Electronically Tunable Phase Shifter Using CDTAs

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Abstract— **The realization of an electronically tunable phase shifter using current differencing transconductance amplifiers (CDTAs) as active components is presented. The proposed filter employs only two CDTAs and one virtually grounded capacitor, which its phase shift can be electronically adjusted by varying the bias current of the CDTA. The circuit also exhibits high-output impedance, which is easy cascading in the current-mode operation. As application example, the current-mode biquad filter based on the proposed CDTA-based phase shifter circuit is also presented. PSPICE simulation results of the proposed circuit and its application are given to confirm the theoretical analysis.**

I. Introduction

The phase shifter is widely used in analog signal-processing applications. In general, it is used for phase shifting from 0° to 180° (or from 180° to 0°), while keeping the amplitude of the signal constant over the frequency range of interest. It can also be used to realize universal biquadratic filters, to synthesize quadrature and multiphase oscillators, and to implement high quality factor frequency selective filters [1]-[6]. Current-mode circuits are receiving much attention because of their potential advantages such as wider bandwidth, wider dynamic range, simpler circuitry, and lower power consumption. Considering this fact, a number of current-mode first-order allpass filter realizations using different active building blocks were reported in the literature [6]-[10]. Most of these circuits use a large passive component count and suffer from the need of passive component ratio-matching conditions. Moreover, none of them are electronically adjustable. Although first-order translinear-C current-mode allpass sections with electronic tuning properties were reported in [11], they suffers from low output impedances.

In this paper, we propose an electronically tunable phase shifter realization using only two CDTAs and one virtually grounded capacitor. Due to electronically tunability properties of the CDTA [6], [12], the phase response of the proposed circuit can be adjusted by an external bias current. No component-matching condition for realizing the allpass function is required. Also, the circuit is cascadable and suitable for monolithic integration. The second-order current-mode notch and allpass filters consisting of the proposed CDTA-based phase shifter sections are also discussed as an application example. Simulation results that agree very well with the theoretical values are obtained.

II. Current Differencing Transconductance Amplifier (CDTA)

The electrical symbol of the CDTA is shown in Fig.1, where p and n are input terminals, z and x are output terminals. The terminal relations of the CDTA can be expressed by the following equations :

$$v_p = v_n = 0 \, , \; i_z = i_p - i_n \; \text{and} \; i_x = g_m v_z = g_m Z_z i_z \qquad (1)$$

where g_m is the transconductance gain of the CDTA, and Z_z is an impedance connected at the terminal z. From equation (1) can conclude that the current through the terminal z (i_z) follows the difference of the currents through the terminals p and n (i_p-i_n), and flows from the terminal z into an outside impedance Z_z. The voltage drop at the terminal z is transferred to a current at the terminal x (i_x) by a transconductance gain (g_m), which is electronically controllable by an external bias current.
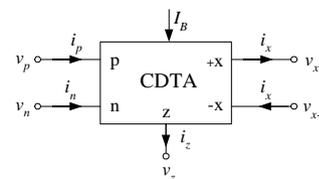
Figure 1. Symbol of the CDTA

The possible bipolar implementation of the CDTA circuit used in this work is shown in Fig.2 [13]-[14]. It mainly consists of a current subtractor formed by current followers Q_{1p}-Q_{4p} and Q_{1n}-Q_{4n}, and a multiple-output transconductance amplifier Q_8-Q_{20} that converts the voltage drop at the terminal z (v_z) to its corresponding differential output currents i_x. In this case, the transconductance gain g_m is directly proportional to the external bias current I_B, which can be written by :

