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

Firs 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 quadarture oscillator [10] and multi-phase 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 (CDTA) [10-11, 24-27]. The literature review of reported current-mode APFs shows that the weaknesses of these APFs are list bellow:

- 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:

$$\begin{bmatrix} I_y \\ V_x \\ I_{z,z_c} \\ I_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ R_x & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & \pm g_m & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ V_z \\ V_o \end{bmatrix}. \tag{1}$$

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

$$R_x = \frac{V_T}{2I_{B1}}, \tag{2}$$

and

$$g_m = \frac{I_{B2}}{2V_T}. \tag{3}$$

V_T is the thermal voltage. I_{B1} and I_{B2} 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 (z-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.

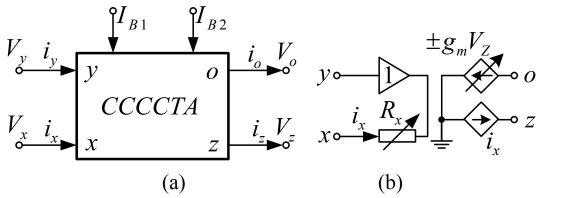

Fig. 1. CCCCTA: (a) Symbol, (b) Equivalent circuit.

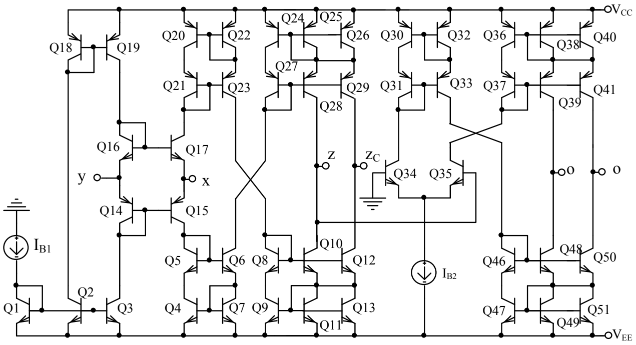

Fig. 2. Schematic of the BJT CCCCTA.

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 ($R_{x1} \cong 0$) by setting value of I_{B1} as high as possible. The sign ± 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

$$\frac{I_{Out}(s)}{I_{in}(s)} = \pm g_{m1} R_{x2} \left(\frac{sC - g_{m2}}{sC + g_{m2}} \right). \tag{4}$$

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

$$\omega_0 = \frac{g_{m2}}{C}, \tag{5}$$

$$G(\omega) = \left| \frac{I_{Out}}{I_{in}} \right| = g_{m1} R_{x2}, \tag{6}$$

$$\phi(\omega)_+ = 180 - 2\tan^{-1}\left(\frac{\omega C}{g_{m2}} \right), \tag{7}$$

and

$$\phi(\omega)_- = -2\tan^{-1}\left(\frac{\omega C}{g_{m2}} \right). \tag{8}$$

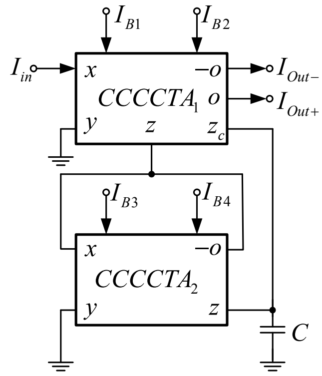

Fig. 3. Proposed gain controllable APF.

If $g_{m1} = I_{B2}/2V_T$, $R_{x2} = V_T/2I_{B3}$ and $g_{m2} = I_{B4}/2V_T$, the natural frequency, current gain and phase responses of the proposed circuit are written as

$$\omega_0 = \frac{I_{B4}}{2V_T C}, \tag{9}$$

$$G(\omega) = \left| \frac{I_{Out}}{I_{in}} \right| = \frac{I_{B2}}{4I_{B3}}, \tag{10}$$

$$\phi(\omega)_+ = 180 - 2\tan^{-1}\left(\frac{2V_T \omega C}{I_{B4}} \right), \tag{11}$$

and

$$\phi(\omega)_- = -2\tan^{-1}\left(\frac{2V_T \omega C}{I_{B4}} \right). \tag{12}$$

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_{B2} or I_{B3} while the natural frequency and phase responses can be electronically adjusted by I_{B4}.

