{o3} \tag{10}$$

$$R_{out,d} = \frac{1}{g_{m3} - g_{m2}} \tag{11}$$

$$A_{dd} = \frac{g_{m1}}{g_{m3} - g_{m2}} \tag{12}$$

The output impedance is considerably lower than (11) for a common-mode signal and is equal to (13). With just consideration of the mismatch on the load impedance, the A_{dc} is according to (14) and the CMRR is calculated as (15).

$$R_{out,c} = 1/g_{m2} \parallel 1/g_{m3} = \frac{1}{g_{m2} + g_{m3}} \tag{13}$$

$$A_{dc} = \frac{\Delta R_{out,c}}{2R_B} \tag{14}$$

$$CMRR = \frac{2g_{m1}R_B}{[g_{m3} - g_{m2}]\Delta R_{out,c}} \tag{15}$$

The $R_{out,c}$ has inherently low value and due to sub-threshold operation, it will have lower variation. Therefore, it proves that cross-coupled amplifiers have high potential to attenuate common-mode signals.

IV. CROSS-COUPLED AMP. SIMULATION RESULTS

Since folded cascode and miller OTAs have low CMRR, a fully differential operational amplifier with a resistive common-mode feedback and a single ended operational amplifier are compared with the cross-coupled amplifier. All of them are designed in a 0.18 μm CMOS technology. The amplifier structures are shown in Fig. 2. In order to fairly compare them, all of them consume 10 μA current from 1.8 V supply voltage source and transistors have same W and L. Since the current mirror load has better matching when they are biased in strong inversion their W/L is changed to put them in the strong inversion region. The mean values of A_{dd}, A_{dc} and CMRR are reported in the table I. These values are extracted from 200 Monte Carlo simulations including both process and mismatch variation.

TABLE I
MEAN VALUE OF DIFFERENT STRUCTURES

	Active Load	FD Active Load	Cross-coupled
A_{dd} (dB)	59	53	37
A_{dc} (dB)	-30	-31	-51
CMRR (dB)	88	85	88

TABLE II
MINIMUM AND MAXIMUM VALUE OF DIFFERENT STRUCTURE

	Active Load	FD Active Load	Cross-coupled
A_{dd} (dB)	52 to 60	52 to 54	34 to 41
A_{dc} (dB)	-70 to -10	-38 to -22	-54 to -47
CMRR (dB)	60 to 130	74 to 92	87-91

As it was expected the gain of cross-coupled is lower than other structures while its output impedance is kept low in order to have fix positive and negative output nodes. But it rejects common-mode signal 20 dB stronger than others. This means that this structure is suitable when the input signal amplitude is significantly lower than the common-mode signals like power line noise. Or in other words, this structure can tolerate 100 times higher common-mode signals. Although the mean value of CMRR is same for different structure, the minimum value is still better for cross-coupled amplifier.

V. MODIFIED CURRENT REUSE OTA WITH CROSS-COUPLEAD LOAD

The gain of cross-coupled amplifiers was low and as the CMRR is related to differential gain as well as common-mode gain, the mean value of CMRR was approximately the same. In order to improve CMRR, the cross-coupled load can be combined with other fully differential amplifiers to achieve high differential gain and high common-mode attenuation

