Microelectronics Journal 40 (2009) 921–927

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

A BJT technology-based current-mode tunable all-pass filter

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A R T I C L E I N F O

Article history:
Received 30 July 2008
Received in revised form
9 February 2009
Accepted 24 February 2009
Available online 25 March 2009

Keywords:
All-pass filter
Current-mode
BJT
Electronic tunability

A B S T R A C T

In this paper, a new bipolar technology-based configuration for providing inverting first-order current-mode (CM) all-pass filter response is proposed. One of the main advantages of the introduced active C topology is to have the property of electronic tunability of its pole frequency without requiring passive component matching condition. To show the performance of suggested filter, simulations are achieved by means of PSPICE program. Moreover, experimental test results are included.

1. Introduction

All-pass filters, namely phase shifters are very popular processing block in analog signal operations to obtain time delays for the input signals while keeping the amplitude constant. All-pass filters being special cases of the filter transfer functions (TFs) offer many advantages in analog filter design [1]. All-pass filters are used to cancel out the unwanted sideband of an AM radio transmission [2]. Zero and pole of a first-order all-pass filter are symmetrically located relative to the imaginary axis. Because of this location, while transmission coefficient is constant at all frequencies, its phase shows frequency selectivity. Many reported voltage-mode (VM) all-pass topologies [3–8] where the circuit of [7] employs five CMOS transistors while others use basic building blocks such as plus-type second-generation current conveyors (CCII+s) composed of a number of bipolar junction transistor (BJT)/ CMOS transistors. Similarly, current-mode (CM) all-pass filters [8–14] include basic building blocks. For example, as a basic building block, a dual-output current-controlled current conveyor (DO-CCCII) used in [15] contains 20 BJTs. Additionally, a tunable all-pass filter and multiband all-pass filter topologies have been reported in [16,17], respectively. On the other hand, CM processes have some important advantages e.g., good linearity, wide bandwidth and large dynamic range [18,19] when compared to their VM counterparts.

In this paper, an electronically tunable first-order inverting CM all-pass filter using only three bipolar junction transistors and current mirrors as active devices and a capacitor as a passive component is suggested. The proposed filter whose pole frequency can be controlled electronically by means of a bias current does not need passive component matching constraints. However, introduced all-pass filter consists of a floating capacitor that can be easily realized by means of advanced IC technologies. These IC technologies offer a second poly layer (poly2) enabling the realization of the floating capacitor as double poly (poly1–poly2) capacitor [20]. Several time-domain and frequency-domain responses, total harmonic distortion (THD) and noise analysis via SPICE simulation program besides experimental test results are given to verify the theoretical results.

2. Proposed first-order all-pass filter

As an active device, a BJT whose electrical symbol is depicted in Fig. 1a, is commonly preferred by the researchers for general purpose where $i_B = i_b + I_B$, $i_C = i_c + I_C$ and $i_E = i_e + I_E$. Furthermore, i_b, i_c and i_e are ac currents while I_B, I_C and I_E are dc currents. Small signal model of the BJT is demonstrated in Fig. 1b. In the equivalent circuit, some parameters of the small signal model are defined as transconductance $g_m = I_C/V_T$, base-emitter voltage v_π and input resistance $r_\pi = V_T/I_B$ where V_T is the thermal voltage approximately equal to 26 mV at room temperature [1]. On the other hand, a BJT has four modes of operation called as OFF, forward active, reverse active and saturation. For large input signals, the BJT behaves like an exponential current–voltage converter while the BJT operates like a linear current–voltage converter for sufficiently small input signals.

As shown in Fig. 1, BJT is a three terminal active device whose terminal currents can be defined as follows:

$$i_C + i_B + i_E = 0 \tag{1a}$$

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doi:10.1016/j.mejo.2009.02.008

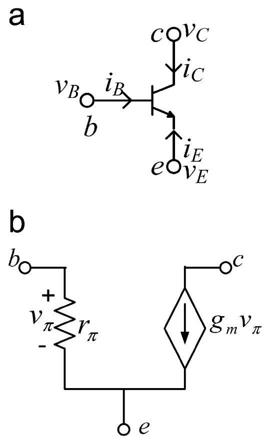

Fig. 1. (a) Circuit symbol of a BJT and (b) its basic small signal equivalent circuit [1].

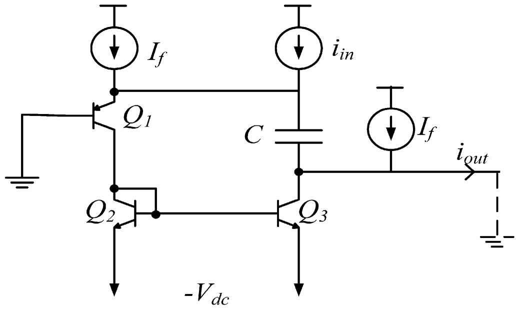

Fig. 2. Proposed first-order all-pass circuit.

