Current and Voltage Conveyors in Current- and Voltage-Mode Precision Full-Wave Rectifiers

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Abstract. *In this paper new versatile precision full-wave rectifiers using current and/or voltage conveyors as active elements and two diodes are presented. The performance of these circuit solutions is analysed and compared to the opamp based precision rectifier. To analyze the behavior of the functional blocks, the frequency dependent RMS error and DC transient value are evaluated for different values of input voltage amplitudes. Furthermore, experimental results are given that show the feasibilities of the conveyor based rectifiers superior to the corresponding operational amplifier based topology.*

Keywords

Precision full-wave rectifier, current conveyor, voltage conveyor, instrumentation, measurements.

1. Introduction

In applications such as ac voltmeters and ammeters, signal-polarity detectors, averaging circuits, peak-value detector rectification function is of great importance [1]. Because of the threshold voltage of the diodes, simple passive rectifiers operate inaccurately, if low-voltage signals are analyzed. Therefore precision rectifiers employing active elements have to be used.

Probably the most known precision rectifiers are based on operational amplifiers (opamps) [1]. However, because of the finite slew-rate and effects caused by diode commutation, these circuits operate well only at low frequencies [2], [3]. This problem can be overcome by the use of current conveyors (CCs), where the diodes are connected to the high-impedance current outputs of the active elements. In [4]–[7] the same precision full-wave rectifier is analyzed (Fig. 2b). It uses two second-generation CCs and four diodes. To further extend the frequency range the voltage [4], [7] or current [6], [7] biasing scheme can be used. Another precision full-wave rectifier is presented in [8] that is based on the standard opamp rectifier shown in Fig. 2a. Here, the OPA1 is replaced by the operational conveyor and later by second-generation CC [3]. A full-wave rectifiers using second-generation and dual-X current conveyors are presented in [9] and [10], respectively, where the required diodes are suitably replaced by NMOS transistors. The use of fully differential operational transconductance amplifiers (BOTA) operating in weak inversion region for the design of precision full-wave rectifiers is presented in [11], which is based on the idea discussed in [12], where simple transconductance amplifiers (OTA). Here, the transconductance of OTA is controlled by the current derived from the input signal to be rectified. In another group of precision rectifiers, a transistor connected to the current output of an active element operates as a switch. For this purpose the current conveyor [13] or transconductance amplifiers [14]–[16] are used.

All the circuit solutions in [4]–[16] operate in the voltage or mixed mode. The current research in analog functional block design gets more focused on the realization of the current-mode (CM) circuits [17]. In this area mainly the frequency filters can be mentioned, e.g. [18]–[21]. However, a number of current-mode full-wave rectifiers can also be found in the literature [22]–[25], where unity-gain cells or current differencing transconductance amplifiers are used.

In this paper two new precision full-wave rectifiers employing current and/or voltage conveyors together with two diodes are presented. They are of minimal configuration and can operate both in the voltage- and current-mode. The behavior of these circuits is compared to the known conveyor based solution presented in [4]–[7] and also to the opamp based full-wave rectifier. Simulation and furthermore experimental measurement results are given that show the feasibility of the newly designed circuits to rectify signals up to 1 MHz and beyond with no or little distortion.

2. Current and Voltage Conveyors

In 1968, the current conveyors were presented for the first time [26], however they did not find any significant usage since the operational amplifiers were more attractive at that time. Current conveyors received considerable attention after the second (CCII) [27] and later third (CCIII) [28] generation current conveyors were designed. These elements are now advantageously used in applications, where the wide bandwidth or current output response is necessary. Nowadays, different types of current conveyors are described that are mostly based on the CCII, e.g. current controlled CC (CCCII) [29], differential voltage CC (DVCC) [30], or electronically tunable CC (ECCII) [19], [31]. The behavior of a four-terminal CCII (Fig. 1(a)) is described by the following equations:

$$v_X = v_Y, \quad i_Y = 0, \; i_{Z+} = i_X, \; i_{Z-} = -i_X. \tag{1}$$

Another flexible building block for active circuit synthesis is the voltage conveyor (VC) [32]. Based on the duality to current conveyors, first-, second-, and third-generation voltage conveyors can be described [33]. The current differencing buffered amplifier (CDBA) [34] can be identified as the differential current voltage conveyor (DCVC+) [35]. In [36]-[38], the universal voltage conveyor (UVC) has been described (Fig. 1(b)). It is a 6-port active element that has one voltage input X, two current differencing inputs YP and YN, and two mutually inverse voltage outputs ZP and ZN. The auxiliary voltage input W is used to determine the generation of the voltage conveyor [38]. The relation between the terminal currents and voltages is described by the following set of equations:

