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Low Voltage Rail to Rail CMOS Current Feedback Operational Amplifier and its Applications for Analog VLSI

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Abstract. This paper presents a new CMOS current feedback operational amplifier (CFOA) with rail to rail swing capability at all terminals. The circuit operates as a class AB for lower power consumption. Besides operating at low supply voltages of ± 1.5 V, the proposed CFOA has a standby current of 200 μA. The proposed CFOA circuit is thus a versatile building block for low voltage low power applications. The applications of the CFOA to realize a transconductor/multiplier cell, MOS-C differential integrator, MOS-C bandpass filter and MOS-C oscillator are given. PSpice simulations based on 1.2 μm level three parameters obtained from MOSIS are given.

Key Words: current feedback op-amp, filters, oscillators

1. Introduction

Recently, the demand for ever smaller and cheaper electronic systems had led manufactures to integrate entire systems on a single chip. This push towards higher component densities require lower supply voltages to allow for more integration with reasonable power dissipation. It is inevitable that this will be true for both digital as well as analog circuits. Analog circuits operating from low supply voltage must be designed to have rail to rail voltage swing [1]. This is important to keep the signal to noise ratios as large as possible. Unfortunately, this usually results in complicated circuit that withdraws more quiescent current resulting in high standby power dissipation. Thus the goal is to design compact low voltage analog cells which are simple and power efficient. Op-amps operating from low supply voltage have been introduced in Vost et al. [1]. These op-amps usually require a complicated input stage to guarantee a rail to rail input common mode operation while maintaining a constant transconductance. This is important to allow optimal frequency compensation. However, the use of the compensation capacitor results in a finite gain bandwidth product for op-amp based circuits. Hence, the bandwidth is not utilized effectively for higher gain values. Another disadvantage is the slew rate, which can result in a smaller bandwidth for signals with large voltage swing. A useful block for high slew rate and bandwidth applications is the current feedback operational amplifier (CFOA) [2]. The CFOA is a versatile four terminal active building block represented symbolically as shown in Fig. 1. The versatility of the CFOA is the availability of the Z terminal that enables the realization of many useful analog circuits such as voltage amplifiers, voltage integrators, inductors, frequency dependent negative resistors, filters and oscillators [3–5]. The CFOA is also known as the transimpedance operational amplifier is now commercially available in bipolar integrated circuit from several manufacturers [6,7]. Although CMOS realization of the CFOAs are available [8,9], they usually operate in a class A mode with limited voltage swing capability.

In this paper, novel CMOS rail to rail CFOA circuit for low voltage and low power applications is proposed. The CFOA operates as a class AB from ± 1.5 V and has a standby current of 200 μA. The applications of the CFOA in realizing transconductor/

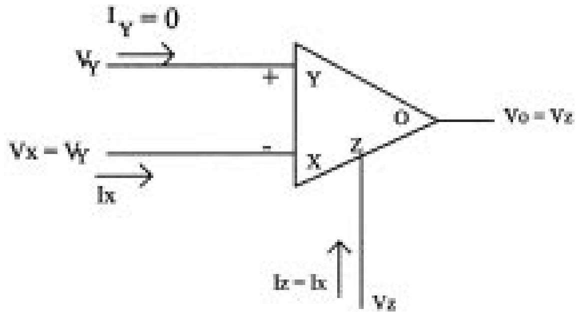

Fig. 1. The symbol of the CFOA.

multiplier cell, MOS-C integrator, MOS-C bandpass–lowpass filter and oscillator are given. PSpice simulation for the proposed CFOA and its applications based on 1.2 μm level 3 parameters are given.

