

A SINGLE MO-CFTA BASED ELECTRONICALLY/TEMPERATURE INSENSITIVE CURRENT-MODE HALF-WAVE AND FULL-WAVE RECTIFIERS

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Abstract. *The article presents a current-mode full-wave rectifier employing multiple output current follower transconductance amplifier (MO-CFTA). The both circuits description is very simple, it merely comprises only single MO-CFTA, without external passive element. In addition, the magnitude and direction of output currents can be controlled via electronically method. Furthermore, the outputs are independent of the thermal voltage (V_T). The performances of the proposed circuits are investigated through PSpice. They show that the proposed circuits can function as a current-mode precision half-wave and full-wave rectifiers where input current range from $0 \mu\text{A}$ to $514 \mu\text{A}$ and $-518 \mu\text{A}$ to $518 \mu\text{A}$, respectively. They can be achieved at $\pm 2\text{V}$ power supplies. The maximum power consumption is $3,01 \text{ mW}$.*

Keywords

Current-mode, MO-CFTA, rectifier.

1. Introduction

A rectifier has been found widely useful in signal processing circuits, such as a signal polarity detector, a peak signal detector, an RMS to DC converter, an amplitude demodulation circuit, and an automatic gain control system [1], [2]. Basically, an op-amp and diode are used to design a voltage-mode precision rectifier [3], its output signal confronts a zero crossing distortion due to characteristic of the diode [4]. Thus, novel precision rectifiers are design without a diode [5].

In addition, the precision rectifiers are modified to use high performance active elements to achieve wider frequency response such as current conveyor [6] and current feedback operational amplifier [7]. However,

these circuits use many active and passive elements. When they are fabricated in IC, it affects to have more chip area. Furthermore, they are lack of electronically adjustment.

There has been much effort to reduce the supply voltage of analog systems since the last two decades. This is due to the command for portable and battery-powered equipments. Since a low-voltage operating circuit becomes necessary, the current-mode technique is ideally suited for this purpose. Presently, there is a growing interest in synthesizing current-mode circuits because of more their potential advantages such as larger dynamic range, higher signal bandwidth, greater linearity, simpler circuitry, and lower power consumption [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19].

In 2008, a reported active element, namely current follower transconductance amplifier (CTFA) [20], [21], seems to be a versatile component in the realization of a class of analog signal processing circuits. It is really current-mode element whose input and output signals are currents.

In addition, output current of CFTA can be electronically adjusted. Furthermore, it can offer advantageous features such as high-slew rate, high speed, wide bandwidth and simple implementation.

The purpose of this paper is to introduce MO-CFTA based current-mode half-wave and full-wave rectifiers. The features of the proposed both circuits are that; output gain can be adjusted via input bias current; magnitude of the output signal is temperature-insensitive; the proposed circuit consists of only single MO-CFTA and without passive element, which is convenient to fabricate in integrated circuit architecture.

The PSpice simulation and experimental results are also shown, which are in correspondence with the theoretical analysis.

2. Circuit Configuration

2.1. Basic Concept of MO-CFTA

This section describes the operation of MO-CFTA, its symbol and equivalent circuit are display in Fig. 1(a) and Fig. 1(b), respectively. In the ideal case, the voltage and current relationships of MO-CFTA are shown in (1),

$$\begin{bmatrix} V_f \\ I_z \\ I_{x1} \\ I_{x2} \\ I_{-x} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & g_{m1} & 0 & 0 & 0 \\ 0 & g_{m2} & 0 & 0 & 0 \\ 0 & g_{m3} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_f \\ V_z \\ V_{x1} \\ V_{x2} \\ V_{-x} \end{bmatrix}, \quad (1)$$

where

$$g_{m1} = \frac{I_{B1}}{2V_T}, \quad g_{m2} = \frac{I_{B2}}{2V_T} \text{ and } g_{m3} = \frac{I_{B3}}{2V_T}. \quad (2)$$

g_{m1} , g_{m2} and g_{m3} are the transconductances of the MO-CFTA at x_1 , x_2 , x_3 terminals, respectively V_T is the thermal voltage, its value is about 26 mV at 27 °C.