$$g_m = \frac{I_B}{2V_T} \qquad (2)$$

where $V_T \cong 26$ mV at 27°C is the thermal votage.
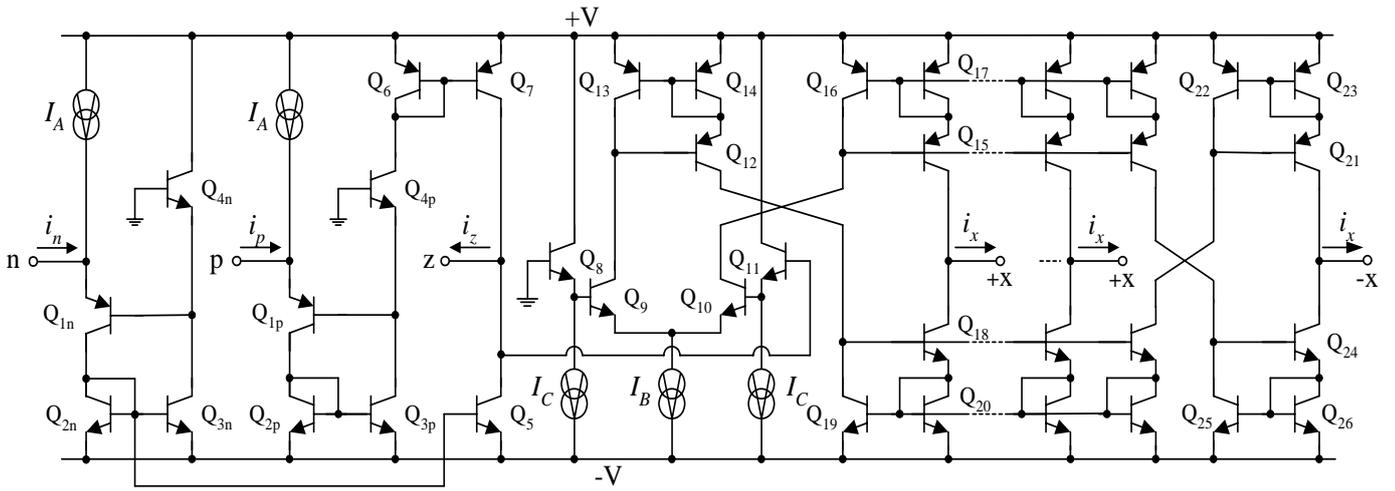
Figure 2. Possible bipolar implementation of the CDTA.
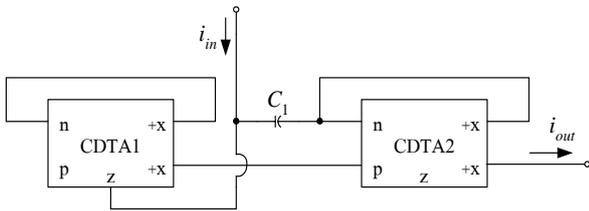
Figure 3. Proposed electronically tunable phase shifter using CDTAs.

III. PROPOSED CIRCUIT

The proposed electronically tunable phase shifter employing two CDTAs and one virtually grounded capacitor is shown in Fig 3. From routine calculations for the proposed filter, the current transfer function can be given by :

$$H(s) = \frac{I_{out}(s)}{I_{in}(s)} = \frac{\left(1 - s\dfrac{C_1}{g_{m1}}\right)}{\left(1 + s\dfrac{C_1}{g_{m1}}\right)}. \tag{3}$$

Equation (3) shows that the circuit in figure 3 realizes the first-order allpass transfer function. Because the output terminal of the proposed first-order allpass filter is connected to the x terminal of the CDTA2, the output terminal can be directly connected to the next stage. Where g_{m1} is the transcondutance of CDTA1. For CDTA2, its transconductance can be set arbitrary. The pole frequency (ω_o) and the phase response (ϕ) can be found as :

$$\omega = \frac{g_{m1}}{C_1} \tag{4}$$

and

$$\phi = -2\tan^{-1}\left(\frac{\omega C_1}{g_{m1}}\right). \tag{5}$$

Therefore, the phase response of the proposed phase shifter can be electronically controlled through CDTA's bias current.

IV. SIMULATION RESULTS

To verify the theoretical analysis, PSPICE simulation has been used to confirm the characteristics of the proposed filter of Fig.3. In simulations, the CDTA was performed with the transistor model of PR100N (PNP) and NP100N (NPN) of the bipolar arrays ALA400 from AT&T [15]. The bias conditions were chosen as : V = ±3V, I_A = 100 μA, I_C = 50 μA and C_1 = 1 nF. I_B is given externally to control the transconductance.
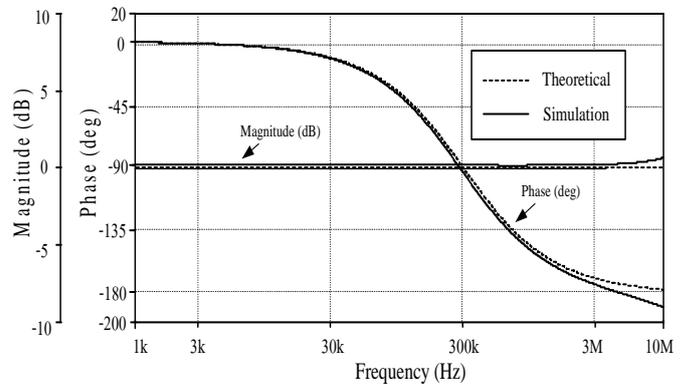
Figure 4. Magnitude and phase responses of the proposed electronically tunable phase shifter.