3. Non-ideal Cases

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

$$I_z = \alpha I_x; V_x = \beta V_y + I_x R_x; I_{zc} = \gamma I_z, \tag{13}$$

where α and γ are the parasitic current transfer gains from x, and z_c terminals to z terminal, respectively. β is the parasitic voltage transfer gain from y terminal to x. Considering the current transfer gains, the modified current transfer function of Fig. 3 can be expressed as

$$\frac{I_{Out}}{I_{in}} = \pm \alpha_1 g_{m1} R_{x2} \left(\frac{sC - \gamma_1 g_{m2}}{sC + \alpha_2 g_{m2}} \right). \tag{14}$$

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

$$\omega_0 = \frac{\alpha_2 g_{m2}}{C}, \tag{15}$$

$$G(\omega) = \left| \frac{I_{Out}}{I_{in}} \right| = \alpha_1 g_{m1} R_{x2} \sqrt{\frac{(\omega C)^2 + (\gamma_1 g_{m2})^2}{(\omega C)^2 + (\alpha_2 g_{m2})^2}}, \tag{16}$$

$$\phi(\omega)_+ = 180 - \tan^{-1}\left(\frac{\omega C}{\gamma_1 g_{m2}} \right) - \tan^{-1}\left(\frac{\omega C}{\alpha_2 g_{m2}} \right), \tag{17}$$

and

$$\phi(\omega)_- = -\tan^{-1}\left(\frac{\omega C}{\gamma_1 g_{m2}} \right) - \tan^{-1}\left(\frac{\omega C}{\alpha_2 g_{m2}} \right). \tag{18}$$

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 $R_O >> R_X$), for the circuit of Fig. 3, is given as

$$\frac{I_{Out}}{I_{in}} = \pm g_{m1} R_{x2} \left[\frac{sC_B - g_{m2}}{sC_B(sC_A R_{x2} + 1) + g_{m2}} \right], \tag{19}$$

where $C_A = C_{z1} + C_{o2}$ and $C_B = C + C_{z1} + C_{z2}$. It is found that (19) is second order transfer function. Then, the natural frequency, current gain and phase responses of the proposed circuit are

$$\omega_0 = \frac{g_{m2}}{C_A C_B R_{x2}}, \tag{20}$$

$$G(\omega) = \left| \frac{I_{Out}}{I_{in}} \right| = g_{m1} R_{x2} \sqrt{\frac{(\omega C_B)^2 + g_{m2}^2}{(\omega C_B)^2 + (g_{m2} - \omega C_A C_B R_{x2})^2}}, \tag{21}$$

$$\phi(\omega)_+ = 180 - \tan^{-1}\left(\frac{\omega C_B}{g_{m2}} \right) - \tan^{-1}\left(\frac{\omega C_B}{g_{m2} - \omega C_A C_B R_{x2}} \right), \tag{22}$$

and

$$\phi(\omega)_- = -\tan^{-1}\left(\frac{\omega C_B}{g_{m2}} \right) - \tan^{-1}\left(\frac{\omega C_B}{g_{m2} - \omega C_A C_B R_{x2}} \right). \tag{23}$$

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 nF, $I_{B1} = I_{B4}$ = 100 µA, I_{B2} = 200 µA and I_{B3} = 50 µA. 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_{B2} 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).

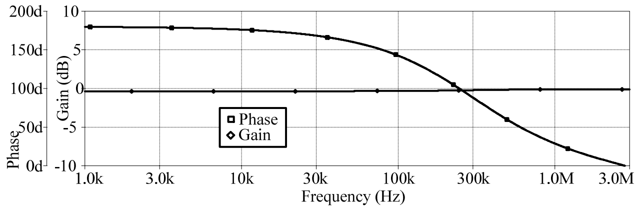

Fig. 4. Gain and phase responses of the proposed allpass filter.