$$i_X = i_{YP} - i_{YN}, \;\; v_{YP} = v_{YN} = v_W, \tag{2}$$

$$v_{ZP} = v_X, \;\; v_{ZN} = -v_X. \tag{3}$$

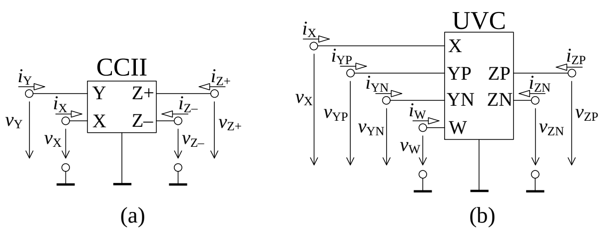


Fig. 1. Circuit symbol of (a) the four-terminal CCII, (b) the universal voltage conveyor UVC.

3. New Precision Full-Wave Rectifiers

The standard opamp based circuit from Fig. 2(a) [1] is a connection of an inverting half-wave rectifier (OPA_1) and summing amplifier (OPA_2). For the desired full-wave rectification the following conditions have to be fulfilled:

$$R_1 = R_2, \;\; R_4 = 2R_3, \tag{4}$$

or

$$R_2 = 2R_1, \;\; R_3 = R_4, \tag{5}$$

which generally means that the half-wave rectified signal must be amplified two times higher than the original input signal $v_{IN}(t)$, either more commonly by the summing amplifier (according to (4)) or by the half-wave rectifier (according to (5)).

A well known circuit topology of the full-wave rectifier using two second-generation current conveyors CCII+ is shown in Fig. 2(b) [4]-[7]. Both CCIIs form a differential voltage-to-current converter. During the positive and negative input cycle the output currents make only the diodes D_2, D_4 and D_1, D_3 active, respectively. On the resistor R_2 the output current is converted back to voltage. Both circuits from Fig. 2 can operate only in the voltage-mode, or in case of the conveyor based rectifier (Fig. 2(b)) in the transadmittance-mode.

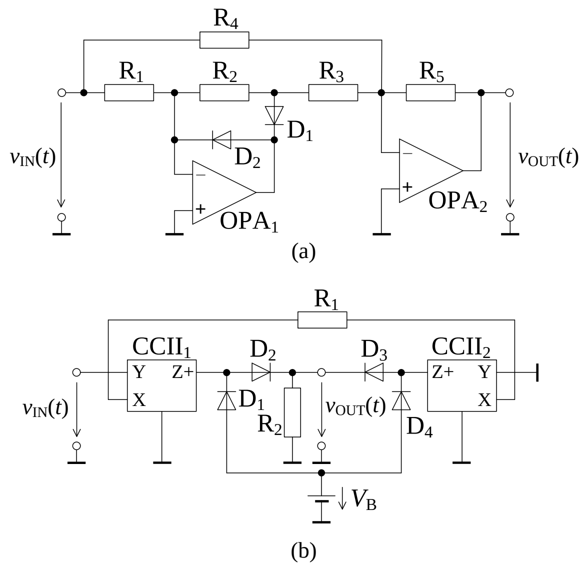


Fig. 2. Voltage-mode (a) standard opamp based [1], (b) known conveyor based full-wave rectifier from [4]-[7].

New conveyor based precision full-wave rectifiers working in the current-mode are shown in Fig. 3, where the structure in Fig. 3(a) and Fig. 3(b) employs two second-generation current conveyors, and one CCII and one universal voltage conveyor, respectively. Both solutions are of minimal configuration since only two active elements and two diodes have to be used. Routine analysis leads to the following expressions of the output currents:

$$i_{OUT+}(t) = |i_{IN}(t)|, \;\; i_{OUT-}(t) = -|i_{IN}(t)|. \tag{6}$$

In theory, since the input signal $i_{IN}(t)$ is directly applied to the current terminal X of the $CCII_1$ and the current responses are taken from the Z-terminals of the $CCII_2$ (Fig. 3(a)) or from the X-terminal of the UVC (Fig. 3(b)) the input and output impedances of the proposed rectifiers are zero and infinitely high, respectively. Therefore, both rectifiers are easily cascadable.

