SPICE SIMULATIONS OF CURRENT SOURCES BIASING OF LOW VOLTAGE

MONICA-ANCA CHITA, MIHAI IONESCU

Key words: Bias circuits, Current mirrors, Current sources biasing of low voltage, SPICE simulations.

In this paper are presented simulation results for some bias circuits that operate at very low-voltage. It was started from two current mirror circuits: Nagata and Widlar. A Nagata current mirror is very suitable for battery operation because of current regulation and also for superior start-up circuitry. An inverse-Widlar current mirror is a non-linear current mirror for which the temperature characteristic is an inverse of the Widlar current mirror. A Nagata/inverse-Widlar current mirror is a proportional to absolute temperature (PTAT) current mirror or an inverse PTAT current mirror, depending on the relation between two resistors of circuit. As an application of these current mirrors, are presented a self-biasing Nagata current reference with start-up circuitry and a mutual-biasing Nagata/inverse-Widlar current reference with start-up circuitry. Also, a self-biasing Nagata voltage reference that is derived from the self-biasing Nagata current reference by inserting a resistor is presented.

1. INTRODUCTION

In the last time, the necessity of circuit design for operation at very low supplies is in continuous increase. They are used in portable electronic equipment that is supplied from single battery cell, recently. In the paper are presented some biasing circuits that operate at low voltage. The following current mirrors analysed here are a variant of a general two-transistor current mirror from Fig. 1.

![Fig. 1 – General two-transistor mirror.](image)

The fundamental characteristics and temperature characteristics simulated with SPICE [1].

2. CURRENTS MIRROR

The Nagata current mirror [2] showed in Fig. 2a was obtained from circuit in Fig. 1, by setting both R2 and R3 resistors to zero. Expression of the collector current IC is:

\[
I_C = I_S \left[ \exp \left( \frac{V_{BE}}{V_T} \right) \right] \left[ 1 + \frac{V_{CE}}{V_A} \right]
\]  \hspace{1cm} (1)

where: \( V_T = kT/q \) is the thermal voltage, \( k \) is Boltzmann’s constant, \( T \) is absolute temperature in degrees Kelvin, \( q \) is the charge of an electron, \( I_S \) is the saturation current of base-emitter junction, \( V_A \) is the Early voltage, \( V_{BE} \) is the base-to-emitter junction voltage, \( V_{CE} \) is the collector-to-emitter voltage. Ignoring the base-width modulation \( (V_A \rightarrow \infty) \), results expression for \( I_C \):

\[
I_C = I_S \exp \left( \frac{V_{BE}}{V_T} \right)
\]  \hspace{1cm} (2)

From circuit analyse results the relation between \( I_1 \) and \( I_2 \) in Nagata current mirror:

\[
I_2 = K_I I_1 \exp \left( -\frac{R_I I_1}{V_T} \right)
\]  \hspace{1cm} (3)

Fig. 2 – Nagata current mirror: a) circuit; b) simulated temperature characteristics.

The peak value of \( I_2 \) is \( K_I T/e \) and is obtained for \( R_I I_1 = V_T \).
The fractional temperature coefficient (TCF) of the Nagata current mirror is:

\[
TC_F(I_2) = \frac{1}{I_2} \left( \frac{dI_2}{dT} - \frac{I_1}{kT^2} \frac{dR_1}{dT} \right)
\]  

(4)

If \( \frac{dR_1}{dT} = 0 \) then \( TC_F(I_2) > 0 \) and the mirror current will have a positive TC.

Fig. 2b shows the characteristics of the Nagata current mirror at –25, 25 and 75 °C, for \( R_1=100 \, \Omega \), \( K_1=1 \) and \( V_{CE2}=0.5 \, V \). It is observed that Nagata current mirror has two operating regions: before the peak point the output current increase when the reference current increase, and after the peak point the output current decrease when the reference current increase.

By setting resistors, the transfer characteristics can be sharpened, so, the mirror current can be set at a low value at operating point, near zero. The desired value of supply voltage at peak point can be obtained by setting the value of \( \Delta V_{BE} \) to \( V_T \) (\( \Delta V_{BE} = V_{BE1} - V_{BE2} \)). For this reason, the Nagata current mirror is very suitable for start-up circuitry in self-biasing circuits.

The Widlar and inverse-Widlar current mirrors are presented in Fig. 3.

Thus the Widlar current mirror (Fig. 3a) is derived from Fig. 1 by setting both resistors \( R_1 \) and \( R_2 \) to zero [2]. It is a proportional to absolute temperature.
(PTAT) current mirror and the mirror current increase monotonically when the reference current increase.

This current mirror is used in low current source. The output current is:

\[ I_2 = \frac{V_T}{R_1} \ln \left( \frac{I_1 K_1}{I_2} \right) \]

(5)

and the characteristics are showed in Fig. 3c.

The inverse-Widlar current mirror diagram is an inverse of the Widlar current mirror, and the temperature characteristics of the mirror current show that the inverse-Widlar current mirror is an inverse PTAT current mirror (it can be seen from Fig. 3d). This current mirror is useful to provide a temperature-independent bias current by cancelling the TC of the base-to-emitter voltage \((V_{BE})\) with a positive TC.