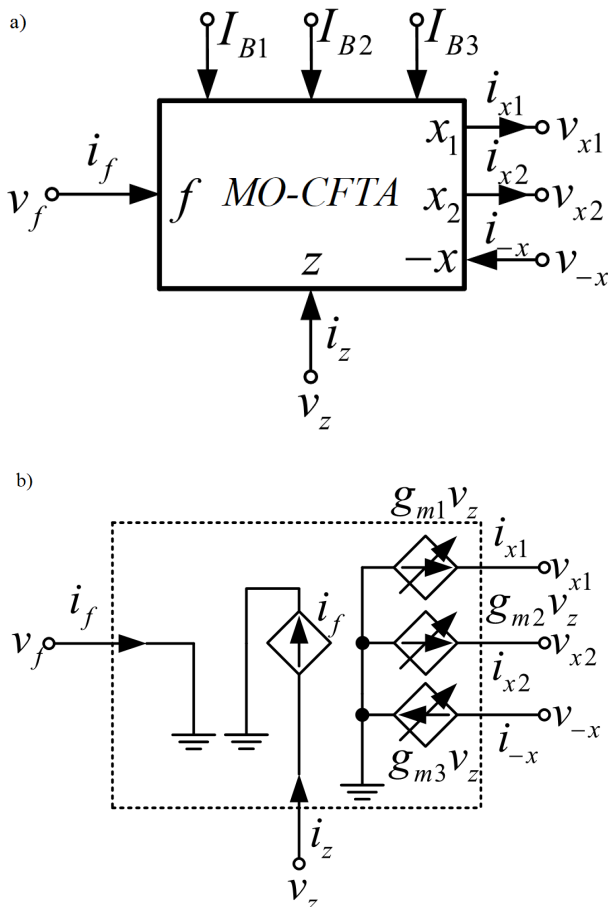


Fig. 1: MO-CFTA a) Schematic symbol, b) Equivalent circuit.

2.2. The Current-Mode Half-Wave Rectifier

This section is explained the operating of the half-wave rectifier, it is shown in Fig. 2. It can be seen that it consists of single only MO-CFTA without passive element. From MO-CFTA properties, the I_z and V_z can be found to be:

$$I_z = I_f = I_C = I_{-x}, \quad (3)$$

and

$$V_z = \frac{I_{-x}}{g_{m3}} = \frac{I_C}{g_{m3}}. \quad (4)$$

Cosequently, the I_{x1} can be written as:

$$I_{x1} = g_{m1}V_z = \frac{I_{-x}}{g_{m3}} = \frac{g_{m1}I_C}{g_{m3}}. \quad (5)$$

From the half-wave rectifier as demonstrated in Fig. 2, $I_{B1} = I_{in}$. Hence, $g_{m1} = I_{in}/2V_T$, Eq. (5) can be modified to be:

$$I_{x1} = \begin{cases} \frac{I_{in}I_C}{I_{B3}} & \text{if } I_{in} > 0 \\ 0 & \text{if } I_{in} < 0 \end{cases}. \quad (6)$$

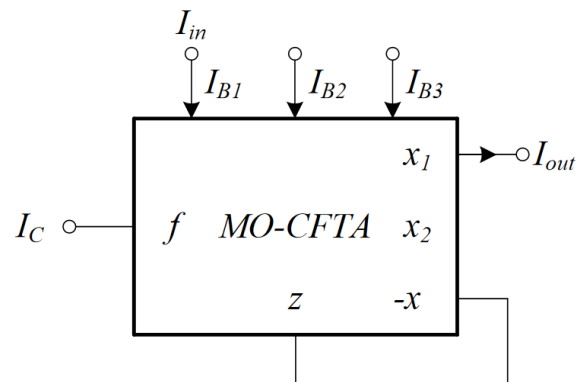


Fig. 2: Circuit diagram of current-mode half-wave rectifier.

2.3. The Current-Mode Full-Wave Rectifier

The proposed full-wave rectifier using MO-CFTA is display in Fig. 3, where I_{B1} , I_{B2} and I_{B3} are current bias currents of the MO-CFTA, respectively. By routine analysis circuit in Fig. 3 and using the properties of MO-CFTA. The output current at z terminal of MO-CFTA is obtained in:

$$I_z = I_f = I_C, \quad (7)$$

and

$$I_z = I_{-x}. \quad (8)$$

Then, the output voltage at z terminal (V_z) of MO-CFTA can be found to be:

$$V_z = \frac{I_{-x}}{g_{m3}} = \frac{I_C}{g_{m3}}. \tag{9}$$

Subsequently, the output current at x_1 and x_2 terminals (I_{x1} and I_{x2}) can be expressed to be:

$$I_{x1} = g_{m1}V_z = \frac{g_{m1}I_C}{g_{m3}}, \tag{10}$$

and

$$I_{x2} = g_{m2}V_z = \frac{-g_{m2}I_C}{g_{m3}}. \tag{11}$$

From Fig. 2, it is found that I_{in} and $-I_{in}$ are equal to I_{B1} and I_{B2} respectively. Then, $g_{m1} = I_{in} / 2V_T$, $g_{m2} = -I_{in} / 2V_T$ and $g_{m3} = -I_{B3} / 2V_T$. From MO-CFTA properties, the values of currents bias only are positive. Thus, I_{x1} and I_{x2} can be rewritten to be:

$$I_{x1} = \begin{cases} \frac{I_{in}I_C}{I_{B3}} & \text{if } I_{in} > 0 \\ 0 & \text{if } I_{in} < 0 \end{cases}, \tag{12}$$

and

$$I_{x2} = \begin{cases} 0 & \text{if } I_{in} > 0 \\ \frac{I_{in}I_C}{I_{B3}} & \text{if } I_{in} < 0 \end{cases}. \tag{13}$$

From Eq. (12) and Eq. (9), the output current I_{out} can be found to be:

$$I_{out} = I_{x1} + I_{x2} = \frac{|I_{in}| I_C}{I_{B3}}. \tag{14}$$

From Eq. (6) and Eq. (14), it can be seen that the amplitude of the output current can be controlled by I_{B3} and I_C , the polarity of the output signal can be electronically tune by I_C . Furthermore, in the ideal case, the current output is temperature-insensitive.

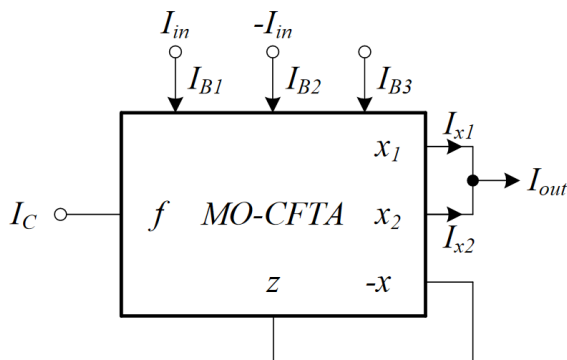


Fig. 3: Circuit diagram of current-mode full-wave rectifier.

2.4. Non-Ideal Case

In non-ideal case, the MO-CFTA can be characterized by:

$$\begin{bmatrix} V_f \\ I_z \\ I_{x1} \\ I_{x2} \\ I_{-x} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 & 0 \\ 0 & \gamma g_{m1} & 0 & 0 & 0 \\ 0 & \gamma g_{m2} & 0 & 0 & 0 \\ 0 & \gamma g_{m3} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_f \\ V_z \\ V_{x1} \\ V_{x2} \\ V_{-x} \end{bmatrix}, \tag{15}$$

where α and γ are transferred error values, these values can be deviated from one. In the case of non-ideal and reanalyzing the proposed half-wave and full-wave rectifiers in Fig. 2 and Fig. 3, respectively, they yield the output currents as:

$$I_{x1} = \begin{cases} \frac{\alpha I_{in}I_C}{I_{B3}} & \text{if } I_{in} > 0 \\ 0 & \text{if } I_{in} < 0 \end{cases}, \tag{16}$$

and

$$I_{out} = I_{x1} + I_{x2} = \frac{\alpha |I_{in}| I_C}{I_{B3}}. \tag{17}$$

From small-signal analysis of MO-CFTA, it can be found that α can be express as:

$$\alpha = \frac{g_{m6}g_{m8}g_{m13}}{g_{m6}g_{m13}(g_{m8} + g_{m10})}. \tag{18}$$

If these error factors are close to unity, the deviations of the output levels in Eq. (16) and Eq. (17) can be neglected. Practically, the α , and γ originate from intrinsic resistances and stray capacitances in the MO-CFTA. These errors affect the sensitivity to temperature and high frequency response of the proposed circuits. Then the MO-CFTA should be carefully designed to achieve these errors as low as possible.