Adding the resistors R_1, R_2, or R_3 into the current-mode rectifiers from Fig. 3, new voltage-mode precision rectifiers can be obtained (Fig. 4). The resistors represent simple voltage-to-current and current-to-voltage converters and the output voltages can be expressed as:

$$v_{OUT1+}(t) = \frac{R_3}{R_1}|v_{IN}(t)|, \;\; v_{OUT1-}(t) = -\frac{R_2}{R_1}|v_{IN}(t)|, \tag{7}$$

$$v_{OUT2+}(t) = -v_{OUT2-}(t) = \frac{R_2}{R_1}|v_{IN}(t)|. \tag{8}$$

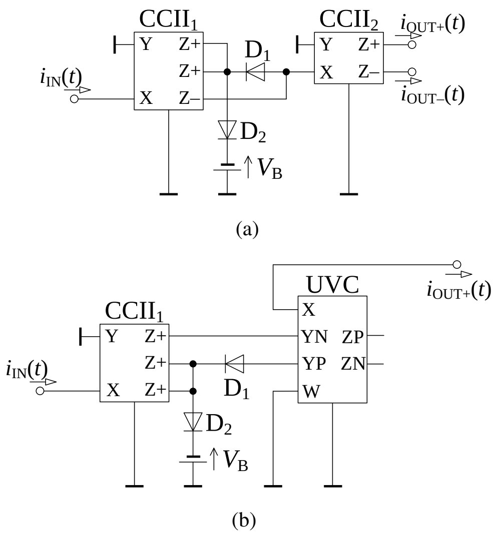


Fig. 3. New current-mode precision full-wave rectifiers using (a) two current conveyors, (b) one current and voltage conveyor.

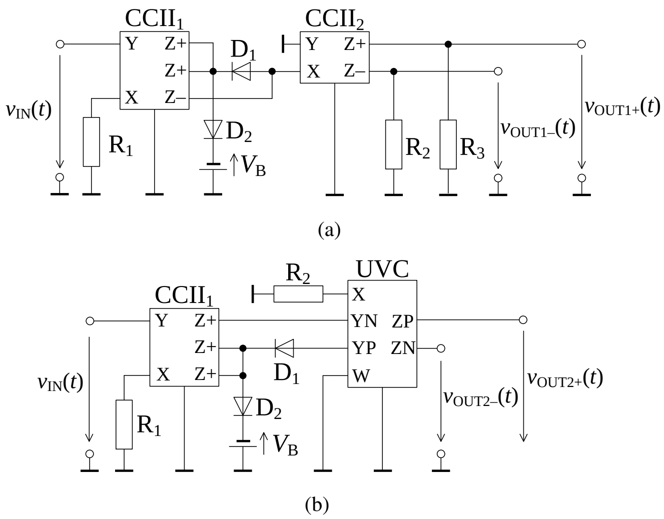


Fig. 4. New voltage-mode precision full-wave rectifiers using (a) two current conveyors, (b) one current and voltage conveyor.

In Fig. 4, the input voltage $v_{\mathrm{IN}}(t)$ is directly connected to the Y-terminal of the CCII_1 and therefore the input impedance of both rectifiers is infinitely high in theory. In case of circuit from Fig. 4(b), the output impedance is theoretically zero, since the ZP and ZN terminals of the universal voltage conveyor represent outputs of voltage followers (3).

4. DC and RMS Error Analyses

To evaluate and compare the accuracy of the voltage-mode full-wave rectifiers from Fig. 2 and Fig. 4 the DC value transfer p_{DC} and RMS error p_{RMS} have been analyzed [39]:

$$p_{\mathrm{DC}} = \frac{\int_T y_{\mathrm{R}}(t)\,\mathrm{d}t}{\int_T y_{\mathrm{ID}}(t)\,\mathrm{d}t}, \tag{9}$$