2. The CFOA Circuit

The proposed class AB-CFOA circuit is shown in Fig. 2, where two differential pairs are used to provide a rail to rail operation at the Y and the X terminals. Transistors M1 and M2 conduct till the positive supply rail while transistors M3 and M4 conduct for the signal swing down to the negative supply rail. By the current mirroring action of the transistors (M5, M6) and (M7, M8), the currents of the two differential pairs are summed at the drains of the transistors M1 and M2. Transistors M9 and M10 force these currents to be equal and hence:

$$V_X = V_Y \tag{1}$$

To provide a low impedance at the X terminal, a suitable buffer circuit should be used. It is worth noting that the traditional source follower is not suitable since it will not provide a rail to rail swing capability [10]. In the proposed CFOA circuit shown in Fig. 2, transistors M13 to M16 provide the necessary buffering action with a rail to rail swing capability. The transistors M15 and M16 form the push pull output stage at the X terminal, transistors M13 and M14 are level shifting transistors providing proper biasing for the transistor M15. If the current is withdrawn from the X terminal then the gate voltages of the transistors M15 and M16 are lowered. Thus the current through transistor M16 increases while that through transistor M15 decreases. Similarly, if the X terminal is required to sink current, then the gate voltages of the transistors M15 and M16 are increa-

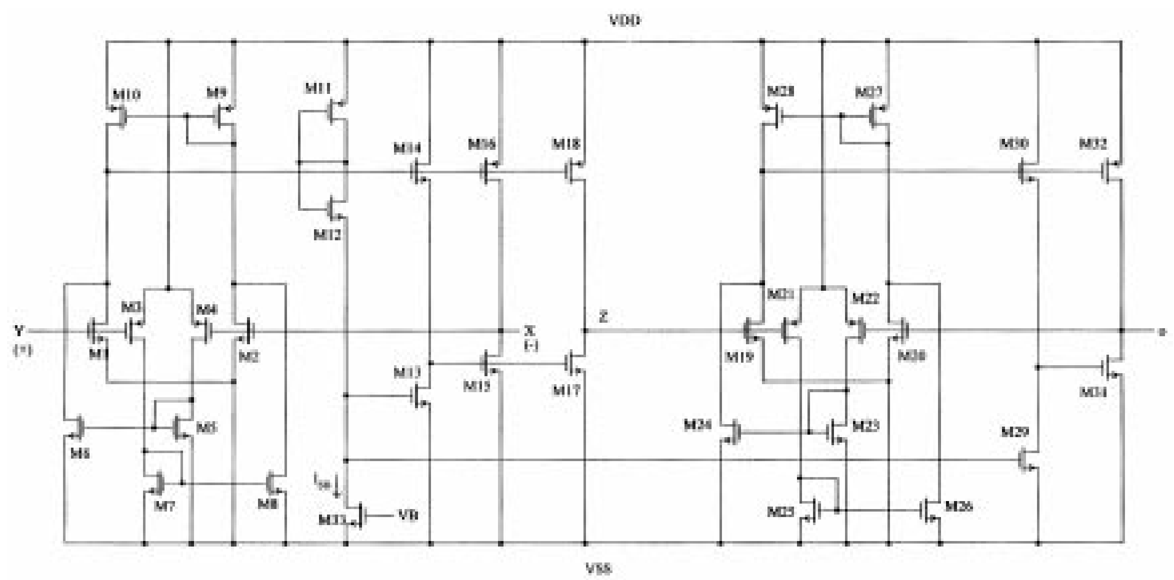

Fig. 2. The rail to rail CFOA CMOS circuit.

sed. Thus, the current through transistor M16 decreases while that through transistor M15 increases. This push pull action of the transistors M15 and M16 reduce the power dissipation. To prevent the cross over distortion, both transistors M15 and M16 must be ON when no current withdrawn from the X terminal (standby), yet this current should be small and controlable. This is achieved by using a suitable gate voltage of M13 which sets the voltage level shift between the gates of M15 and M16. Assuming all transistors to be working in the saturation region, it is clear that:

$$V_{SG16} + V_{GS14} + V_{GS15} = V_{DD} - V_{SS} \tag{2}$$

$$V_{SG11} + V_{GS12} + V_{GS13} = V_{DD} - V_{SS} \tag{3}$$

Since the matched transistors M13 and M14 have equal currents, therefore they have the same gate to source voltages. From equations (2) and (3):