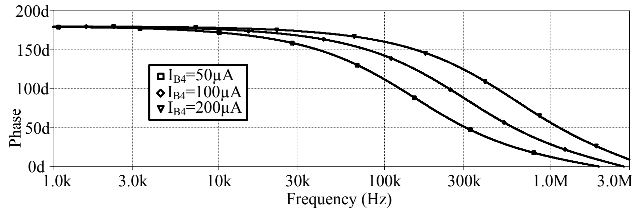

Fig. 5. Simulated phase responses of the proposed allpass filter when I_{B4} is varied.

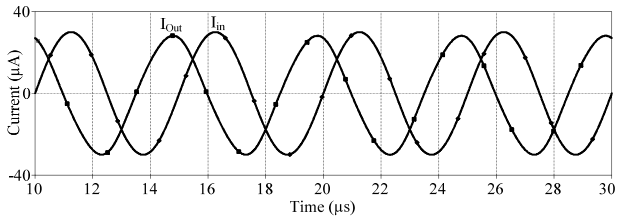

Fig. 6. Filter response to a 0.2 MHz sinusoidal input signal.

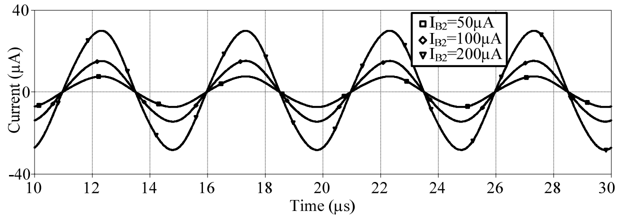

Fig. 7. Output currents for different values of I_{B2}.

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 $k_1 = g_{m1} R_{x2}$, $k_2 = g_{m3} R_{x4}$, $a_1 = g_{m2}/C_1$ and $a_2 = g_{m4}/C_2$, the following characteristic equation can be obtained

$$s^2 + 2sa_1a_2\left(\frac{1-k_1k_2}{1+k_1k_2}\right) + a_1a_2 = 0 \,. \tag{24}$$

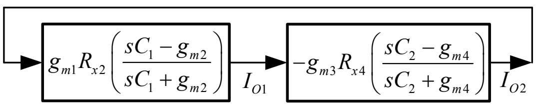

Fig. 8. Block diagram for quadrature oscillator.

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

$$g_{m1}R_{x2}g_{m3}R_{x4} = 1\,, \tag{25}$$

and

$$\omega_{osc} = \sqrt{\frac{g_{m2}g_{m4}}{C_1C_2}}\,. \tag{26}$$

If $g_{mi} = I_{Bi}/2V_T$ and $R_{xi} = V_T/2I_{Bi}$, the oscillation condition and oscillation frequency can be expressed as

$$\frac{I_{B2}I_{B6}}{16I_{B3}I_{B7}} = 1\,, \tag{27}$$

and

$$\omega_{osc} = \frac{1}{2V_T}\sqrt{\frac{I_{B4}I_{B8}}{C_1C_2}}\,. \tag{28}$$

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.

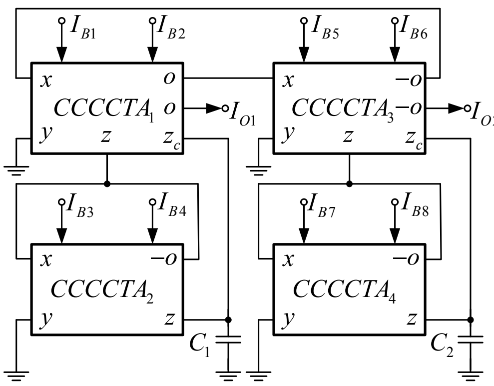

Fig. 9. Current-mode quadrature oscillator.

The confirmed performances of the oscillator can be seen in Fig. 10 and 11, showing the responses of the oscillator, the bias currents $I_{B1} = I_{B5} = 100$ µA, $I_{B2} = I_{B4} = I_{B8} = 200$ µA, $I_{B3} = I_{B7} = 50$ µA and $I_{B6} = 215$ µA, $C_1 = C_2 = 1$ nF. This yields oscillation frequency of 555.56 kHz. The total harmonic distortion (THD) is about 0.619%.