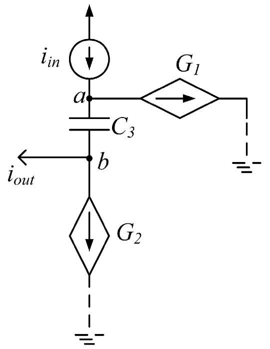

Fig. 3. Concept of suggested current-mode all-pass filter.

$$\begin{aligned}\frac{|i_E|}{i_B} &= \frac{i_C}{i_B}+1 \\ &= \beta+1\end{aligned} \tag{1b}$$

where $\beta = i_C/i_B$ is the frequency-dependent current gain and using a single pole model, β can be described by

$$\beta = \frac{\beta_0}{1+(j\omega/\omega_C)} \tag{2}$$

in Eq. (2), β_0 is dc current gain and ω_C is cut-off frequency of the current gain, respectively. The following equation describes TF of the developed first-order all-pass filter depicted in Fig. 2.

$$H(s) = \frac{i_{out}}{i_{in}} = \frac{s-\omega_0}{s+\omega_0} \tag{3}$$

Here, $\omega_0 = I_f/(CV_T)$, if capacitor voltage is equal to emitter-base voltage of Q_1, determines resonance frequency. In frequency-domain, phase responses of the introduced filter whose TF is given in Eq. (3) is found as

$$\varphi(\omega) = \pi - 2\arctan\left(\frac{\omega}{\omega_0}\right) \tag{4}$$

The proposed CM first-order all-pass filter employing only three BJTs (one PNP and two NPNs), current mirrors and a capacitor. In the ideal case, current gain is large enough, values of the base currents are zero whereas in the real design, base currents should be taken into consideration. Collector currents of the transistors of the introduced CM circuit are determined as

$$I_{C1} = \frac{\beta_1}{\beta_1+1} I_f \tag{5a}$$

$$I_{C2} = \left(\frac{\beta_1}{\beta_1+1}\right)\left(\frac{\beta_2\beta_3}{\beta_2\beta_3+\beta_2+\beta_3}\right) I_f + \left(\frac{\beta_2}{\beta_2\beta_3+\beta_2+\beta_3}\right) I_{D23} \tag{5b}$$

$$I_{C3} = \left(\frac{\beta_1}{\beta_1+1}\right)\left(\frac{\beta_2\beta_3}{\beta_2\beta_3+\beta_2+\beta_3}\right) I_f - (\beta_2+1)\left(\frac{\beta_3}{\beta_2\beta_3+\beta_2+\beta_3}\right) I_{D23} \tag{5c}$$

where, $I_{D23} = I_{C2} - I_{C3}$.

As observed from the above three equations that each collector current varies with frequency-dependent forward current gain β_i ($i = 1, 2, 3$). In Fig. 3, model of the presented inverting CM all-pass filter is shown. If matching condition for the circuit in Fig. 3 is not considered, $G_1 = G_2 = G$ and $C_3 = C$, the following TF can be easily obtained

$$H(s) = \frac{i_{out}}{i_{in}} = \frac{sC(v_a - v_b) - G}{sC(v_a - v_b) + G} \tag{6}$$

where $G = \omega_0 C(v_a - v_b)$ is voltage-controlled current source. If the component of C having a constant value is tied between nodes a and b, then the first term of numerator and denominator describes current of the capacitor.

By using small signal approximation, input and output currents of the proposed all-pass filter in Fig. 2 can be, respectively, obtained by the following equations:

$$i_{in} = i_{cap} + \left(\frac{\beta_1+1}{\beta_1}\right) g_{m1} v_{\pi 1} \tag{7a}$$

$$\begin{aligned} i_{out} = i_{cap} &- \left(\frac{\beta_2\beta_3}{\beta_2\beta_3+\beta_2+\beta_3}\right) g_{m1} v_{\pi 3} \\ &+ (\beta_2+1)\left(\frac{\beta_3}{\beta_2\beta_3+\beta_2+\beta_3}\right)(g_{m2} - g_{m3}) v_{\pi 3} \end{aligned} \tag{7b}$$

in (7a) and (7b), i_{cap} is capacitor current. From (7a) and (7b), the TF of suggested configuration is calculated as

$$H(s) = \frac{i_{cap} - ((\beta_2\beta_3)/(\beta_2\beta_3+\beta_2+\beta_3)) g_{m1} v_{\pi 3} + (\beta_2+1)(\beta_3/(\beta_2\beta_3+\beta_2+\beta_3))(g_{m2} - g_{m3}) v_{\pi 3}}{i_{cap} + ((\beta_1+1)/\beta_1) g_{m1} v_{\pi 1}} \tag{8}$$

here, extra terms multiplied by the angular resonance frequency in numerator and denominator, are errors due to non-zero base currents. If $\beta_1 = \beta_2 = \beta_3 \gg 1$, the angular resonance frequency in