Current mirrors

Current mirrors are important blocks in electronics. They are widely used in several applications and chips, the operational amplifier being one of them.

Current mirrors consist of two branches that are parallel to each other and create two approximately equal currents. This is why these circuits are called current mirrors. These currents are used to load other stages in circuits and they are designed in such a way so that current is constant and independent of loading.

Current mirrors come in different varieties:

- Simple current mirror (BJT and MOSFET)
- Base current corrected simple current mirror
- Widlar current source
- Wilson current mirror (BJT and MOSFET)
- Cascoded current mirror (BJT and MOSFET)

For best performance, transistors should be matched, temperature should be the same for all devices and collector-base/drain-gate voltages should also be matched. This will provide equal currents on both sides of the current mirror.

All of the circuits have a compliance voltage which is the minimum output voltage required to maintain correct circuit operation: the BJT should be in the active/linear region and the MOSFET should be in the active/saturation region.
**Simple current mirror**

Two implementations exist for the simple current mirror: BJT and MOSFET.

**BJT**

The BJT implementation of the simple current mirror is used as a block in the operational amplifier.

The compliance voltage is roughly given by

\[ V_{o(min)} = V_{CE2(sat)} = 0.2V \]
The collector resistor is given by

\[ R = \frac{V_{CC} - V_{RE}}{I_{REF}} \]

The collector current is given by

\[ I_C = I_S \left( \frac{V_{RE}}{V_T} e^{V_{BB} / V_T} - 1 \right) \left( 1 + \frac{V_{CE}}{V_A} \right) \]

From KCL analysis at the collector of Q1, the reference current is defined as

\[ I_{REF} = I_C + 2I_B = I_C + 2 \frac{I_C}{\beta_o} = I_C \left( 1 + \frac{2}{\beta_o} \right) \]

where \( \beta_o \) is the value of \( \beta \) for \( V_{CB}=0V \) (Q1 is diode-connected).

The output current is given by

\[ I_o = I_C = I_S \left( \frac{v_{RE}}{v_T} e^{V_{BB} / v_T} - 1 \right) \left( 1 + \frac{V_{CE}}{V_A} \right) \]

When \( V_{CB}=0V \) the Early effect is eliminated and it does not affect the equation. As the value of \( V_{CB} \) increases, \( \beta \) values for both transistors no longer match and the output current is no longer flat but it's tilted with a slope of \( 1/r_o \).

The output resistance is

\[ R_o = r_o = \frac{|v_A| + V_{CE}}{I_o} \]
The MOSFET implementation of the simple current mirror is as follows:

![Simple current mirror (MOSFET)](image)

The parameters for the transistors are $W=900\,\text{n}$, $L=90\,\text{n}$ and $V_{TN}=0.25\,\text{V}$.

The compliance voltage is roughly given by

$$V_{\text{v}_\text{v}} = V_{DS2\text{(sat)}} = V_{GS2} - V_{TN} = 2.5\,V - 0.25\,V = 2.25\,V$$

*Note: the subscript $N$ is added to $V_T$ to avoid confusion with the thermal voltage ($V_T=25\,\text{mV}$).*
The drain resistor is given by

\[ R = \frac{V_{DD} - V_{GS1}}{I_{REF}} \]

Both transistors work in the active/saturation region and their drain current is given by

\[ I_D = K_n (V_{GS} - V_{TN})^2 (1 + \lambda \cdot (V_{DS} - (V_{GS} - V_{TN})) \]

Since no current enters the gates, reference and output currents match.

When \( V_{DS} - V_{GS} + V_{TN} = 0 \text{V} \) the channel-length modulation is eliminated and it does not have affect the equation. If the value of \( V_{DS} - V_{GS} + V_{TN} \neq 0 \text{V} \), the output current is no longer flat but it’s tilted with a slope of \( 1/r_0 \).

