New Gain Controllable Resistor-less Current-mode First Order Allpass Filter and its Application

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Abstract. New first order allpass filter (APF) in current mode, constructed from 2 CCCCTAs and grounded capacitor, is presented. The current gain and phase shift can be electronically/orthogonally controlled. Low input and high output impedances are achieved which make the circuit to be easily cascaded to the current-mode circuit without additional current buffers. The operation of the proposed filter has been verified through simulation results which confirm the theoretical analysis. The application example as current-mode quadrature oscillator with non-interactive current control for both of oscillation condition and oscillation frequency is included to show the usability of the proposed filter.

Keywords
First order allpass filter, CCCCTA, current-mode.

1. Introduction

A first order all-pass filter or phase shifter is a very useful function blocks of many analog signal processing applications. It is frequently used in many active circuits such as phase shifters, oscillators and high-Q band-pass filters [1-5]. In recent years, a number of papers have been published dealing with the realization of current-mode circuits [6-8] due to their certain advantages compared to voltage-mode circuits. They offer to the designer several excellent features such as inherently wide bandwidth, greater linearity, wider dynamic range, simple circuitry and low power consumption [9]. Especially, the first order all-pass filter with gain controllability is very useful for design in many analog circuits to avoid the use of external amplifiers, for examples quadrature oscillator [10] and multiphase sinusoidal oscillator [11] with non-interactive control for oscillation condition and oscillation frequency.

Several realizations of current-mode first order all-pass filter using different active building blocks have appeared in the literature. These include realizations using current conveyors [12-15], OTAs [16-20], current controlled current conveyors (CCCIIs) [21], differential voltage current conveyor (DVCC) [22], current operational amplifier (COA) [23], current differencing buffered amplifier (CDBA) [5] and current differencing transconductance amplifier (CTA) [10-11, 24-27]. The literature review of reported current-mode APFs shows that the weaknesses of these APFs are list below:

- use of floating capacitor which is not desirable for IC implementation [5, 10, 12, 13, 15, 20-26],
- lack of electronic adjustability [5, 12-15, 22-23],
- requirement of element-matching conditions [12, 14, 15-19, 22],
- non-availability of the current-output from a high output impedance terminal [13, 20],
- uncontrollability of current gain [5, 12-22-24, 26-27],
- requirement of external resistor [5, 10-16, 18-19, 22, 23-25].

The aim of this paper is to propose a gain controllable current-mode first-order all-pass filter, emphasizing on the use of the CCCCTAs. The features of the proposed circuit are that: the current gain and phase shift can be electronically controlled; the circuit employs 2 CCCCTAs and single grounded capacitor as passive component, which is suitable for fabricating in monolithic chip. The proposed APF also exhibits high-output and low-input impedances, which is easy cascading in the current-mode operation. The performances of the proposed circuit are illustrated by PSpice simulations, they show good agreement with the calculation. The application example of the proposed all-pass filter as a quadrature oscillator is included.

2. Theory and Principle

2.1 Basic Concept of CCCCTA

The principle of the CCCCTA was published in 2008 by S. Siripruchyanun and W. Jaikla [28]. The schematic...
symbol and the ideal behavioral model of the CCCCTA are shown in Fig. 1(a) and (b). The characteristics of the ideal CCCCTA are represented by the following hybrid matrix:

\[
\begin{bmatrix}
I_x \\
V_x \\
I_z \to x \\
I_y \\
I_z \\
V_x \\
I_x \\
0 \\
0 \\
\end{bmatrix} = 
\begin{bmatrix}
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
I_x \\
V_x \\
I_z \to x \\
I_y \\
I_z \\
V_x \\
I_x \\
0 \\
0 \\
\end{bmatrix}
\]

(1)

If the CCCCTA is realized using BJT technology, \(R_x\) and \(g_m\) can be respectively written as

\[
R_x = \frac{V_T}{2I_{B_1}},
\]

(2)

and

\[
g_m = \frac{I_{B_2}}{2V_T}.
\]

(3)

\(V_T\) is the thermal voltage, \(I_{B_1}\) and \(I_{B_2}\) are the bias currents used to control the parasitic resistance and transconductance, respectively. In some applications, to utilize the current through \(z\) terminal, an auxiliary \(z_c\) (\(x\)-copy) terminal is used [29]. The internal current mirror provides a copy of the current flowing out of the \(z\) terminal to the \(z_c\) terminal. The BJT implementation of the CCCCTA is shown in Fig. 2.