2.5. Non-Linear Case

This section expands the proposed rectifiers operating in non-linear case. From Eq. (1) and Eq. (2), the currents at x_1 , x_2 and x_3 terminals can be found to be $\frac{I_{B1}V_z}{2V_T}$, $\frac{I_{B2}V_z}{2V_T}$ and $\frac{I_{B3}V_z}{2V_T}$, respectively. These are the first approximation of Taylor's series, it can be describe as:

$$\tanh x = x - \frac{1}{3}x^3 + \frac{2}{15}x^5 - \frac{17}{315}x^7 + \dots \tag{19}$$

Actually, I_{x1} , I_{x2} and I_{x3} can be express to be:

$$I_{x1} = I_{B1} \tanh \left(\frac{V_z}{2V_T} \right), \tag{20}$$

$$I_{x2} = I_{B2} \tanh \left(\frac{V_z}{2V_T} \right), \tag{21}$$

and

$$I_{x3} = I_{B3} \tanh\left(\frac{V_z}{2V_T}\right). \quad (22)$$

Subsequently, the output current of the half-wave rectifiers can be obtained by:

$$I_{out} = \begin{cases} I_{in} \tanh \frac{I_C}{I_{B3}} & \text{if } I_{in} > 0 \\ 0 & \text{if } I_{in} < 0 \end{cases}. \quad (23)$$

Likewise, the amplitude of the full-wave rectifier can be found to be:

$$I_{x1} = \begin{cases} I_{in} \tanh \frac{I_C}{I_{B3}} & \text{if } I_{in} > 0 \\ 0 & \text{if } I_{in} < 0 \end{cases}, \quad (24)$$

$$I_{x2} = \begin{cases} 0 & \text{if } I_{in} > 0 \\ I_{in} \tanh \frac{I_C}{I_{B3}} & \text{if } I_{in} < 0 \end{cases}, \quad (25)$$

and

$$I_{out} = I_{x1} + I_{x2} = |I_{in}| \tanh \frac{I_C}{I_{B3}}. \quad (26)$$

From Eq. (22) and Eq. (24), it can be clearly seen that the proposed circuits can be used rectifier while perform in non-linear mode.

3. Simulation and Experimental Results

The performance of the proposed half-wave and full-wave rectifiers can be proved by simulation and experimental results.

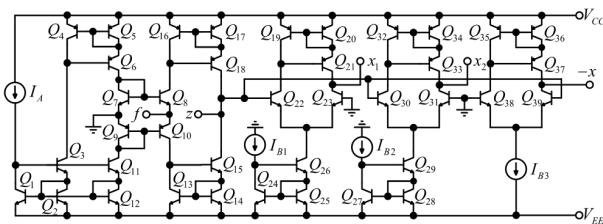


Fig. 4: Transistor-level implementation of MO-CFTA.

The PSpice simulation program was used for the examinations. The circuit diagram of MO-CFTA is displayed in Fig. 4. The PNP and NPN transistors employed in MO-CFTA were simulated by respectively using the parameters of the PR200N and NR200N bipolar transistors of ALA400 transistor array from AT&T [22] with ±2 V supplies voltages and I_A was set to 100 μA. Figure 4 and Fig. 5 depict DC transfer characteristics of the half-wave and

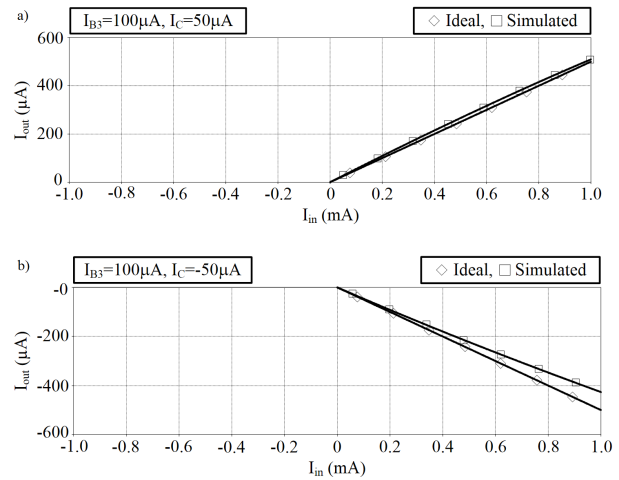


Fig. 5: DC transfer characteristic of the half-wave rectifier.