$$\sqrt{\frac{2I_{M16}}{K_P}} + \sqrt{\frac{2I_{M15}}{K_N}} = \sqrt{\frac{2I_{SB}}{K_P}} + \sqrt{\frac{2I_{SB}}{K_N}} \tag{4}$$

where I_{SB} is the current through the current source transistor M33, $K_P = \mu_P C_{ax}(W/L)_{11,16}$ and $K_N = \mu_N C_{ax}(W/L)_{12,15}$. In the standby mode, no current is withdrawn from the X terminal hence M15 and M16 have equal currents and equal to the standby current I_{SB} which is controlled by the biasing voltage V_B. From Fig. 2, the X terminal current is mirrored to the Z terminal by the action of transistors M17 and M18, therefore:

$$I_Z = I_X \tag{5}$$

Finally, a suitable buffer must be available between the Z and the O terminals that is similar to the buffer between the Y and the X terminals and consisting from the transistors M19–M32, therefore:

$$V_O = V_Z \tag{6}$$

PSpice simulations using 1.2 μm (SCNA Vendor: ORBIT Semiconductors) technology of the class AB-CFOA circuit with supply voltages of ± 1.5 V have been carried out using the aspect ratios given in Table 1.

Fig. 3(a) shows the current at the Z terminal when the X terminal current is scanned from -100 to 100 μA while the Y and Z terminals are grounded. Fig. 3(b) shows the X terminal voltage offset variation versus I_X when the Y terminal is grounded.

Table 1. The transistor apsect ratio of the CFOA of Fig. 2.

MOS transistor	Aspect ratio (W μm/L μm)
M1, M2, M19, M20	6/2.4
M3, M4, M21, M22	6/2.4
M5-M8, M23–M26	12/2.4
M9, M10, M27, M28	360/2.4
M11, M12	2.4/2.4
M13, M14, M29, M30	2.4/2.4
M15–M18, M31, M32	420/3.6

The X terminal output resistance is less than 20 Ω. Fig. 3(c) shows the voltage swing at the X, Z and the O terminals when used to realize a voltage amplifier of gain two. The values of the grounded resistors used at the X and Z terminals are 20 and 40 kΩ respectively. The frequency response of the CFOA based voltage amplifier of gain 1, 2, 4, 8, 16 is shown in Fig. 3(d) where the X terminal resistance is 5 kΩ and the Z terminal resistance has been scanned from 5 to 80 kΩ. It is clear from Fig. 3(d) that the amplifier circuit realized from the proposed CFOA experience no loss of bandwidth when the gain is increased. The parasitic capacitance C_Z and the resistance R_Z at the compensation node are 1.44 pF and 4.3 MΩ respectively.

3. The CFOA Based Applications

In the following subsections, the applications of the CFOA in realizing a tranconductor/multiplier cell, a MOS-C differential integrator, a continuous-time bandpass–lowpass filter and a MOS-C oscillator are given. The PSpice simulation results are also given to verify the analytical results.

A. *The Transconductor/Multiplier Cell*

The CFOA can be used to realize a transconductance/multiplier cell as shown in Fig. 4. The transconductance multiplying action is achieved by the four transistors M1 to M4 [11]. The four transistors cell provide two output currents $(I_1 + I_3)$ and $(I_2 + I_4)$ which are subtracted by the CFOA through the feedback from the Z terminal to the Y terminal and thus the output current is given by:

