

A Low Voltage Very High Impedance Current Mirror Circuit and Its Application

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ABSTRACT: Current mirror circuit has served as the basic building block in analog circuit design since the introduction of integrated circuits. In this paper, “A Very high impedance current mirror, operating in reduced power supply which does not use any additional biasing circuit and its application” is proposed. The design uses a high swing super Wilson current mirror which has negative feedback. A feedback action is used to force the input and output currents to be equal. The output current is expected to be mirrored with a transfer error less than 1% when the input current is increased from $5\mu\text{A}$ to $40\mu\text{A}$. As an application, the current mirror circuit has been used in the design of a high gain, improved output swing differential amplifier. A telescopic differential amplifier is chosen for designing since it is used in low power application. A comparative study of different current mirror circuits and amplifier is also made. The output swing of the circuit is improved than what is expected.

KEYWORDS: Current mirror, Wilson current mirror, Output Impedance, CMRR, Telescopic Differential Amplifier

I. INTRODUCTION

In the early 1980s many experts predicted the demise of analog circuits. Many functions that had been traditionally realized in analog form were now easily performed in the digital domain, suggesting that with enough capability in IC fabrication all processing of signals would eventually occur digitally. But still analog designers are of great demand today. This is because there are many areas where it is very difficult or even impossible to replace analog functions with their digital counterparts regardless of advancements in technology. Digitization often requires analog blocks before digitizing. A major component in these analog circuits is the current mirror, especially a high impedance current mirror in the case of biomedical applications. The project aims at the design of a current mirror circuit and its application in an amplifier circuit. In this paper, “A very high impedance current mirror, with less number of transistors which can operate at low voltage without any additional biasing circuitry” [1] is proposed. The fundamental design of this circuit is a high-swing super-Wilson, which offers high output impedance using negative feedback. The proposed current mirror uses MOS current dividers to sample the output current to achieve very high impedance with a large output and voltage range. A feedback action is used to force the input and output currents to be equal. The proposed circuit is also insensitive to the biasing current. This implementation yields an increase in the output impedance by a factor of about g_{mF_0} compared with that of the super-Wilson current mirror, thus offering a potential solution to mitigate the effect of the low output impedance of deep submicron CMOS transistors used in low voltage current mirrors and current sources. An NMOS version of the proposed current mirror circuit is aimed to be implemented using CMOS process and simulated using SPICE to validate its performance. The output current is expected to be mirrored with a transfer error lower than 1% when the input current is increased from $5\mu\text{A}$ to $40\mu\text{A}$. The project is further extended in designing an amplifier circuit using the proposed current mirror circuit. A high performance Telescopic differential amplifier involving less power consumption, high gain etc is designed. The Telescopic differential amplifier has the inherent disadvantage of low output swing. A high-swing, high performance single stage CMOS Telescopic operational amplifier is analyzed and the results are presented. The high swing of the op-amp is achieved by employing

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the tail and current source transistors in the deep linear region. Also the tail current transistor is replaced by the current mirror circuit as a modified circuit.

II. LITERATURE SURVEY

A. Basic Inspiration Circuits for the Proposed Current Mirror Circuit

The basic inspirational circuits for the project are the high swing super Wilson current mirror circuit[2],[3], the improved high swing super Wilson Current mirror circuit [3] and the high swing low voltage super Wilson Current Mirror Circuit[1]. All these are high output impedance current mirror circuits. The high-swing super-Wilson CM [3] achieves a high output resistance by using negative feedback. Assuming that the output resistance of the current sources is very large and that transistors are saturated, the output resistance r_{out} of the high -swing super-Wilson CM [3] can be approximated as: $r_{out} = g_{m2}r_{o2}r_{o3}$ where g_{m2} and r_o are respectively the transconductance and the output resistance. In the high-swing super -Wilson CM discussed above, a diode-connected transistor is used. It is to reduce current mismatch between I_{IN} and I_{OUT} by keeping the drain of mirroring transistors approximately to the same voltage.