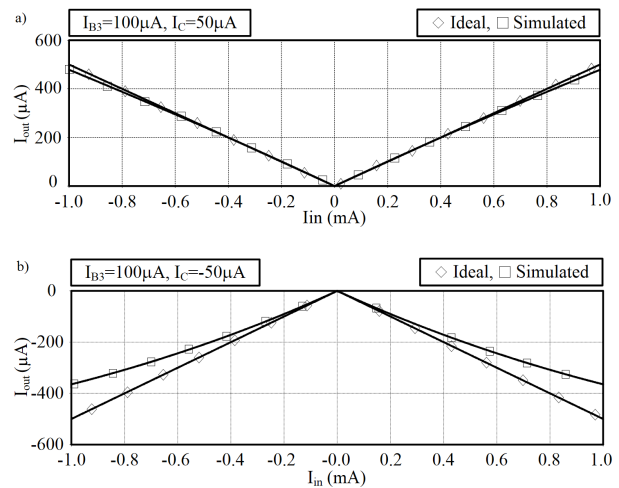


Fig. 6: DC transfer characteristic of the full-wave rectifier.

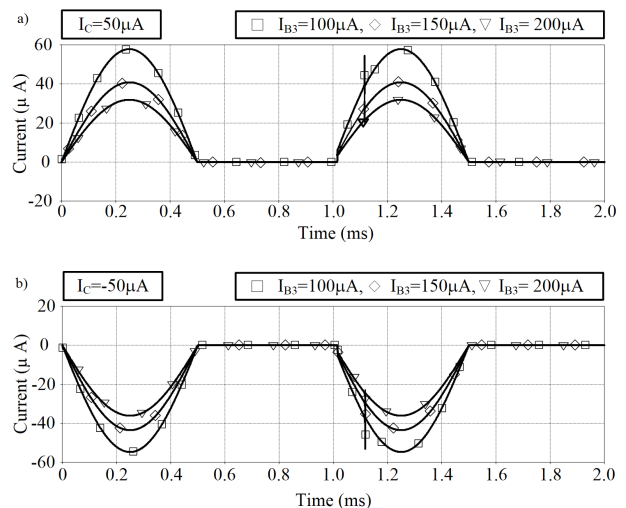


Fig. 7: The simulation results of the half-wave rectifier where $I_{B2} = 100 \mu\text{A}$, $150 \mu\text{A}$ and $200 \mu\text{A}$.

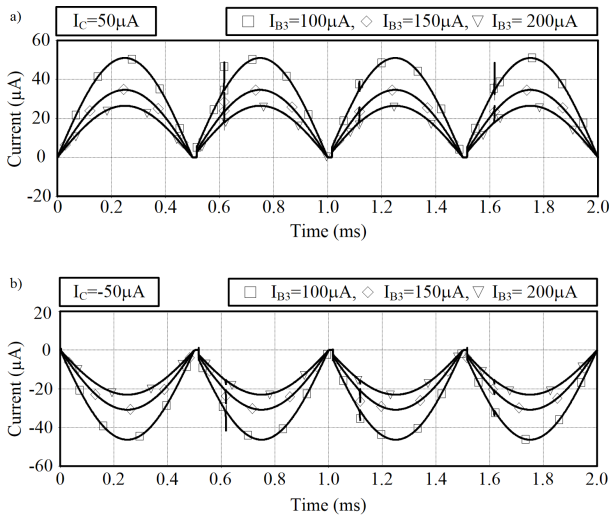


Fig. 8: The simulation results of the full-wave rectifier where $I_{B2} = 100 \mu\text{A}$, $150 \mu\text{A}$ and $200 \mu\text{A}$.

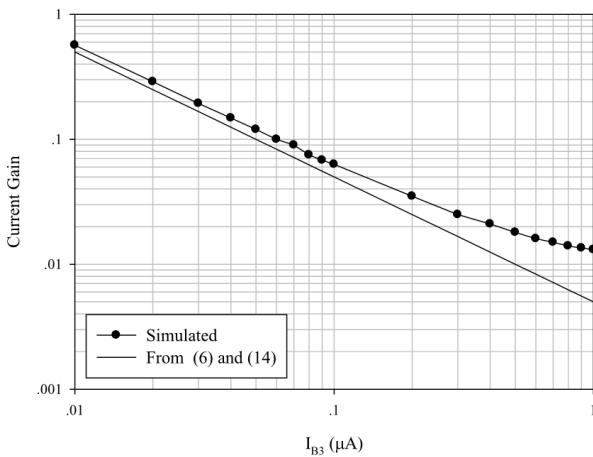


Fig. 9: The current gain where I_{B3} is varied.

