An insight into analog current mirrors

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***Abstract:* - Current mirrors based on active devices are important analog building blocks necessary in current or voltage-mode designs. They used for biasing, for transferring current from one part of the circuit to another and as load for amplifier stages. This paper presents the theoretical analysis, the simulation and the circuit built on PCB of five current mirror topologies. The analysis is focused in the investigation of the current transfer ratio and the output impedance of each one of the circuits, the two most important parameters of current mirrors. A current mirror with superior performance is presented, although that is in the expense of voltage-headroom.**

***Index Terms:* current mirror, wilson, cascode, precise multiple output mirror**

I. IDEAL AND PRACTICAL CURRENT MIRRORS

A current mirror, Fig. 1, is a topology with three terminals (at least) which is mainly used for biasing, instead of passive resistors, to provide insensitivity to power supply variations as well as temperature. Ideally, the output current is identical to the input current, the input voltage is zero and the output impedance is infinite [1].

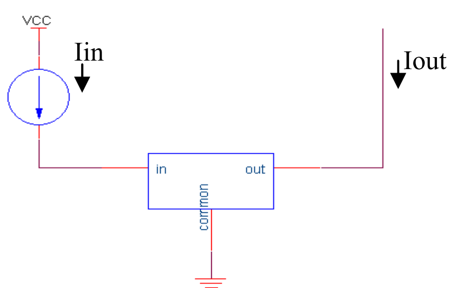

Fig. 1. The ideal current mirror

In practice no such ideal unit exists but it is the object of design to approximate ideal performance as closely as possible. To do that, practical transistor characteristics have to be taken into account such as the finite β value, the Early voltage, the internal parasitic capacitances etc. Other factors such as the matching between devices and the sensitivity to temperature variations need to be considered to realize performance close to ideal. The difference between the ideal and non-ideal current mirror will be examined in this paper by investigating on the output impedance, the input impedance, the current gain and the power supply of the output stage of the current mirror.

A. The output impedance

Investigating on the output stage of a practical current mirror it can be seen that the output current changes when altering the output voltage [2]. That means that the output AC impedance of the configuration is not constant. Looking from the output of the circuit towards the input, this impedance is in parallel with a current source and the current depends on the input current of the circuit. The higher the output impedance, the less sensitive the output current will be on a change of the output voltage. Practically, reducing the output current increases the output impedance and the performance of the entire unit. Nevertheless, when designing for higher operating frequencies it is essential to maintain the output current high enough to allow better performance of the entire system.

B. The input impedance

Under ideal conditions, connecting a current source in the input or a current mirror, the entire input voltage should drop in the current source, since the input impedance of the current mirror is zero. Practically, a voltage drop is created in the input terminals of the mirror, which is subtracted from the voltage applied to the current source. The result is the input current to be different than the calculated value, consequently the output current to be other than the expected one.

C. Current Gain

Ideally, the output current of a current mirror is a replica of the input current, under any operating conditions. Practically, the two currents are not identical due to the gain-error source, which is divided into the systematic and the random gain error. The first one exists even when all transistors in the circuit are well matched and the second is caused when transistors, which should theoretically be matched, are not practically matched.

D. Output stage power supply

Practically, in order the output to mirror the input current it is necessary to be supplied with a voltage, high enough to provide the proper biasing to the output transistors. This voltage should be high enough to keep transistors in the active region and low enough to maximize the range of output voltages where the output impedance is constant.

II. SIMPLE CURRENT MIRROR

The simple current mirror is the heart of several other current mirrors. It consists of two transistors, one of them diode-connected, as shown in Fig. 2 [1].

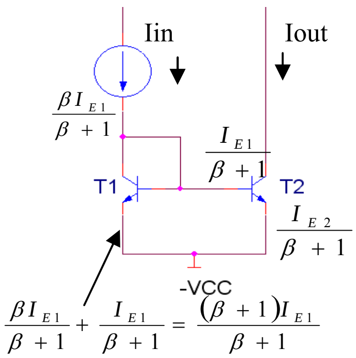

Fig. 2. Simple current mirror

Since,

$$I_{E1} = I_{S1}\left(\frac{\beta_1+1}{\beta_1}\right)e^{\frac{V_{BE1}}{V_T}} \quad (1)$$

with straightforward analysis on currents, for $V_{BE1} = V_{BE2}$, the current transfer ratio, λ, can be calculated

$$\lambda = \frac{I_{OUT}}{I_{IN}} = \frac{1}{\frac{I_{S1}}{I_{S2}}\left(1+\frac{1}{\beta_1}\right)+\frac{1}{\beta_2}} \quad (2)$$

It is obvious that matched transistors with high current gain are necessary to eliminate the term I_{S1}/I_{S2} and obtain a unity current transfer ratio.