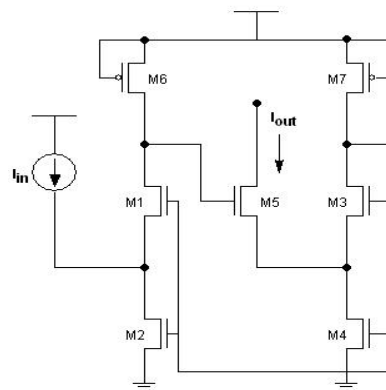


Fig.1 Low Voltage High Swing Super Wilson Current Mirror

In high swing Super Wilson current mirror [2], the output resistance of the diode connected transistor is only $1/g_m$. Therefore, to increase of the loop gain the diode connection of transistor was replaced with a cascode one [6]. Unfortunately, doing so would introduce an undesired current offset since the drains of current mirrors would not be at the same voltage anymore. The goal is then to find a way to maintain high impedance without breaking the drain symmetry of the current mirror. The new high output impedance CM, i.e. improved high swing super Wilson current mirror was evolved. The main idea is to increase the loop gain by a factor $g_m r_o$ by cascoding transistor M1 while maintaining the drain symmetry of the current mirror formed by current mirror. The output impedance of the proposed CM can be found as $r_{out} \approx g_{m1}g_{m2}r_{o1}r_{o2}r_{o5}$. Comparing this result with that of high swing super Wilson current mirror, it can be seen that the proposed implementation produces an increase of the output impedance by a factor of $g_m r_o$ over that offered by the high-swing super- Wilson current mirror. All the current mirrors explained in the previous sections have mainly three disadvantages:

- (1) Low output impedance
- (2) All the circuits perform well when the input is in the range of $30\mu A$ to $40\mu A$. At lower input current these circuits failed to produce the exact mirroring due to the presence of leakage currents.
- (3) Auxiliary Current sources were needed for keeping drain symmetry.

The new high output impedance current mirror in Fig.1 is evolved from the Improved High swing Wilson current mirror circuit described above to overcome these disadvantages. The drain symmetry current mirror is achieved without the need of an auxiliary current source. It is achieved by replacing the auxiliary current source with the PMOS. The

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M2-M4 transistors formed as part of the current mirror are used to achieve high output impedance. The diode connected transistor M1 is modified as a cascoded one. The transistors M2-M4 samples the output current I_{out} and compares it with the input current I_{in} which changes the conduction of the transistor M5 and the output current I_{out} is made equal to the input current I_{in} . The diode connected transistors M6-M7 acts as an active load and increase the output impedance as well as the output current. The increased output impedance [1], [3] can be expressed as:

$$r_{out} = \frac{1}{g_{05}} \left(\frac{1 + \frac{g_{05}}{g_{m4} + g_{04}} + \frac{g_{m5}}{g_{m4} + g_{04}}}{\frac{g_{m5}}{g_{m4} + g_{04}} \cdot (g_{m1} \parallel g_{m6}) g_{m2} + (g_{m1} \parallel g_{m6}) g_{02} + g_{m2} g_{02}} + \frac{g_{01} g_{02}}{g_{m5}} \right)$$

where g_{m1} , g_{m2} , g_{m4} , g_{m5} and g_{o1} , g_{o2} , g_{o4} , g_{o5} are respectively the transconductance and the output conductance of the transistors M1, M2, M4 and M5. If we further assume that the transconductance g_m of the transistors is much larger than their output conductance then the equation reduces to: $r_{out} = (g_{m1} \parallel g_{m6}) g_{m2} r_{o1} r_{o2} r_{o5}$

The earlier proposed circuits are performing well when the input current is in the range of $30\mu A$ to $40\mu A$. At lower input current, these circuits have failed to produce the exact mirroring due to the presence of negative leakage current. This is because NMOS are more prone to leakage currents. While using PMOS, value of leakage current in PMOS is lesser as compared to NMOS. It is because the mobility of holes in PMOS is lesser than mobility of electrons in NMOS. As a result even though NMOS wants to conduct more leakage current, it cannot do so because PMOS don't allow much leakage current. As a result the negative leakage current which cancels the current below $30\mu A$ is reduced in the new circuit and as a result much lower currents can be mirrored. Thus proposed circuit performs well in the lower input range from $5\mu A$ to $40\mu A$ range. Also, the proposed circuit provides very less transfer error compared to the earlier proposed structures.

