

values of IC_0 . The output voltage is always *larger* than the input voltage, but the difference becomes very small for $I_1 \gg I_b$. For a given value of I_1/I_b , the difference is minimum if $IC_0 \ll 1$ (OTA without feedback in weak inversion).

A high current efficiency can be obtained by choosing $B \gg 1$ (ratio of mirror M_3 - M_7).

As long as the differential pair remains in weak inversion, (8.25) reduces to

$$\frac{V_i - V_o}{nU_T} = -\ln \left(1 + \frac{I_b}{I_1} \right). \quad (8.26)$$

8.4 Exponential Characteristics

8.4.1 Voltage and Current Reference

The exponential dependency of the drain current on V_S/U_T makes it possible to extract a voltage proportional to U_T as shown in Figure 8.8. The basic

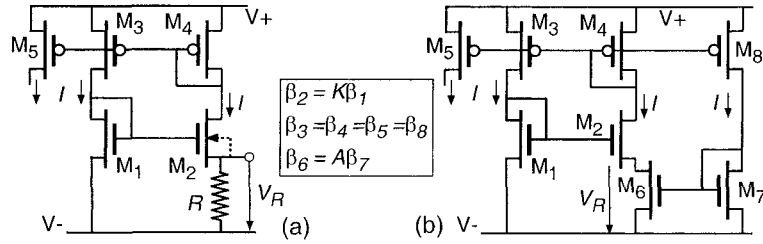


Fig. 8.8. Voltage and current reference: (a) basic circuit; (b) resistor-less current reference.

circuit [31] shown in part (a) of the figure contains a 1-to- K N-channel current mirror M_1 - M_2 , with the source of M_2 degenerated by a resistor R . A 1-to-1 P-channel current mirror M_3 - M_4 (or any equivalent circuit) imposes the same current in the two branches. Therefore, a source voltage V_R builds-up across resistor R to compensate the ratio K of the N-channel mirror. If this mirror is in weak inversion, then

$$V_R = RI = U_T \ln K. \quad (8.27)$$

This voltage should be sufficiently larger than the threshold mismatch of M_1 - M_2 . In practice, it cannot be made much larger than $4U_T$, which corresponds to $K = 55$. It can be used as a PTAT voltage reference, or as a compensation voltage in a band gap voltage references [32].

A reference current I can be extracted by the additional mirror transistor M_5 . Thanks to the small value of V_R a small current can be obtained with a reasonably low value of R .

If the transistor M_2 is in a separate well connected to its source, as shown by the dotted line, then $V_{S2} = V_{S1} = 0$. The factor K is then compensated by a difference of gate voltages, and U_T is multiplied by n in (8.27).

Figure 8.8(b) shows a variant of the basic circuit in which the resistor is replaced by transistor M_6 [166]. This transistor is the output transistor of a current mirror M_7 - M_6 of ratio 1 to A , that operates in *strong inversion*, with the reference current itself as its input. If $A \gg 1$, then $I_{F6} = AI_{F7} = AI \gg I$. Hence, far from being saturated, M_6 is biased close to $V_D = V_S = 0$ where it behaves like a resistor of value $R = 1/G_{ms6}$ given by (5.45):

$$1/R = G_{ms6} = \sqrt{2n\beta_6 AI}. \quad (8.28)$$

By introducing this value in (8.27) we obtain, after arranging the result

$$I = 2n\beta_6 U_T^2 \cdot A(\ln K)^2 = I_{spec6} \cdot A(\ln K)^2. \quad (8.29)$$

This current is obtained without using any resistor, and is proportional to the specific current of transistor M_6 . Therefore, as noticed at the end of Section 5.7, it becomes almost independent of the temperature if the mobility is proportional to $T^{-\alpha}$ with $\alpha \cong 2$.

In practice, (8.28) is an acceptable approximation for $A > 5$.

It should be mentioned that the loop M_6 - M_2 - M_4 - M_8 - M_7 implements a positive feedback. However, the gain of this loop can be shown to be $1/2$ at equilibrium.

8.4.2 Amplitude Regulator

The exponential characteristics of transistors in weak inversion are exploited in the amplitude regulator depicted in Figure 8.9(a) [31]. The sinusoidal signal of amplitude V produced by the oscillator enters the regulator through capacitor C_1 , and transistor M_5 delivers the output current used to bias the oscillator.

When no oscillation is present ($V = 0$), the circuit is reduced to the current

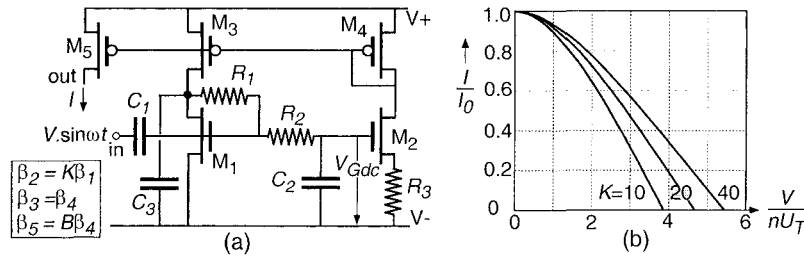


Fig. 8.9. Amplitude regulator for oscillators: (a) circuit; (b) transfer characteristics.

reference of Figure 8.8(a). According to (8.27), it delivers an output current