The output stage of the simple current mirror is a single transistor. Since the Early voltage of transistors is not infinite, the output impedance can be found by the I_C over V_{CE} characteristics of the transistor. Hence, the output impedance will be,

$$R_O = \frac{V_A}{I_{OUT}} \quad (3)$$

where V_A is the Early voltage of the transistor, typically around 50V. For a quiescent current of 1mA the output impedance is some 50KΩ.

III. BUFFERED SIMPLE CURRENT MIRROR

The buffered simple CM, Fig. 3, incorporates an extra transistor which buffers the input current reducing the current needed to drive the bases of transistors T_1 and T_2. Thus, the emitter current of T_1 is closer to the input current hence closer to the input current is the collector current of T_2, too [3].

Hence, the current transfer ratio will be improved. The current in the base of T_3 will be,

$$I_{B3} = \frac{\frac{I_{E1}}{\beta_1+1}+\frac{I_{E2}}{\beta_2+1}}{\beta_3+1} \quad (4)$$

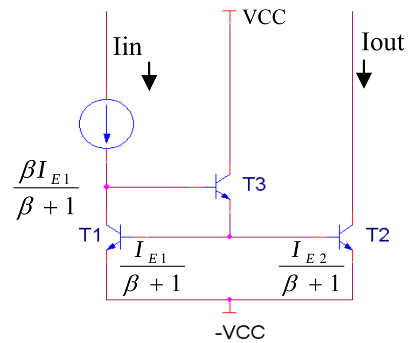

Fig. 3. Buffered Simple current mirror

Following the same analysis on currents as before, for $V_{BE1} = V_{BE2}$, the current transfer ratio, λ, will be,

$$\lambda = \frac{1}{\frac{I_{S1}}{I_{S2}}\left(1+\frac{1}{\beta_1(\beta_3+1)}\right)+\frac{1}{\beta_2(\beta_3+1)}} \quad (5)$$

Consequently, the current transfer ratio of the mirror will be much better compared to the previous due to the β^2 term. Nevertheless, matched transistors are also necessary.

On the other hand, the output impedance will be identical to that of the simple CM, given in (3).

IV. WILSON CURRENT MIRROR

When higher output impedance is necessary, keeping the circuitry relatively simple, Wilson current mirror, Fig. 4, is the most appropriate type of current mirror. The input current is fed into a simple current mirror via transistor T_3 which provides negative feedback to the circuit operation, too [1].

Following the same methodology as before, having identified the current in every part of the circuit, the current transfer ratio for $V_{BE1} = V_{BE2}$ will be,

$$\lambda = \frac{1}{\frac{I_{S1}\beta_2(\beta_3+1)}{I_{S2}\beta_3(\beta_2+1)+\frac{I_{S1}\beta_2\beta_3}{\beta_1}}+\frac{1}{\beta_3}} \quad (6)$$

Consequently, the λ will be somewhere near the current transfer ratio of the buffered simple current mirror.

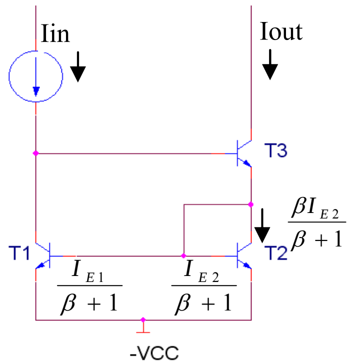

Fig. 4. Wilson current mirror

The investigation of the output impedance can be carried out using the small signal equivalent model of the current mirror. Having done some approximations, the circuit will be as shown in Fig. 5.