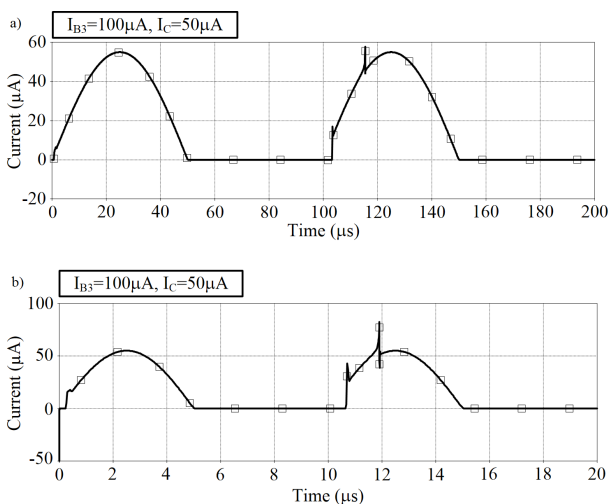


Fig. 10: The results of output current of the half-wave rectifier for different input frequencies a) 10 kHz b) 100 kHz.

full-wave rectifiers, respectively. It can be seen that the proposed circuits offers a wide-range of input current to be both rectifiers. Additionally, its output current direction can be controlled by I_C .

The simulation results of the both rectifiers, where $I_{B3} = 100 \mu\text{A}$, $150 \mu\text{A}$ and $200 \mu\text{A}$ are displayed in Fig. 7 and Fig. 8. From these results, they are confirmed that the output amplitude can be controlled by I_{B3} and I_C , respectively. The plot of the current gain relative to the I_{B3} variations is display in Fig. 6. The transient responses of the output current for different input frequencies are also shown in Fig. 10 and Fig. 11. It is concluded that the proposed circuits can operate well for a wide range of frequency; even frequency is up to 100 kHz without disturbing magnitude of the output current. The output signals of the proposed rectifiers relative to temperature variations for 27°C , 50°C and 100°C are respectively shown in Fig. 12. It is clearly observed that the output currents are slightly dependent on the wide temperature variations due to independency of V_T , as explained in Section 2.2.

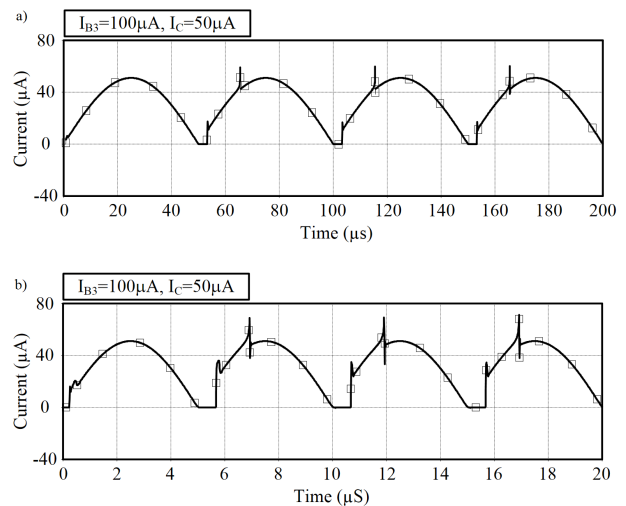


Fig. 11: The results of output current of the current-mode full-wave rectifier for different input frequencies a) 10 kHz b) 100 kHz.

The deviation values of amplitude of the output currents relative to the temperature variations are demonstrated in Fig. 13. It is found that the maximum absolute deviation of the magnitude of the output current is less than $-0,7\%$, for temperature variations of $0 - 100^\circ\text{C}$. These deviations originate from the effect of the intrinsic resistances and stray capacitances of the transistors used in the MO-CFTA, as depicted in Section 2.3.