To obtain $f_o \cong 292$ kHz, while their theoretical value is $f_o = \omega_o/2\pi \cong 318$ kHz, the active and passive components were chosen as : g_{m1} = 2 mA/V (I_B = 100 μA), and C_1 = 1 nF. Fig.4 shows the magnitude and phase responses of the electronically tunable phase shifter, which is obvious that the

simulated responses are found to be in good agreement with the theoretically predicted behavior.
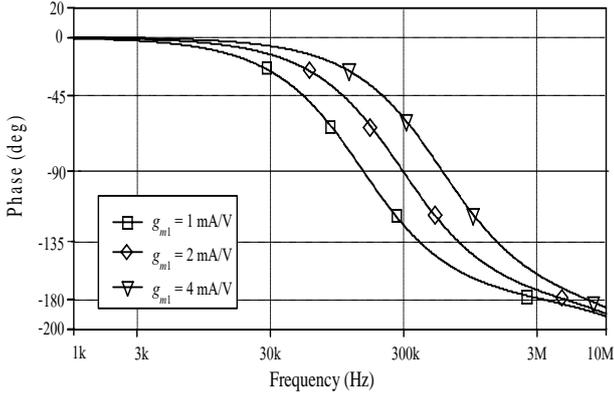
Figure 5. Simulated phase responses of the proposed electronically tunable phase shifter when g_{m1} is varied.

To demonstrate the electronically controllability property of the phase shift, Fig.5 shows the simulated phase responses of the proposed electronically tunable phase shifter when g_{m1} is respectively adjusted to 1 mA/V, 2 mA/V and 4 mA/V. From the simulations, it can be observed that the phase shift are approximately located at -127°, -90° and -53°, while the theoretical values are -126°, -90° and -50°, respectively.

V. APPLICATION EXAMPLE

As an application of the proposed CDTA-based phase shifter circuit, the current-mode biquadratic filter realizing both notch and allpass functions is implemented.   The resulting circuit is now shown in Fig.6. By setting $i_1 = i_2 = i_{in}$, the current transfer function of this circuit can be given by:

$$\frac{I_{out}(s)}{I_{in}(s)} = \frac{\left[s^2 + s\left(\frac{g_{m2}}{C_2} - 3\frac{g_{m1}}{C_1} \right) + \frac{g_{m1}g_{m2}}{C_1C_2} \right]}{\left[s^2 + s\left(\frac{g_{m1}}{C_1} + \frac{g_{m2}}{C_2} \right) + \frac{g_{m1}g_{m2}}{C_1C_2} \right]} \quad (6)$$

From equation (6), if $g_{m2} = 3g_{m1}$ and $C_1 = C_2$, a second-order notch funtion can be realized. Moreover, if $g_{m1} \geq g_{m2}$ and $C_2 \geq C_1$, a second-order allpass funtion can also be obtained. The pole angular frequency (ω_o) and the quality factor (Q) of the proposed filter can be expressed as:

$$\omega_o = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \quad (7)$$

and
$$Q = \frac{\sqrt{g_{m1}g_{m2}C_1C_2}}{g_{m1}C_2 + g_{m2}C_1} \quad (8)$$

The sensitivities with respect to the active and passive parameters can be written as :

$$S_{g_{m1},g_{m2}}^{\omega_0} = -S_{C_1,C_2}^{\omega_0} = \frac{1}{2} \quad (9)$$

and
$$S_{g_{m1},C_2}^{Q} = -S_{g_{m2},C_1}^{Q} = -\frac{1}{2}\frac{\left(g_{m1}C_2 - g_{m2}C_1 \right)}{\left(g_{m1}C_2 + g_{m2}C_1 \right)} \quad (10)$$

It is important to node that the active and passive sensitivities are lower than 0.5 in magnitude.
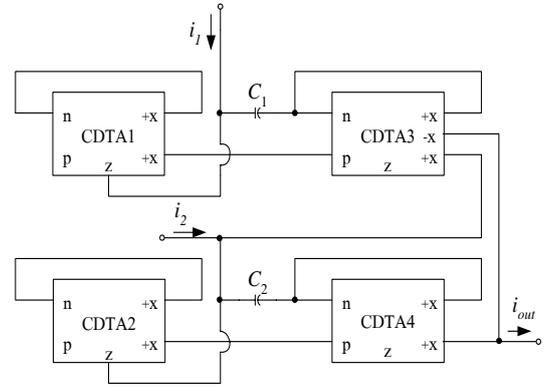
Figure 6. Current-mode biquadratic filter using the proposed CDTA-based phase shifter sections.