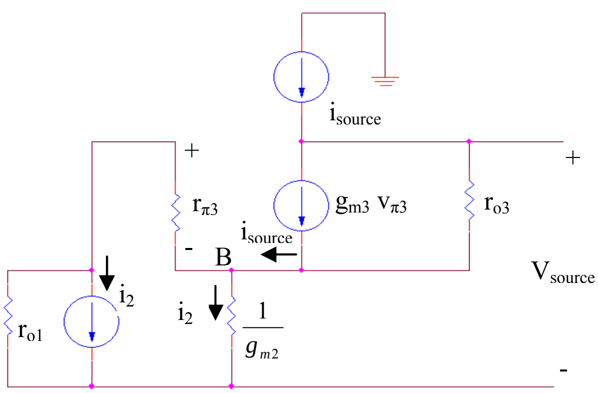

Fig. 5. Small signal equivalent model of the Wilson current mirror

Applying a small current in the output of the circuit and investigating on the output voltage, will give the output impedance of the circuit.
Using Kirchhoff laws around the circuit will end up with,

$$\frac{V_{source}}{i_{source}} = R_o = \frac{1}{2g_{m1}} + r_{o2} + \frac{g_{m2} r_{\pi 2} r_{o2}}{2} \qquad (7)$$

and,

$$R_o \approx r_{o2} + \frac{\beta_o r_{o2}}{2} \approx \frac{\beta_o r_o}{2} \qquad (8)$$

The output impedance will be β times the impedance of the simple current mirror and will keep constant for any output voltage, due to the negative feedback.

V. CASCODE CURRENT MIRROR

The cascode current mirror, which is two simple current mirrors one on top of the other, Fig. 6, offers similar performance to the Wilson current mirror but it can operate on higher frequencies, since it can reduce the Miller capacitance between input and output [4].

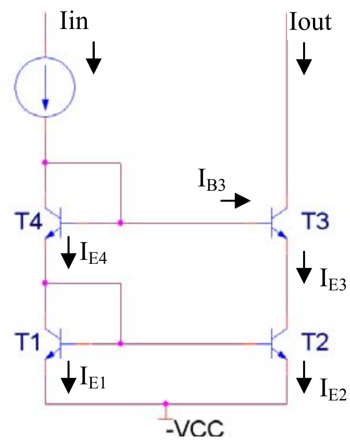

Fig. 6. Cascode current mirror

Straightforward analysis on currents, for $V_{BE1} = V_{BE2}$ gives a current transfer ratio,

$$\lambda = \frac{1}{\frac{I_{S1}}{I_{S2}}\left(1 + \frac{1}{\beta_1} + \frac{1}{\beta_3} + \frac{1}{\beta_1\beta_3}\right) + \frac{1}{\beta_2} + \frac{1}{\beta_3} + \frac{1}{\beta_2\beta_3}} \qquad (9)$$

which is slightly worse of that of the Wilson current mirror due to the extra β factors.

The output impedance is that of a common base transistor since the simple current mirror of T1 and T2 is fed by T3 [5]. Consequently, the output impedance will be,

$$R_o \approx \frac{\beta_3 r_{o3}}{2} \qquad (10)$$

VI. PRECISE MULTIPLE OUTPUT CM

The best current transfer ratio combined with the highest output impedance can be achieved with the precise multiple output current mirror, Fig. 7, at the expense of extra power supply [5].

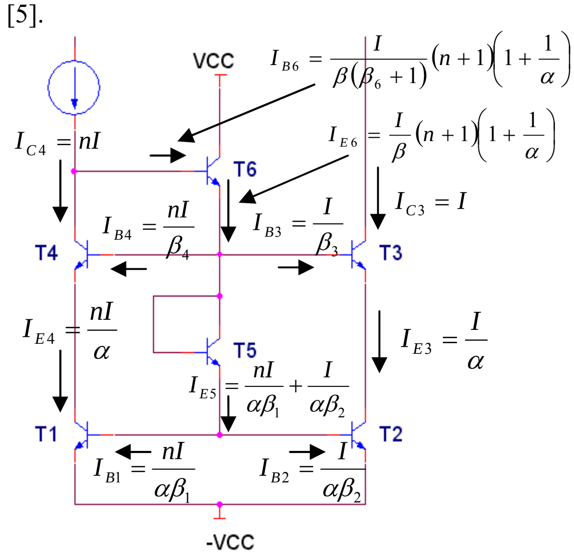

Fig. 7. Precise multiple output current mirror

Straightforward analysis on currents, for $V_{BE1} = V_{BE2}$ and $\beta_6 \approx \beta$, the current transfer ratio, λ, will be,

$$\lambda = \frac{1}{1 + \frac{4}{\beta^2}} \tag{11}$$

Hence, under the same approximations, the λ will theoretically be closer to unity than the rest of the current mirrors considering that $4 << \beta^2$.