Currents are related by the following expression:

\[ \frac{I_o}{I_{REF}} = \frac{W_2/L_2}{W_1/L_1} \left( \frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}} \right) \]

The above relationship says that current in the two branches of the current mirror depends on the aspect ratio of the two transistors.

The output resistance is

\[ R_0 = r_0 = \frac{1}{\lambda I_o} \]
The currents of the BJT implementation of the simple current mirror are somewhat dependent on the value of $\beta$ for both transistors. In order to minimize this dependency and decrease the error in current matching, a transistor is added to the original simple current mirror circuit.

The compliance voltage is roughly given by

$$V_{v_{\text{sat}}} = V_{CE2}^{\text{sat}} = 0.2V$$
The collector resistor is given by

\[ R = \frac{V_{CC} - V_{BE3} - V_{BE1}}{I_{REF}} \]

The collector current is given by

\[ I_c = I_S \left( \frac{\frac{V_{BE}}{T_T}}{1 + \frac{V_{CE}}{V_A}} \right) \]

From KCL analysis at the collector of Q1, the reference current is defined as

\[ I_{REF} = I_{C1} + I_{B3} = I_c + \frac{2I_c}{\beta(\beta + 1)} = \frac{V_{CC} - V_{BE3} - V_{BE1}}{R} \]

The output current is given by

\[ I_o = I_c = I_S \left( \frac{\frac{V_{BE}}{T_T}}{1 + \frac{V_{CE}}{V_A}} \right) \]

The output resistance is

\[ R_0 = r_o = \frac{|V_A| + V_{CE}}{I_o} \]

Note: the MOSFET implementation of this circuit does not exist since current does not enter the gate of a MOSFET.
The Widlar current source, a variation of the simple current mirror, was advanced by Bob Widlar in the mid 1960s. The only difference between the two circuits is the introduction of an emitter resistor. This additional component forces the currents in the two branches of the circuit to be unequal so this is why the circuit is called a source rather than a mirror. This specific circuit is used as a block in the operational amplifier.

Note: the circuit presented here has been designed so that $I_{C1}$ is twice the value of $I_{C2}$.

The compliance voltage is roughly given by

$$V_{o(min)} = V_{CE2(sat)} + V_R + 0.2V + I_{R2}R_2$$
The collector resistor is given by

\[ R_1 = \frac{V_{CC} - V_{BE1}}{I_{REF}} \]

The base voltage is defined by

\[ V_B = V_{BE1} = V_{BE2} + I_{E2} R_2 \equiv V_{BE2} + I_o R_2 \]

The difference in base-emitter voltages is

\[ V_{BE1} - V_{BE2} = I_o R_2 \]

The base-emitter voltages are given by

\[ V_{BE1} = V_T \ln \left( \frac{I_{REF}}{I_S} \right) \quad \text{and} \quad V_{BE2} = V_T \ln \left( \frac{I_o}{I_S} \right) \]

Subtracting base-emitter voltages again,

\[ V_{BE1} - V_{BE2} = V_T \ln \left( \frac{I_{REF}}{I_S} \right) - V_T \ln \left( \frac{I_o}{I_S} \right) = V_T \ln \left( \frac{I_{REF}}{I_o} \right) \]

so that

\[ V_{BE1} - V_{BE2} = I_o R_2 = V_T \ln \left( \frac{I_{REF}}{I_o} \right) \]

and the emitter resistor is

\[ R_o = \frac{V_T}{I_o} \ln \left( \frac{I_{REF}}{I_o} \right) \]

Note that if the condition \( I_{REF} = I_o \) is forced, the argument of the logarithm is 1 which produces 0 and therefore a 0Ω resistance (simple current mirror configuration). This is why reference and output currents do not match.

The output resistance is higher than the one for the simple current mirror:

\[ R_o = r_o \left[ 1 + g_m (R_o \parallel r_x) \right] \]

Note: the MOSFET implementation of the Widlar current source is not used and if it were, it would behave similarly to the simple current mirrors.
Wilson current mirror

Two implementations exist for the Wilson current mirror: BJT and MOSFET. This circuit employs 3 transistors (4 in the improved version). The major advantages of this circuit over the simple current mirror is that it has a higher output impedance and strongly reduces the base error of the BJT implementation.