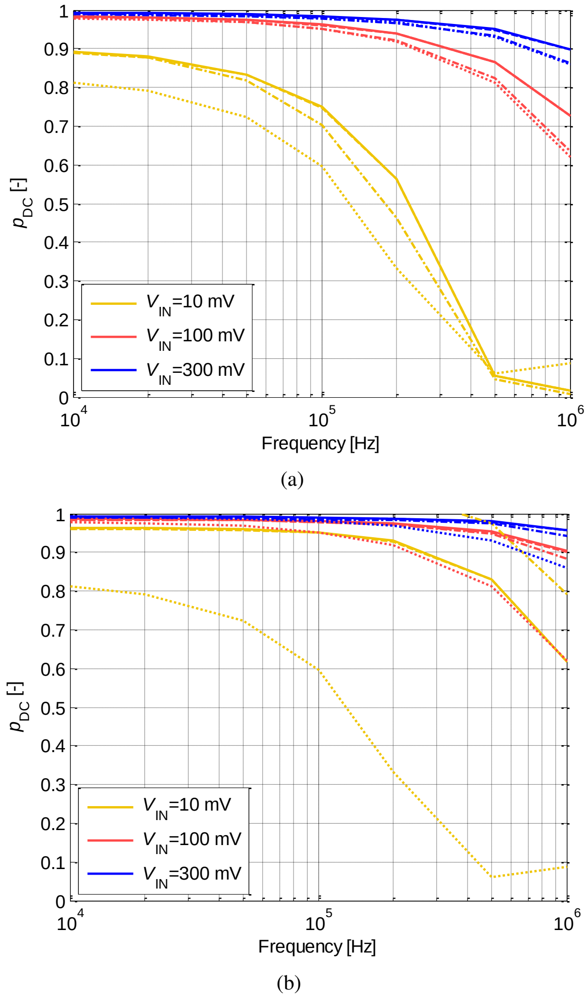


Fig. 5. DC value transfer for (a) $V_{\mathrm{B}} = 0$ V, (b) $V_{\mathrm{B}} = 0.6$ V of the rectifiers from Fig. 2a (dotted line), Fig. 2b (dash-dotted line), Fig. 4a (dashed line), and Fig. 4b (solid line), for input voltage amplitudes 10 mV, 100 mV, and 300 mV.

$$p_{\mathrm{RMS}} = \sqrt{\frac{\int_T \left[y_{\mathrm{R}}(t) - y_{\mathrm{ID}}(t)\right]^2 \mathrm{d}t}{\int_T y_{\mathrm{ID}}^2(t)\,\mathrm{d}t}} \tag{10}$$

where the $y_{\mathrm{R}}(t)$ and $y_{\mathrm{ID}}(t)$ represent the actual and ideally rectified signal and T is the period of the input signal. The ideal behavior of the rectifier is characterized by the values $p_{\mathrm{RMS}} = 0$ and $p_{\mathrm{DC}} = 1$.

Using (9) and (10) the behavior of the newly proposed voltage-mode rectifiers (Fig. 4) has been compared with the standard opamp and known conveyor based circuits from Fig. 2(a) and Fig. 2(b). As active elements the universal current conveyor UCC-N1B and universal voltage conveyor UVC-N1C have been used [38], [40]. The current and voltage transfer bandwidths of the UCC and UVC are about 35 MHz [40]. Therefore, in the standard opamp based rectifier the AD8656 has been used [41]. The diodes are general purpose 1N4148 and all resistors are 1 kΩ (in Fig. 2(a) $R_3 = 500\ \Omega$).