To confirm that the half-wave and full-wave rectifiers can operate practically, they were constructed via using commercial ICs, it is shown in Fig. 14 where it is implemented by using AD844 and LM13700s. In this work, the current follower circuit and OTAs inside the

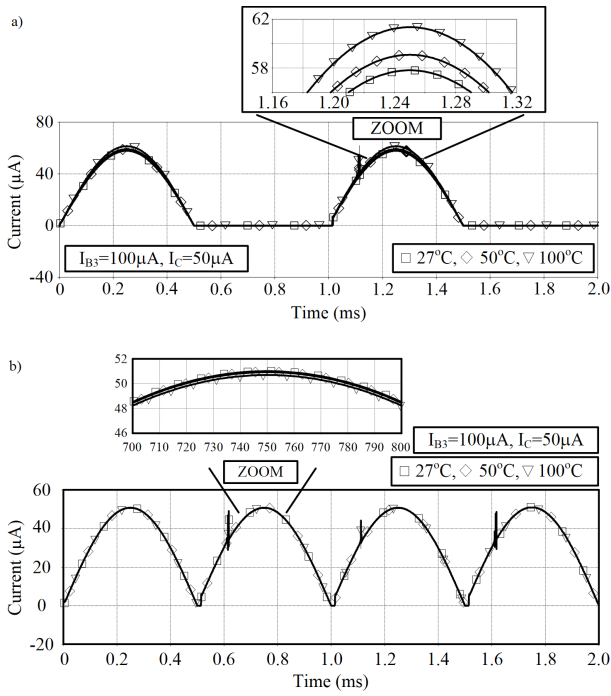


Fig. 12: Output current deviations for different temperature values a) Half-wave rectifier b) Full-wave rectifier.

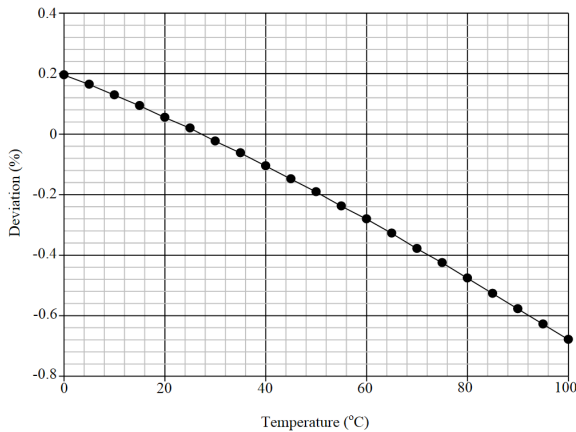


Fig. 13: The output amplitude deviation of the full-wave rectifier due to temperature variations.

MO-CFTA can be realized by using two AD844s and LM13700Ns, respectively.

Figure 15 and Fig. 16 demonstrate the practical implementation used for experimental inspection of the proposed half-wave and full-wave rectifiers, respectively. Since, the input signal is voltage form, the CFA1-CFA2 of the half-wave rectifier and the CFA1-CFA4 of the full-wave rectifier are used to be a V to I converters where both R_L is used to be able to measure the output current by an oscilloscope. The experimental results the half-wave and full-wave rectifiers are illustrated in Fig. 17 and Fig. 18, respectively, it

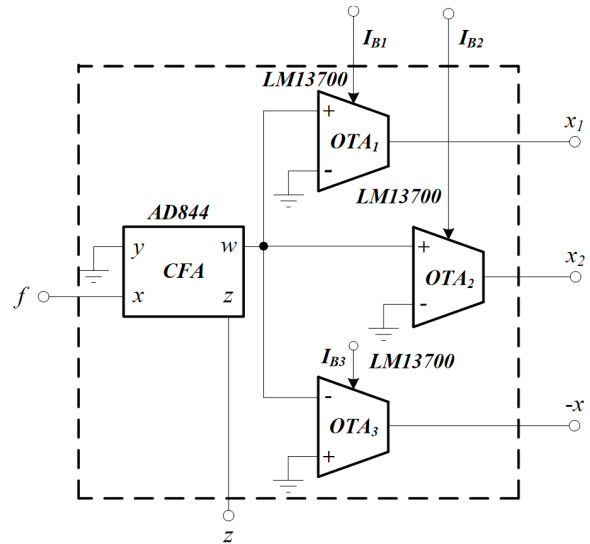


Fig. 14: A possible implementation of MO-CFTA employing AD844 and LM13700s.