\[\text{Fig. 2. Schematic of the BJT CCCCTA.}\]

2.2 Proposed Current-mode First-order Allpass Filter

The proposed current-mode APF is illustrated in Fig. 3. It consists of 2 CCCCTAs and 1 grounded capacitor. It should be noted that to achieve low input impedance of the filter, the first CCCCTA should has low impedance \((R_x \approx 0)\) by setting value of \(I_{B_1}\) as high as possible. The sign \(\pm\) in the first CCCCTA shows plus or minus polarity of the current output. Considering the circuit in Fig. 3 and using CCCCTA properties in section 2.1, the current transfer function can be rewritten to be

\[
\frac{I_{n\text{out}}(s)}{I_n(s)} = \pm g_m R_x \left( \frac{sC + g_m}{sC + g_m} \right).
\]

(4)

From (4), the natural frequency, current gain and phase responses of the proposed circuit are

\[
o_m = \frac{g_m}{C},
\]

(5)

\[
G(\omega) = \left| \frac{I_{n\text{out}}(s)}{I_n(s)} \right| = g_m R_x,
\]

(6)

\[
\phi(\omega) = 180 - 2 \tan^{-1} \left( \frac{\omega C}{g_m} \right),
\]

(7)

and

\[
\phi(\omega) = -2 \tan^{-1} \left( \frac{\omega C}{g_m} \right).
\]

(8)

From (9)-(12), it can be seen that the current gain can be adjusted electronically/independently from the natural frequency and phase responses by varying \(I_{B_2}\) or \(I_{B_3}\) while the natural frequency and phase responses can be electronically adjusted by \(I_{B_4}\).

3. Non-ideal Cases

In practice, the CCCCTA is possible to work with non-idealities. Its properties will change to

\[\text{Fig. 3. Proposed gain controllable APF.}\]
\( I_y = \alpha I_x; \beta V_y + I_R z; I_{\omega} = \gamma I_x \),

where \( \alpha \) and \( \gamma \) are the parasitic current transfer gains from \( x \), and \( z \), terminals to \( z \) terminal, respectively. \( \beta \) is the parasitic voltage transfer gain from \( y \) terminal to \( x \). Considering the current transfer gains, the modified current parasitic voltage transfer gain from \( y \) terminal to \( x \), and \( z \) terminals to \( z \) terminal, respectively.

From (14), the natural frequency, current gain and phase responses of the proposed circuit are

\[
\omega_0 = \frac{\alpha g_m R_2}{C},
\]

\[
G(\omega) = \frac{I_{\omega}}{I_o} = \pm \alpha g_m R_2 \sqrt{\frac{(\omega C)^2 + (\gamma g_m)^2}{(\omega C)^2 + (\alpha g_m)^2}},
\]

\[
\phi(\omega)_+ = 180 - \tan^{-1} \left( \frac{\omega C}{\gamma g_m} \right) - \tan^{-1} \left( \frac{\omega C}{\alpha g_m} \right),
\]

and

\[
\phi(\omega)_- = -\tan^{-1} \left( \frac{\omega C}{\gamma g_m} \right) - \tan^{-1} \left( \frac{\omega C}{\alpha g_m} \right).
\]

On the other hand, the influence of parasitic terminal impedances of CCCCTA will be also considered. These are terminal \( y \) \((R_y/C_y)\), terminal \( z \) \((R_z/C_z)\) and terminal \( o \) \((R_o/C_o)\). The simplified current transfer function (assuming \( R_y, R_z \) and \( R_o > > R_{\omega} \)), for the circuit of Fig. 3, is given as

\[
\frac{I_{\omega}}{I_o} = \pm g_m R_2 \left[ \frac{\alpha g_m R_2}{\omega C + (\gamma g_m)^2} \right],
\]

where \( C_2 = C_1 + C_{o2} \) and \( C_0 = C + C_1 + C_{z2} \). It is found that (19) is second order transfer function. Then, the natural frequency, current gain and phase responses of the proposed circuit are

\[
\omega_0 = \frac{g_{o2}}{C_{\omega2} R_2},
\]