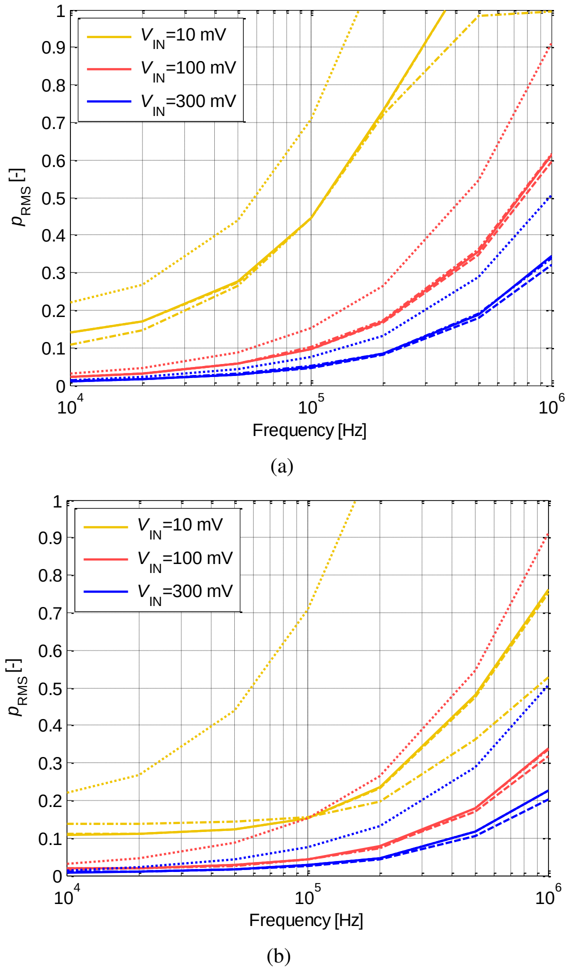


Fig. 6. RMS error for (a) $V_B = 0$ V, (b) $V_B = 0.6$ V of the rectifiers from Fig. 2a (dotted line), Fig. 2b (dash-dotted line), Fig. 4a (dashed line), and Fig. 4b (solid line), for input voltage amplitudes 10 mV, 100 mV, and 300 mV.

The simulation results of the frequency dependent DC value transfer and RMS error for chosen values of amplitudes V_{IN} are shown in Fig. 5 and Fig. 6, where the solid, dashed, dash-dotted and dotted lines stand for the circuits from Fig. 4(b), Fig. 4(a), Fig. 2(b), and Fig. 2(a), respectively. (The solid and dashed lines are almost identical.) If the frequency increases and/or amplitude decreases distortions occur and the p_{DC} decreases below one and p_{RMS} increases. From Fig. 5 and Fig. 6 it is evident that the best results are achieved with the new minimal configuration rectifiers. For an appropriate value of the bias voltage (here $V_B = 0.6$ V), the conveyor based precision rectifiers can operate at higher frequencies (Fig. 5(b), Fig. 6(b)).

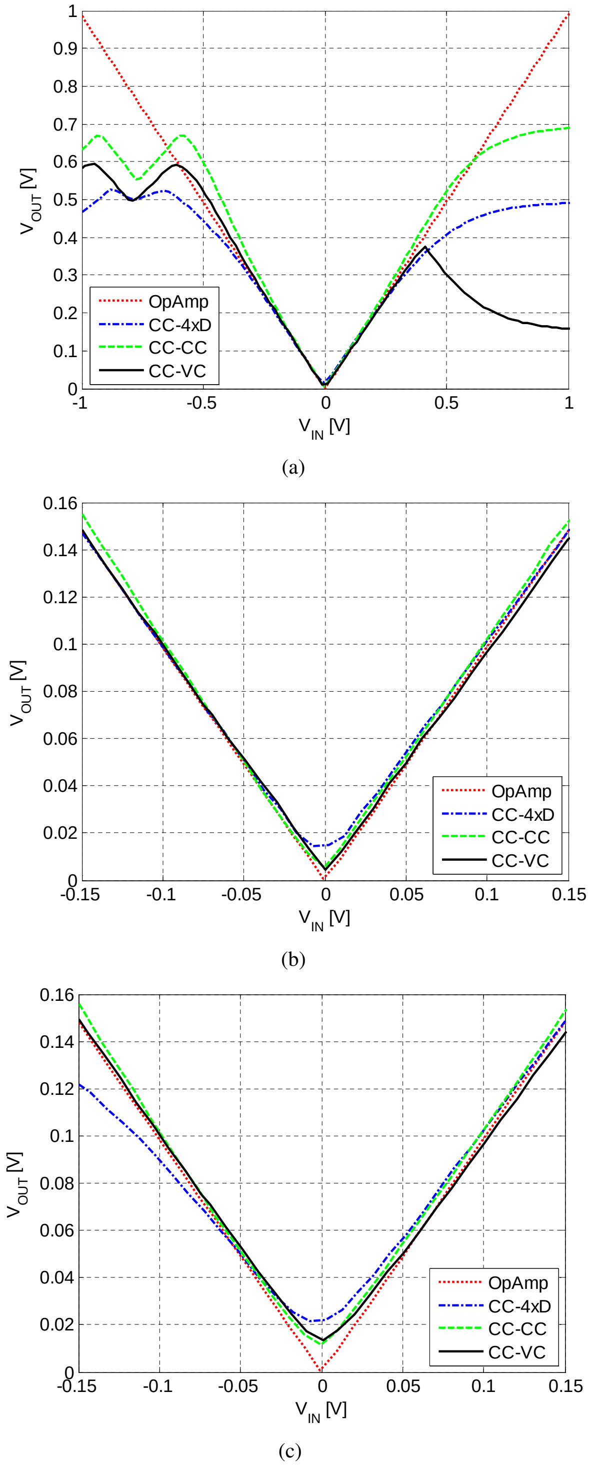
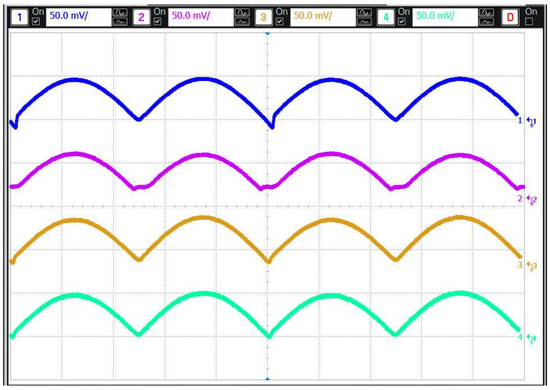