But the circuit has a major drawback. In the PMOS the source and gate are shorted and as a result V_{gs} is always zero. For the PMOS to act as constant current source, it should be in saturation. i.e. $V_{gs} - V_t \geq V_{ds,sat}$. In this circuit V_{gs} is zero and hence the equation reduces to $-V_t \geq V_{ds,sat}$. This limits the value of overdrive voltage, V_{ov} depending on the value of V_t to make the transistor operate in the saturation region. In order to overcome this limit the gate source voltage is maintained a value other than zero so that the transistor can be designed for various overdrive voltages. So the circuit is modified by removing the shorting between the gate and the source. It is the proposed circuit for the project. It is explained in the next section.

B. Proposed Current Mirror Circuit

The improved high impedance low voltage current mirror is modified so that the circuit can be designed for various overdrive voltages. The modification is made by removing the short circuit between gate and source of the biasing voltages at the gate of the PMOS transistors in Fig.2.

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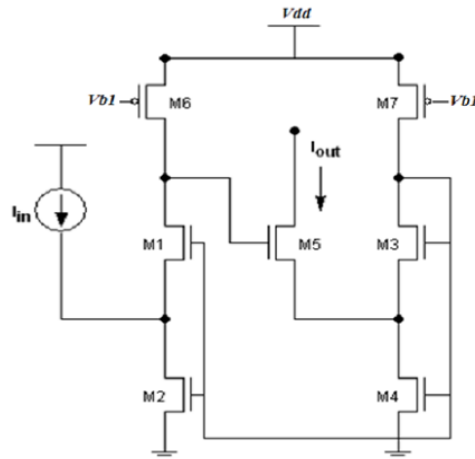


Fig.2 Proposed Current Mirror Circuit

This helps in designing the circuit for different overdrive voltages. The new current mirror circuit has a biasing voltage V_{b1} at the gates of transistors M6 and M7. This voltage is selected such that the transistors obey the condition for saturation, i.e. $V_{gs} - V_t \geq V_{ds,sat}$, where $V_{gs} = V_g - V_s = V_{b1} - V_{dd}$, i.e. the biasing voltage is greater than supply voltage plus minimum overdrive or minimum saturation voltage. The modified circuit diagram is shown in figure.

C. Application of the current mirror circuit

Current mirrors [7], [8] can be used in where constant current is needed and the following example is one such application. The telescopic architecture [7] is the simplest version of a single stage operational transconductance amplifier. In it, the input differential pair injects the signal currents into common gate stages. Then, the circuit achieves the differential to single ended conversion with a cascode current mirror. The transistors are placed one on the top of the other to create a sort of Telescopic composition [6] (from this the name of the circuit). The small signal resistance at the output node is quite high: it is the parallel connection of two cascode configurations. Such a high resistance benefits the small signal gain without limiting the circuit functionality when we require an OTA function. Fig.3 shows an improved telescopic op-amp. In a simple telescopic op-amp, it has all transistors from M1 to M8 and instead of rest of the circuit a tail transistor M9 will be connected to ground. Here the transistors M1 and M2 form a current mirror. Similarly M3 and M4 form another current mirror. This cascode connection of the current mirrors improves the gain of the circuit. The tail transistor carries the tail current. It is biased such that it could carry the tail current of the circuit. The common mode voltage of the circuit is sensitive to the changes in the current of the tail transistor.