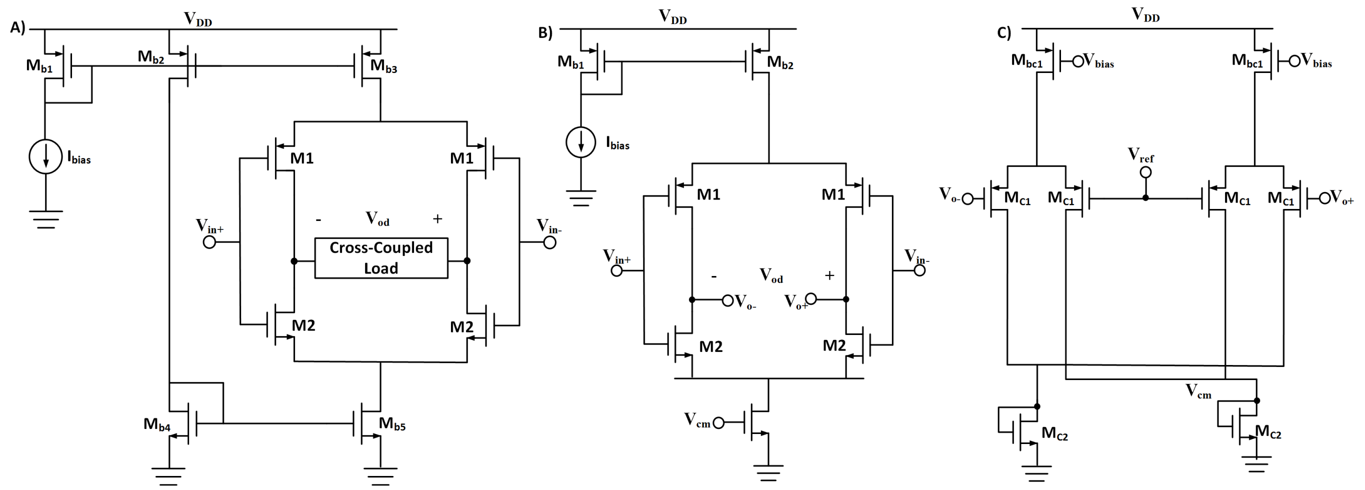

Fig. 3. A) The modified current-reuse amplifier with cross-coupled load B) A normal current-reuse amplifier C) the common-mode feedback used for the normal current-reuse amplifier

which leads to high CMRR. To do this, a current-reuse amplifier is chosen because it has low thermal noise and it's a good choice for highly precise operational amplifiers. So, a normal and modified current-reuse amplifier as it's shown in Fig. 3 are compared together and the simulation results are according to table III and IV. Although the differential gain is still attenuated because of the loading effect of cross-coupled amplifier, the total CMRR increased 20 dB.

These simulation and equations proves that cross-coupled load behavior has the potential to combine with other fully differential amplifiers to reach high differential gain as well as very low common-mode gain. Therefore, the final circuit can have approximately 30 dB higher CMRR than same circuit with common-mode feedback if there is no loading effect of cross-coupled load for differential signals.

TABLE III
THE SIMULATED MEAN VALUE OF TWO STRUCTURES

	Current reuse	Modified Current reuse
A_{dd} (dB)	60	46
A_{dc} (dB)	-19	-52
CMRR (dB)	80	98

TABLE IV
THE SIMULATED MIN. AND MAX OF TWO STRUCTURES

	Current reuse	modified current reuse
A_{dd} (dB)	58 to 62	44 to 48
A_{dc} (dB)	-59 to -5	-85 to -35
CMRR (dB)	62 to 121	83 to 128

VI. CONCLUSION

In this article, the potential of cross-coupled load to attenuate common-mode signal and ultimately increase the CMRR of operational amplifiers, has been investigated. Since the differential gain of cross-coupled amplifiers is low, their load is combined with a current-reuse amplifier which has lower thermal noise than conventional amplifiers to achieve a high CMRR amplifier. The circuits were designed in a $0.18\mu m$ CMOS technology. In order to simulate the common-mode gain, differential mode gain and CMRR, 200 Monte Carlo simulations were performed. The CMRR mean value of modified current-reuse amplifier with cross-coupled load was 98 dB, while the input common-mode signal was 400 times attenuated. Finally, it has been shown that by employing cross-coupled load in other fully differential amplifiers, the CMRR could be increased about 30 dB if there is no loading effect on the differential gain. Overall, this modified amplifier can be a good choice for biomedical applications and other applications where input signals are significantly smaller than common-mode signals.

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