The small signal equivalent circuit of Fig. 8 can be used to investigate on the output impedance of the circuit. Following the same procedure as for the Wilson current mirror, the circuit will be as follows.

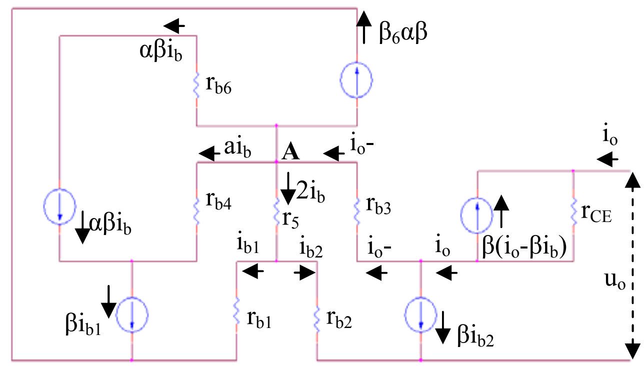

Fig. 8. Small signal equivalent circuit of the Precise multiple output CM

Ignoring r_{CE} of all transistors apart from that of T_3, the output impedance will be equal to,

$$R_O \approx r_O \beta \tag{12}$$

Consequently, the output impedance is roughly double that of the Wilson current mirror.

VII. SIMULATION AND LAB EVALUATION

The current mirrors presented here have been simulated in Orcad-Pspice software package to investigate on their current transfer ratio and output impedance. Table I presents the simulation results.

Table I Simulation results

Configuration	**Input and output currents**	**Transfer ratio, λ**
Simple CM	Iin=0.999mA Iout=0.979mA	1.02
Buffered simple CM	Iin=1mA Iout=0.987mA	1.013
Wilson CM	Iin=1mA Iout=0.996mA	1.004
Cascode CM	Iin=1mA Iout=0.996mA	1.004
Precise multiple output CM	Iin=1mA Iout=0.989mA	1.011

The investigation on current mirrors finished with the implementation of each current mirror in PCB, using transistor arrays (HFA3096B), shown in Fig. 9. Table II presents the current transfer ratio measured.

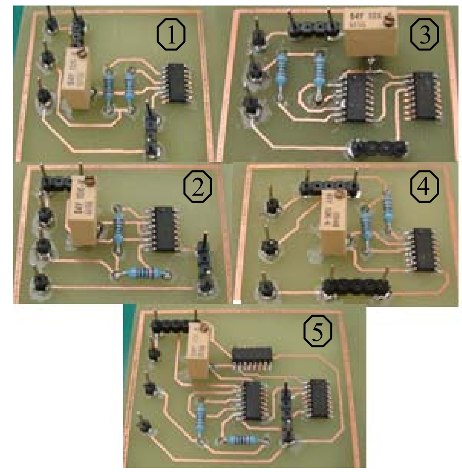

Fig. 9. Current mirror circuits
1. Simple CM, 2. Buffered simple CM, 3. Cascode CM, 4. Wilson CM and 5. Precise multiple output CM

Table II Measured current transfer ratio

Configuration	**Transfer ratio, λ**	**Output impedance**
Simple CM	1.022	85KΩ
Buffered simple CM	1.03	83KΩ
Wilson CM	0.991	1.83MΩ
Cascode CM	0.993	1.9MΩ
Precise multiple output CM	0.999	3.5MΩ

VIII. CONCLUSION

The analysis, simulation and implementation of five current mirrors have been presented. The Precise multiple output CM presented better overall performance, although its current transfer ratio was slightly worse than others, at the expense of some extra headroom due to the extra transistors used. This research work is still on going. A CMOS version of the presented current mirrors is planned to be theoretically analyzed, simulated and built on PCB, to identify potential advantages over their BJT versions.

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