\[
G(\omega) = \frac{I_{\omega}}{I_o} = g_m R_2 \sqrt{\frac{(\omega C_\omega)^2 + (g_{o2})^2}{(\omega C_\omega)^2 + (g_{o2} - \alpha g_m C_{z2} R_2)^2}},
\]

\[
\phi(\omega)_+ = 180 - \tan^{-1} \left( \frac{\omega C_\omega}{g_{o2}} \right) - \tan^{-1} \left( \frac{\omega C_\omega}{g_{o2} - \alpha g_m C_{z2} R_2} \right),
\]

and

\[
\phi(\omega)_- = -\tan^{-1} \left( \frac{\omega C_\omega}{g_{o2}} \right) - \tan^{-1} \left( \frac{\omega C_\omega}{g_{o2} - \alpha g_m C_{z2} R_2} \right).
\]

### 4. Results of Computer Simulation

The working of the proposed APF has been verified in PSpice simulation using the BJT implementation of the CCCCTA as shown in Fig. 2. The PNP and NPN transistors employed in the proposed circuit were simulated by using the parameters of the PR200N and NR200N bipolar transistors of ALA400 transistor array from AT&T [30]. The circuit was biased with ±2.5 V supply voltages, \( C = 1 \text{nF} \), \( I_{B1} = I_{B2} = 100 \mu A \), \( I_{B4} = 200 \mu A \) and \( I_{B3} = 50 \mu A \). Simulated gain and phase responses of the non-inverting APF are given in Fig. 4. It can be found that the simulated gain and phase responses are slightly deviated from ideal responses due to the error terms as expressed in (16), (17), (21) and (22). Phase response for different \( I_{B4} \) is shown in Fig. 5. This result confirms that the angle natural frequency can be electronically controlled by setting \( I_{B4} \) as shown in (11). The time-domain response of the proposed filter is shown in Fig. 6 where a sine wave of 30 µA amplitude and 0.2 MHz is applied as the input to the filter and the output is 90 phase-shifted. The output currents for different values of \( I_{B4} \) are shown in Fig. 7. It is seen that the current gain can be electronically/independently adjusted from the natural frequency and its phase shift as expressed in (10).
5. Application Example as Current-mode Quadrature Oscillator

To show an application of the proposed allpass filter, a current-mode quadrature oscillator with non-interactive current control for both of oscillation condition and oscillation frequency is synthesized by cascading an inverting and non-inverting allpass filters as shown in Fig. 8. From the block diagram in Fig. 8, if \( k_1 = g_m a_1 R_{c2} \), \( k_2 = g_m a_2 R_{s4} \), \( a_1 = g_m a_2 / C_1 \) and \( a_2 = g_m a_4 / C_2 \), the following characteristic equation can be obtained

\[
s^2 + 2s a_1 a_2 \left( \frac{1-k_2}{1+k_2} \right) + a_1 a_2 = 0. \tag{24}
\]

From (24), the oscillation condition and oscillation frequency can be written as

\[
g_m a_1 a_2 = 1, \tag{25}
\]

and

\[
\omega_{osc} = \frac{g_m a_1 a_2}{C_1 C_2}. \tag{26}
\]

If \( g_{m1} = I_{B1} / 2V_T \) and \( R_{c1} = V_T / I_{B1} \), the oscillation condition and oscillation frequency can be expressed as

\[
\frac{I_{B1} I_{B2}}{16 I_{B1} I_{B7}} = 1, \tag{27}
\]

and

\[
\omega_{osc} = \frac{1}{2V_T} \sqrt{\frac{I_{B1} I_{B7}}{C_1 C_2}}. \tag{28}
\]

It can be found that both oscillation condition and frequency can be electronically/independently controlled. The circuit description of the quadrature oscillator is shown in Fig. 9.

From (24), the oscillation condition and oscillation frequency can be written as

\[
g_m a_1 a_2 = 1, \tag{25}
\]

and

\[
\omega_{osc} = \frac{g_m a_1 a_2}{C_1 C_2}. \tag{26}
\]

6. Conclusion

An electronically tunable current-mode first-order allpass filter with gain controllability has been introduced via this paper. It consists of 2 CCCCTAs and grounded capacitor. So it is easy to fabricate in IC form to use in battery-powered or portable electronic equipments such as wireless communication devices. The PSpice simulation results were depicted, and agree well with the theoretical anticipation. The application example as the quadrature oscillator is included. It shows good usability of the proposed allpass filter.

References


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