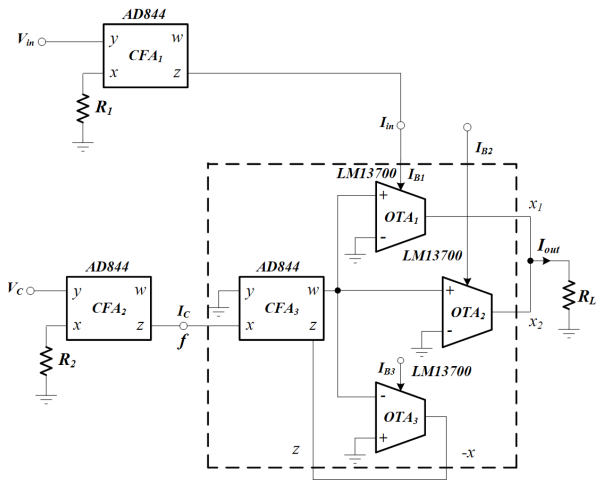


Fig. 15: Practical implementation for experimental inspection of the proposed half-wave rectifier.

is insisted that the proposed both rectifiers practically work.

4. Conclusion

The new current-mode half-wave and full-wave rectifier have been presented in this paper. Its advantages are that; the both rectifiers consist of only one MO-CFTA without any passive element; the output amplitude is slightly dependent on temperature variations. Moreover, they can be electronically adjusted by input bias currents. The proposed circuits can operate at high frequency up to several hundred kilohertz range. The results obtained by PSpice simulation found that the maximum power consumption of the proposed circuits are approximately 3,01 mW at ± 2 V supply voltages.

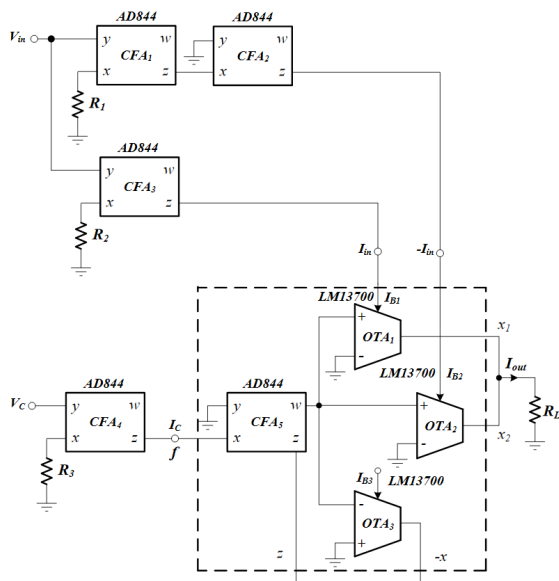


Fig. 16: Practical implementation for experimental inspection of the proposed full-wave rectifier.

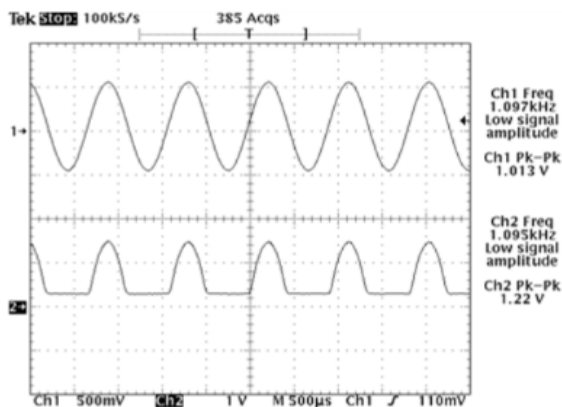


Fig. 17: The experimental result of the proposed half-wave rectifier where $R_1 = R_2 = R_L = 1 \text{ M}\Omega$, $V_C = 1 \text{ V}$ and $I_{B3} = 100 \mu\text{A}$.

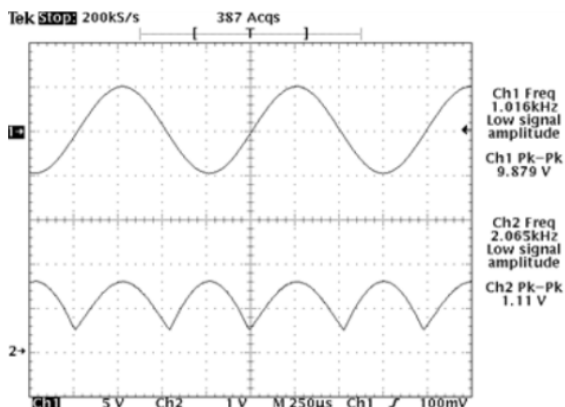


Fig. 18: The experimental result of the proposed full-wave rectifier where $R_1 = R_2 = R_3 = R_L = 1 \text{ M}\Omega$, $V_C = 10 \text{ V}$ and $I_{B3} = 10 \text{ mA}$.

The experimental and simulation results are described, and suited well with the theoretical expectation.

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