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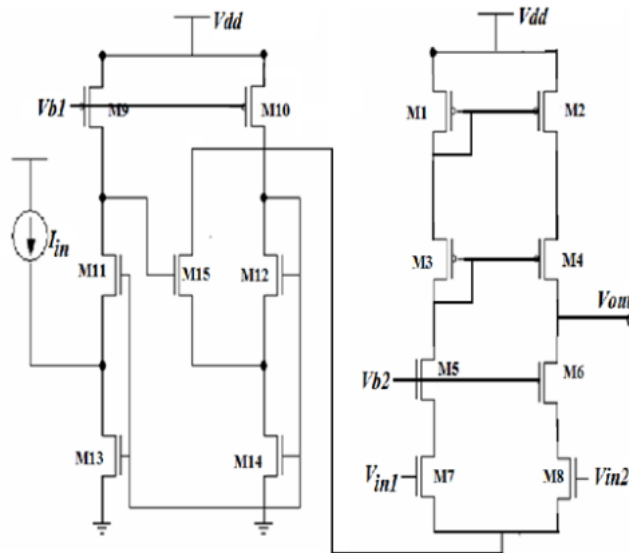


Fig3 Telescopic Differential Amplifier using proposed current mirror circuit

The current through this transistor should be a constant at a particular biasing condition. But the transistor dependence on the temperature and other variations affect the current through the transistor and this affect the common mode voltage of the circuit. This affects the gain of the circuit. So in order to maintain the gain constant the current of M9 should be made constant. So the tail transistor can be replaced by a current source. [5] But it increases the power dissipation. So a better alternative is to replace the tail transistor and place the output terminal of the current mirror at the tail end of the amplifier. Current mirrors have non zero mismatch and as a result the current at tail end is kept constant. In order to increase the gain of the circuit cascade current mirrors is used. But the output swing of telescopic op amp is relatively limited. Another drawback of telescopic cascade is the difficulty in shorting their input and outputs, e.g. to implement a unity gain buffer. The expected output swing of the circuit is given by $V_{b2} - V_{th6} \leq V_{out} \leq V_{b2} - V_{GS6} + V_{th8}$. In the above discussed circuit the tail transistor of the differential amplifier is removed and the current mirror is placed there as shown in Fig.3. The desired current which is flowing through M9 is found out. This current is given as the input current of the current mirror. The output node of the current mirror is connected at the tail end. So the current at the tail end will be that at the input of the mirror. The circuit in figure is the final circuit of the project. It is the High Gain differential Amplifier with high output impedance current mirror circuit at the tail end.

III. SIMULATION RESULTS

The circuits are designed using 180nm TSMC technology. In the technology the supply voltage is 1.8V and the minimum channel length is 180nm. The power dissipation is assumed to be $10\mu W$. The threshold voltage of PMOS is -0.49V and that of NMOS is 0.5V in the 180nm TSMC technology. The design consideration is that the transistors are in saturation and the current equation for transistor under saturation is given as follows,

$$I = (\mu_o * C_{ox} / 2) * W/L * (V_{ov})^2$$

where V_{ov} is the overdrive voltage. It is found out using TSMC 180nm datasheet as $V_{ov,n} = 0.17V$ and $V_{ov,p} = 0.26V$. Also the power dissipation is assumed to be $10\mu W$ and using this current through all transistors is found for V_{dd} of 1.8V. Later these values are submitted to find the (W/L) ratio of all transistors.