The mirror current of the inverse-Widlar current mirror is:

\[ I_2 = \frac{I_1}{K_1} \cdot \exp \left( \frac{R_1 I_1}{V_T} \right) \]

(6)

In Fig. 3d are showed the characteristics of the inverse-Widlar current mirror at –25, 25 and 75 °C, for \(R_1=100\Omega\), \(K_1=1\) and \(V_{CE2}=0.5V\).

The TC of inverse-Widlar current mirror is:

\[ TC_F(I_2) = -\frac{R_1 I_1 k}{kT^2} + \frac{I_1}{V_T} \frac{dR_1}{dT} \]

(7)

The Nagata/inverse-Widlar is presented in Fig. 4.

Fig. 4 – Nagata/Inverse Widlar current mirror: a) circuit; b) simulated temperature characteristics when \(R_1>R_2\); c) Simulated temperature characteristics when \(R_1<R_2\).

The circuit is shown in Fig. 4a and is obtained by combining the Nagata current mirror with inverse-Widlar current mirror. The mirror current is:
\[ I_2 = \frac{I_1}{K_1} \exp \left( \frac{(R_2 - R_1)I_1}{V_T} \right) \]  

(8)

The TC of the Nagata/inverse-Widlar current mirror is:

\[ TC_r(I_2) = -\frac{(R_2 - R_1)I_1q}{kT^2} + \frac{I_1}{V_T} \cdot \frac{d(R_2 - R_1)}{dT} \]  

(9)

If \( R_1 > R_2 \), equation (8) is equivalent to (3) and the current mirror is a PTAT current mirror, and also if \( R_1 < R_2 \), equation (8) is equivalent to (6) and the current mirror is an inverse PTAT current mirror. So, the TC of this current mirror is programmable by relation between resistors \( R_1 \) and \( R_2 \), and it is called a TC programmable current mirror.

The characteristics of the Nagata/inverse-Widlar current mirror at –25, 25 and 75 °C, for \( K_1=1 \), \( V_{CE2}=0.5V \), \( R_1=180\Omega \), \( R_2=50\Omega \) and for \( R_1=50\Omega \), \( R_2=180\Omega \) respectively, are showed in Fig. 4b and 4c.

Fig. 5a shows a general self-biasing current reference block diagram obtained by biasing a non-linear current mirror with a linear current mirror. An example of self-biasing reference is showed in Fig. 5b. It is a self-biasing Nagata current reference which is obtained by self-biasing a Nagata current mirror. The output current of the self-biasing Nagata current reference is obtained by substituting \( I_1 = I_2/K_2 \) into (3):

\[ I_1 = \frac{I_2}{K_2} = \frac{V_T}{R_1} \ln \left( \frac{K_1}{K_2} \right) = \left\{ \frac{k}{R_1q} \ln \left( \frac{K_1}{K_2} \right) \right\} \cdot T \]  

(10)

In Fig. 5c are showed the simulation of characteristics of the self-biasing Nagata current reference with start-up circuitry at –25, 25 and 75 °C, for \( R_1 = 50\Omega \), \( R_2 = 100\Omega \), \( R_3 = 300\Omega \), \( K_1 = 3 \), \( K_2 = 1 \). The self-biasing Nagata current reference is a PTAT current reference.
3. ANALYSIS OF VOLTAGE REFERENCES

A voltage reference can be easily realized by inserting a resistor into a reference current loop.

The self-biasing Nagata voltage reference shown in Fig. 6a is derived from the self-biasing Nagata current reference from Fig. 5b by inserting the resistor $R_2$.

The reference voltage is:

$$V_{\text{REF}} = V_{BE_1} + \frac{R_2}{R_1} \Delta V_{BE} = V_{BE_1} + \frac{R_2}{R_1} V_T \ln \left( \frac{K_2}{K_1} \right)$$ \hspace{1cm} (11)

The peak voltage is obtained when $K_1/K_2 = e$. Setting the operation point to the peak at $\Delta V_{BE} = V_T$, the Nagata voltage reference will have a superior regulation.

The characteristics of the self-biasing Nagata voltage reference with start-up circuitry at −25, 25 and 75 °C, for $R_1 = 270 \, \Omega$, $R_2 = 2.7 \, \text{K}\Omega$, $R_3 = 100 \, \Omega$, $R_4 = 280\Omega$, $K_1 = 3$ and $K_2 = 1$ are showed in Fig. 7b.

4. CONCLUSIONS

In this paper are presented simulation results for some bias circuits that operate at very low-voltage. For these circuits are presented the fundamental characteristics and temperature characteristics simulated with SPICE. A Nagata current mirror is very suitable for battery operation because of current regulation and also for superior start-up circuitry. An inverse-Widlar current mirror is an inverse PTAT current mirror and Nagata/inverse-Widlar current mirror is a PTAT
or inverse-PTAT programmable current mirror. If is inserting a resistor into a reference current loop is obtained a reference voltage with a very small temperature coefficient. The circuits analysed here were implemented in bipolar technology, but they could be realised in another technology, too.

REFERENCES