BJT

The BJT implementation of the Wilson current mirror was invented by George R. Wilson at Tektronix in 1967.

Wilson current mirror (BJT)

Wilson current mirror currents (BJT)
The compliance voltage is roughly given by

\[ V_{\text{sat(min)}} = V_{BE2} + V_{CE3(sat)} = 0.7V + 0.2V = 0.9V \]

The output resistance is very high and it’s given by

\[ R_o = \frac{\beta \cdot r_o}{2} \]

An improved version of the above circuit exists. It uses an additional transistor which improves linearity when higher current levels are needed.
The MOSFET implementation of the Wilson current mirror looks like the following:

The parameters for the transistors are $W=1\mu$, $L=45n$ and $V_{TN}=0.3V$.

The compliance voltage is roughly given by

$$V_{o(min)} = V_{GS2} + V_{DS3(wr)} = V_{GS2} + (V_{GS3} - V_{TN}) = 1.5V + 1.5V - 0.3V = 2.7V$$
Currents are related by the following expression:

\[
\frac{I_o}{I_{REF}} = \frac{W_2/L_2}{W_1/L_1} \left( 1 + \lambda V_{DS2} \right) \left( 1 + \lambda V_{DS1} \right)
\]

The output resistance is very high and it’s given by

\[
R_o = r_o \left( 2 + g_m r_o \right)
\]

An improved version of the above circuit exists. It uses an additional transistor which improves overall match in the two branches.
Cascoded current mirror

The cascoded current mirror resembles a stack of two simple current mirrors and it looks very much like the improved version of the Wilson current mirror (with a diode connection at Q1/M1 instead of Q2/M2). Therefore, this circuit is made up by 4 transistors. The major advantages over the simple current mirror is that this circuit has a higher output impedance and it eliminates Early effect with the MOSFET implementation.

BJT

The BJT implementation of the cascoded current mirror is as follows:
The compliance voltage is roughly given by

\[ V_{\text{e(min)}} = V_{BE2} + V_{BE4} - V_{BE3} + V_{CE3(sat)} = V_{BE2} + V_{CE3(sat)} = 0.7V + 0.2V = 0.9V \]

*Note: \( V_{BE4} \) and \( V_{BE3} \) cancel each other so the base and collector voltages of \( Q_2 \) are the same.*

The collector resistor is given by

\[ R = \frac{V_{CC} - V_{BE4} - V_{BE1}}{I_{REF}} \]

The output resistance is very high and it's given by

\[ R_o = \frac{\beta \cdot r_o}{2} \]
The MOSFET implementation of the cascoded current mirror is as follows:

The parameters for the transistors are $W=450\,\text{n}$, $L=45\,\text{n}$ and $V_{TN}=0.2\,\text{V}$.

The compliance voltage is roughly given by

\[
V_{o(\text{min})} = V_{GS2} + V_{GS3} - V_{DS3(sat)} = V_{GS2} + V_{DS3(sat)} = V_{GS2} + V_{GS3} - V_{TN} \\
= 2V_{GS} - V_{TN} = 2 \cdot 1.6V - 0.2V = 3.0V
\]
Note: the compliance voltage appears to be a little lower (around 2.4V).

The drain resistor is given by

\[ R = \frac{V_{DD} - V_{GS4} - V_{GS1}}{I_{REF}} \]

Currents in each branch are related by the following expression:

\[ \frac{I_s}{I_{REF}} = \frac{W_2 / L_2}{W_1 / L_1} \]

Note: the channel-length modulation factor is not present here since for this circuit there is no Early effect.

The output resistance is very high and it’s given by

\[ R_o = r_{o2} + r_{o3}(1 + g_{m3}r_{o2}) \]