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A. Simulation of Current Mirror Circuit

The circuit diagram of current mirror which is shown in Fig.2 is simulated using NG spice. DC analysis was done for finding the input-output characteristics of the current mirror and also to find the output impedance of the mirror. In order to find the input-output characteristics the input current was varied from $5\mu\text{A}$ to $40\mu\text{A}$ and the output current flowing through M5 was found. The simulation result is shown in Fig.4. It is seen from the graph that the output current nearly equals the input current. Thus the percentage of error is less than 1%. Also the circuit is a high output impedance current mirror circuit. So it is important to find the maximum output impedance of the circuit. The Fig.4 shows the output impedance vs. output voltage of the circuit. The output voltage is increased from 0 to 1.8V and the output impedance across M5 is plotted. The graph is expected to be linearly increasing with the increase in output voltage. But it is seen in the graph that there is a non linearity in the graph till a particular voltage, i.e. till 0.17V. This is because the minimum overdrive chosen is 0.17V and till the voltage reaches 0.17V, the circuit operates in non linear region.

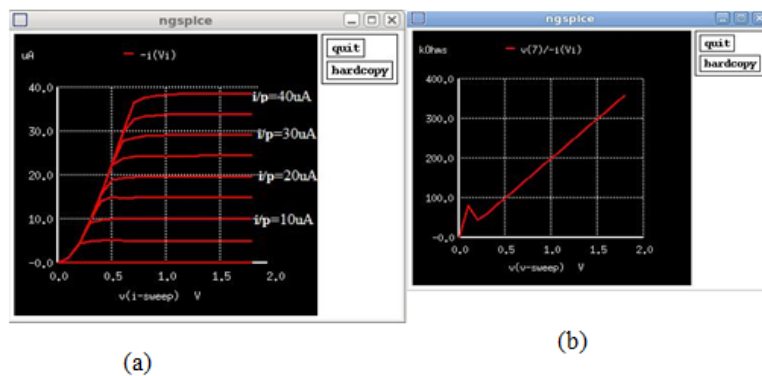


Fig 4. (a) Output Current Characteristics (b) Output Impedance Characteristics

When the overdrive or drain –source voltage of M5 is 0.17V, it goes into the linear region of operation and the output impedance curve is linear thereafter. The maximum output impedance obtained is $357\text{K}\Omega$. This impedance is far better than any other current mirror circuits.

B. Simulation of Differential Amplifier Circuit

The telescopic differential amplifier with the proposed current mirror at the tail end was also simulated in NG Spice. The circuit diagram which is simulated is shown in Fig.3. The equivalent figure is that of an op-amp. In practice the differential amplifier circuit differs from an op amp as they have some resistors connected at some nodes. This schematic is shown in Fig.5.

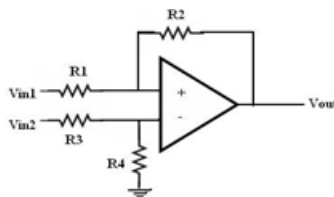


Fig.5. Schematic of Differential Amplifier

The analyses performed are transient analysis and DC analysis. The transient analysis was done for finding the common mode and difference mode gain. The DC analysis was done for finding the output swing and the output

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impedance of the circuit. In an op amp or a differential amplifier it is important to find the difference mode and common mode gain in order to find the CMRR of the circuit. So the transient analysis is performed to find both of these. The transient analysis plotted different voltage values at different time instants. Fig.6. shows the difference mode characteristics. A difference mode gain of 82.264 was obtained when the circuit was designed for 100. The common mode gain obtained was 2.23 E-03. Thus the CMRR is 91.3dB.