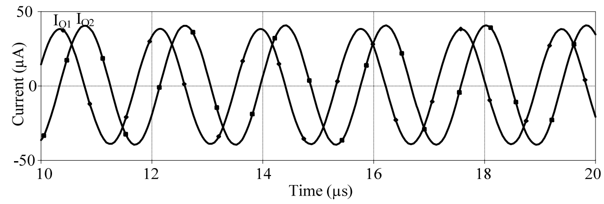

Fig. 10. The simulation result of current waveforms of circuit in Fig. 9.

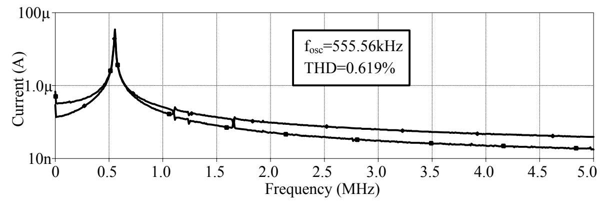

Fig. 11. The output spectrum of the oscillator.

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

[1] SCHAUMAN, R., VALKENBURG, E. *Design of Analog Filters*. New York: Oxford University Press, 2001.

[2] COMER, D. J., MCDERMID, J. E. Inductorless bandpass characteristics using all-pass networks. *IEEE Transactions on Circuits Theory*, 1968, vol. 15, no. 4, p. 501 - 503.

[3] METIN, B., HERENCSAR, N., PAL, K. Supplementary first-order all-pass filters with two grounded passive elements using FDCCII. *Radioengineering*, 2011, vol. 20, no. 2, p. 433-4437.

[4] HORNG, J-W. DVCCs based high input impedance voltage-mode first-order allpass, highpass and lowpass filters employing grounded capacitor and resistor. *Radioengineering*, 2010, vol. 19, no. 4, p. 653-656.

[5] TOKER, A., OZOGUZ, S., CICEKOGLU, O., ACAR, C. Current mode allpass filters using current differencing buffered amplifier and a new high-Q bandpass filter configuration. *IEEE Trans. Circuit and System-II: Analog and Digital Signal Processing*, 2000, vol. 47, p. 949-954.

[6] BAJER, J., LAHIRI, A., BIOLEK, D. Current-mode CCII+ based oscillator circuits using a conventional and a modified Wien-

bridge with all capacitors grounded. *Radioengineering*, 2011, vol. 20, no. 1, p. 245-250.

[7] SIRIPRUCHYANUN, M., JAIKLA, W. Electronically controllable current-mode universal biquad filter using single DO-CCCDTA. *Circuits Systems and Signal Processing,* 2008, vol. 27, p. 113-122.

[8] LI, Y. Current-mode sixth-order elliptic band-pass filter using MCDTAs. *Radioengineering*, 2011, vol. 20, no. 3, p. 645-649.

[9] TOUMAZOU, C. LIDGEY, F. J. HAIGH, D. G. *Analogue IC Design: The Current-Mode Approach*. Stevenage: Peter Peregrinus, 1990.

[10] KESKIN, A. U., BIOLEK, D. Current mode quadrature oscillator using current differencing transconductance amplifiers (CDTA). *IEE Proc.-Circuits Devices Syst.*, 2006, vol. 153, no. 3, p. 214-218.

[11] JAIKLA, W., PROMMEE, P., Electronically tunable current-mode multiphase sinusoidal oscillator employing CCCDTA-based allpass filters with only grounded passive elements *Radioengineering*, 2011, vol. 20, no. 3, p. 594-599.

[12] HIGASHIMURA, M., FUKUI, Y. Realization of current-mode allpass networks using a current conveyor. *IEEE Trans. Circuit and System*, 1990, vol. 37, p. 660-661.

[13] MAHESHWARI, S., KHAN, I .A. Novel first-order current-mode allpass sections using CCIII. *Active and Passive Elec. Comp.*, 2004, vol. 27, p. 111-117.