(a)

(b)
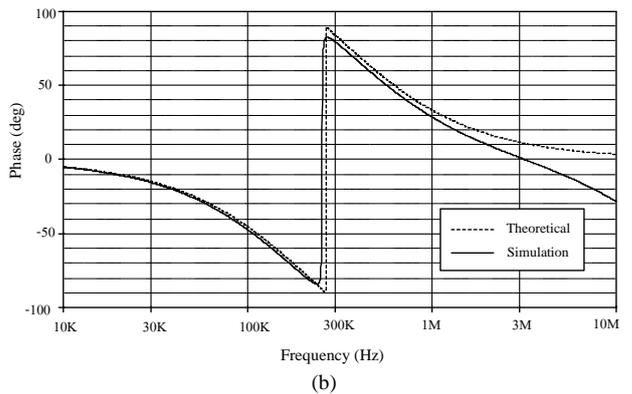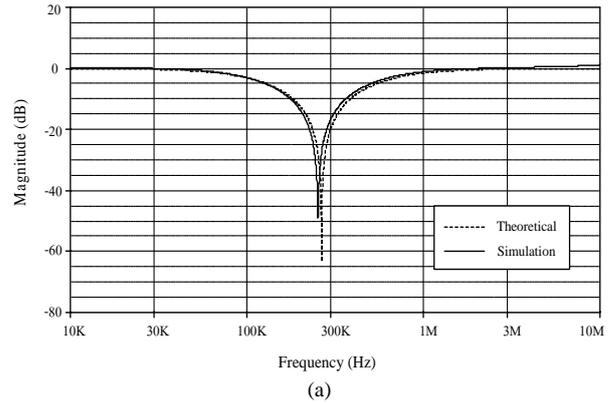
Figure 7. Theoretical and simulated results of the notch filter of Fig.6
(a) magnitude response   (b) phase response

Fig.7 depicts the simulated magnitude and phase responses of the notch filter of Fig.6 with $g_{m1} = 1$ mA/V, $g_{m2} = 3$ mA/V and $C_1 = C_2 = 1$ nF. Fig.8 shows the simulated frequency responses of the allpass filter of Fig.6, comparing with the ideal responses, when $g_{m1} = g_{m2} = 2$ mA/V and $C_1 = C_2 = 1$ nF. It should be noted from both figures that, by properly setting the g_m-value, the filter can realize current-mode second-order notch and allpass filter functions without changing the circuit topology.
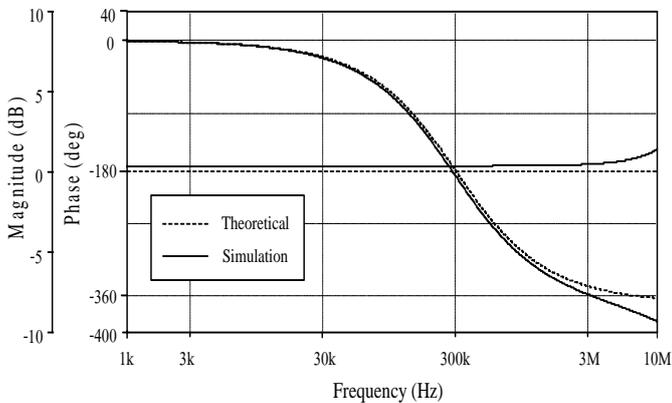
Figure 8. Magnitude and phase responses of the allpass filter of Fig.6

VI. CONCLUSIONS

This paper has been proposed a new configuration for the realization of electronically tunable phase shifter. The proposed filter requires two CDTAs and a single virtually grounded capacitor, thus results in a canonical allpass filter. The output of the proposed circuit exhibits high-output impedance that makes the circuit attractive from the viewpoint of cascading in current mode. An application example of the current-mode second-order notch and allpass filter realization is also given to demonstrate the design possibilities using the proposed CDTA-based phase shifter section. PSPICE simulation results are given to confirm the theory.

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