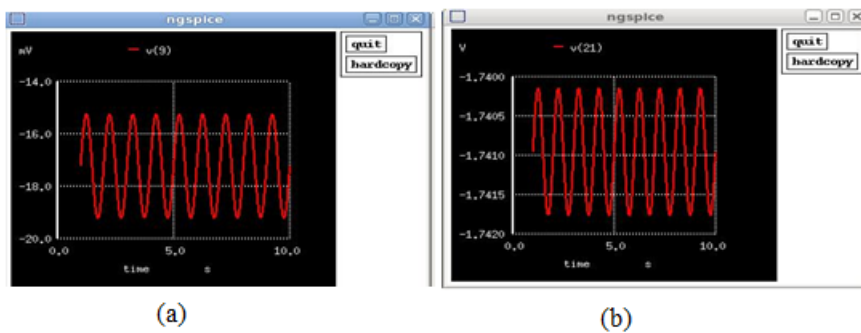


Fig.6 Difference Mode Characteristics (a) Input waveform (b) Output waveform

The output swing defines the minimum and maximum values of output voltages of the circuit. Theoretically the output swing of the telescopic differential amplifier is $V_b - V_{thn} \leq V_{out} \leq V_b - V_{gsn} = V_{thn}$ i.e., $1.3V \leq V_{out} \leq 1.63V$ is the expected value. Upon analysis the output swing obtained graphically is shown in Fig.7. That is the output swing obtained is slightly improved and is obtained as $1.123V \leq V_{out} \leq 1.731V$ instead of $1.3V \leq V_{out} \leq 1.63V$. Thus the circuit has increased output swing which is an added advantage of the amplifier.

The output impedance of an ideal op-amp is zero and in practice it is in the range of several ohms. But when it comes to differential amplifier the output impedance is slightly more and the aim is to reduce the output impedance as far as possible. So it is important to plot the output impedance characteristics.

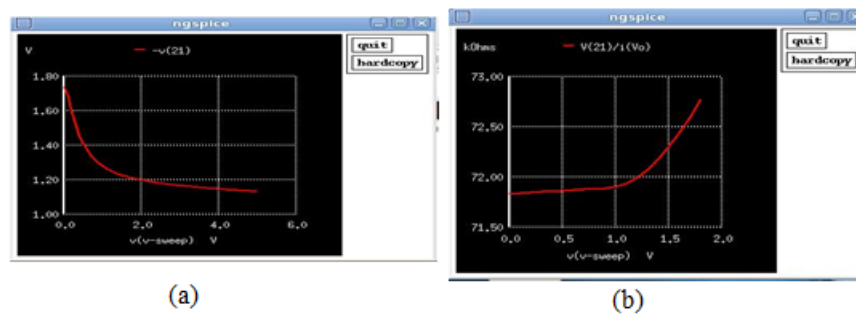


Fig. 7 (a) Output Voltage Characteristics (b) Output Impedance Characteristics

The Fig.7 shows the output impedance versus output voltage of the circuit. The maximum output impedance obtained is 72.8KΩ at an output voltage of 1.8V. The results are shown below in Table I and II.

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TABLE I: COMPARISON OF DIFFERENT CURRENT MIRRORS

V _{dd} =1.8V			
Current Mirror	I _{out} (I _{in} =40uA)	I _{out} (I _{in} =5uA)	Output Impedance (I _{in} =5uA)
Proposed Current Mirror[TSMC 180nm]	38.29uA	4.68uA	357KΩ
Improved High Swing Low Voltage Wilson Current Mirror[1][UMC 180nm]	39.2uA	4.85uA	55KΩ
Super Wilson Current Mirror [1][UMC 180nm]	41.2uA	6.4uA	4.36KΩ
Low Voltage Current Mirror[1][UMC 180nm]	37.7uA	2.64uA	47.6KΩ

TABLE II: COMPARISON OF DIFFERENTIAL AMPLIFIERS

	Telescopic Amplifier with CM	Telescopic Amplifier without CM
CMRR	91.3dB	54dB
Output Impedance	72KΩ	298KΩ
Output Swing	$1.12 \leq V_{out} \leq 1.73$	$1.3 \leq V_{out} \leq 1.63$

IV. CONCLUSION

The proposed circuit offers very high impedance due to the presence of the PMOS at both legs since no auxiliary biasing circuit is used. It can be used for applications which operate with very low current. One such application also is described in the paper, i.e. the high gain improved output swing telescopic differential amplifier. It was found that due to the presence of the current mirror, the gain, CMRR and the output swing of the amplifier is increased. A comparative study is also given. The amplifier circuit can be modified to decrease the output impedance by adding a buffer stage at the output of the amplifier.

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