[14] HORNG, J. W., HOU, C. L., CHANG, C. M., CHUNG, W. Y., LIU, H. L., LIN, C.T. High-output impedance current-mode first-order allpass networks with four grounded components and two CCIIs. *Int. Journal of Electronics*, 2006, vol. 93, p. 613-621.

[15] UN, M., KACAR, F. Third generation current conveyor based current-mode first order all-pass filter and quadrature oscillator. *Istanbul University - Journal of Electrical and Electronics Engineering*, 2008, vol. 8, no. 1, p. 529-535.

[16] TSUKUTANI, T., HIGASHIMURA, M., ISHIDA, M., TSUIKI S., FUKUI, Y. A general class of current-mode high-order OTA-C filters. *Int. Journal of Electronics*, 1996, vol. 81, no. 6, p. 663–669.

[17] AL-HASHIM, B., DUDEK, F., SUN, Y. Current-mode delay equalizer design using multiple output OTAs. *Analog Integrated Circuits and Signal Processing*, 2000, vol. 24, no. 2, p. 163– 169.

[18] CHANG, C., AL-HASHIMI, B. Analytical synthesis of current-mode high-order OTA-C filters. *IEEE Trans. on Circuits and Systems- I*, 2003, vol. 50, no.9, p. 1188 –1192.

[19] PSYCHALINOS, C., PAL, K. A novel all-pass current-mode filter realized using a minimum number of single output OTAs. *Frequenz*, 2010, p. 30-32.

[20] METIN, B., PAL, K., MINAEI, S., CICEKOGLU, O. Trade-offs in the OTA-based analog filter design. *Analog Integrated Circuits and Signal Processing*, 2000, vol. 60, p. 205–213.

[21] SINGTHONG, P., SIRIPRUCHYANUN, M., JAIKLA, W. Electronically controllable first-order current-mode allpass filter using CCCIIs and its application. In *Proceedings of the 18th International Conference Mixed Design of Integrated Circuits and Systems (MIXDES)*, 2011, p. 314-318.

[22] MINAEI, S., IBRAHIM, M. A. General configuration for realizing current-mode first-order all-pass filter using DVCC. *Int. J. Electron.*, 2005, vol. 92, no. 6, p. 347–356.

[23] KILINC, S., CAM, U. Current-mode first-order allpass filter employing single current operational amplifier. *Analog Integrated Circuits and Signal Processing*, 2004, vol. 41, p. 43–45.

[24] JAIKLA, W., SIRIPRUCHYANUN, M., BAJER, J., BIOLEK, D. A simple current-mode quadrature oscillator using single CDTA. *Radioengineering*, 2008, vol. 17, p. 33-40.

[25] JAIKLA, W., SIRIPRUCHYANUN, M., BIOLEK, D., BIOLKOVA, V. High-output-impedance current-mode multiphase sinusoidal oscillator employing current differencing transconductance amplifier-based allpass filters. *Int. J. Electron.*, 2010, vol. 97, no. 7, p. 811–826.

[26] TANGSRIRAT, W., TANJAROEN, W., PUKKALANUN, T. Current-mode multiphase sinusoidal oscillator using CDTA-based allpass sections. *Int. J. Electron. Commu. (AEU)*, 2009, vol. 63, p. 616-622.

[27] LAHIRI, A., CHOWDHURY, A. A novel first-order current-mode all-pass filter using CDTA. *Radioengineering*, 2009, vol. 18, no. 3, p. 300-305.

[28] SIRIPRUCHAYANUN, M., JAIKLA, W. Current controlled current conveyor transconductance amplifier (CCCCTA): a building block for analog signal processing. *Electrical Engineering*, 2008, vol. 90, p. 443-453.

[29] BIOLEK, D., SENANI, R., BIOLKOVA, V., KOLKA, Z. Active elements for analog signal processing: classification, review, and new proposals. *Radioengineering*, 2008, vol. 17, no. 4, p. 15-32.

[30] FREY, D. R. Log-domain filtering: an approach to current mode filtering. *IEE Proc.-Circuits, Devices and Syst.*, 1993, vol. 140, no. 6, p. 406-416.

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