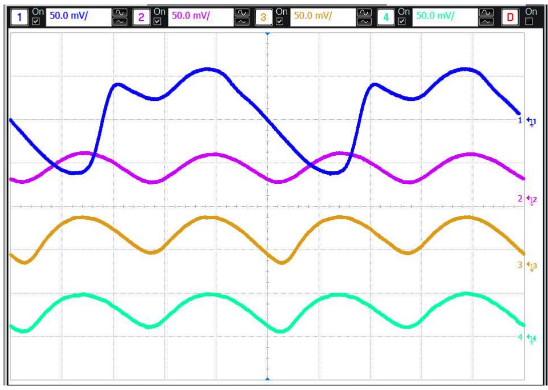
Fig. 7. Measured DC transfer functions of the voltage mode rectifier from Fig. 2(a) (dotted line), Fig. 2(b) (dash-dotted line), Fig. 4(a) (dashed line), and Fig. 4(b) (solid line) for (a), (b) $V_B = 0$ V, (c) $V_B = 0.6$ V.

5. Experimental Measurements

The behavior of the voltage-mode precision full-wave rectifiers from Fig. 4 has also been verified by experimental measurements and compared to the known opamp (Fig. 2(a)) and current conveyor (Fig. 2(b)) based solutions. In Fig. 7 the DC transfer characteristics are shown. Due to high voltage gain of the opamps, the DC error of the circuit from Fig. 2(a) is minimized and the DC transfer is almost ideal (in Fig. 7 dotted line). The non-unity voltage and current transfers of the current conveyors cause higher DC error of the conveyor based full-wave rectifiers (Fig. 7(b)). This error is more evident, mainly in the zero crossing area, if a bias voltage is applied (Fig. 7(c)).



(a)



(b)

Fig. 8. Transient responses of the precision full-wave rectifiers from Fig. 2a (trace 1), Fig. 2b (trace 2), Fig. 3c (trace 3), Fig. 3d (trace 4) for a signal amplitude 50 mV and frequencies (a) $f = 10$ kHz ($V_B = 0$ V), (b) $f = 1$ MHz ($V_B = 0.6$ V).

Although the DC error of the conveyor based full-wave rectifiers is higher, from transient analyses (Fig. 8) it can be seen that the behavior of the conveyor based circuits is superior to the opamp full-wave rectifier. For an input voltage with the 50 mV amplitude at frequency 10 kHz the behavior of all rectifiers is almost identical, only the conveyor based circuit from Fig. 2(b) shows significant error in the zero crossing area (Fig. 8(a)). However, when the frequency grows voltage biasing is necessary. In Fig. 8(b) the measurement results for an 50 mV amplitude input sinusoidal voltage at frequency 1 MHz are shown ($V_B = 0.6$ V). At this frequency the rectification function of the opamp based circuit is totally missing (trace 1), however it can be still observed in the conveyor based circuits.

6. Conclusion

In this paper the performance of conveyor based precision full-wave rectifiers has been analyzed and compared to the standard opamp based topology. Two new minimal configuration rectifiers have been presented, that employ current and/or voltage conveyors and two diodes. These rectifiers can work in the voltage-, current-, and transimmittance-mode. Simulation and experimental measurements were performed that prove the feasibility of the proposed conveyor based full-wave rectifiers.

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