$$I_0 = (I_1 + I_3) - (I_2 + I_4) \tag{7}$$

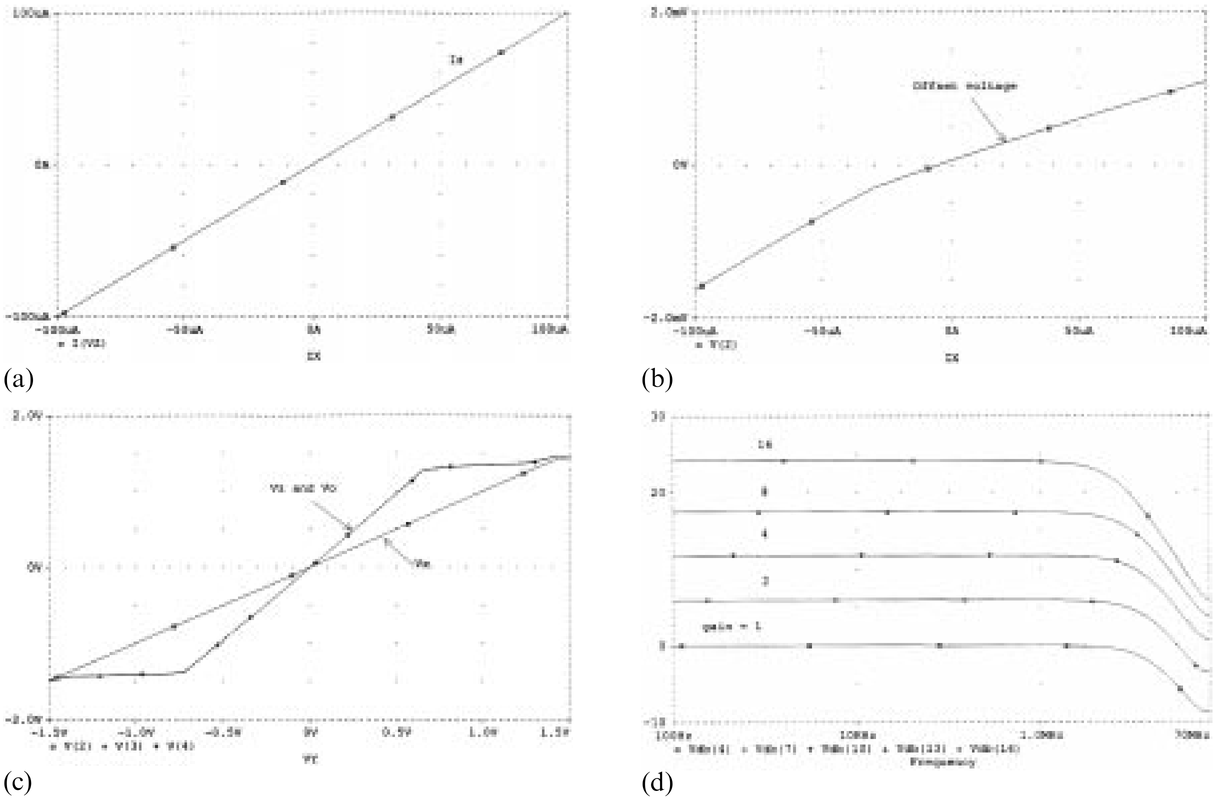

Fig. 3. (a) The Z terminal current, (b) the X terminal offset voltage, (c) the voltage swing at the X, Z, and the O terminals of the CFOA based amplifier, (d) the frequency response of the CFOA based amplifier for different values of gain.

The output current in terms of the input gate voltages V_1 and V_2 and the control voltages V_{C1} and V_{C2} is given by:

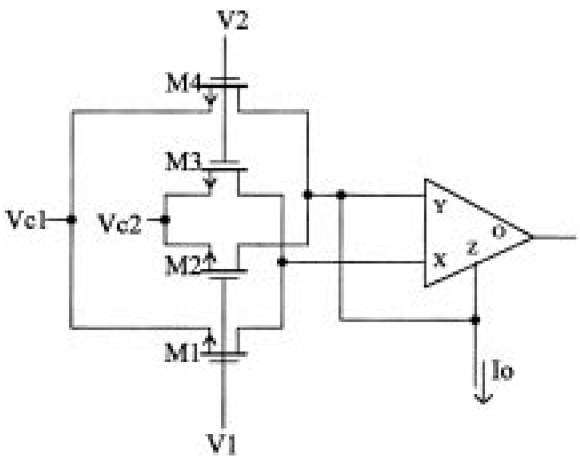

Fig. 4. The transconductor/multiplier cell.

$$I_0 = K(V_{C2} - V_{C1})(V_1 - V_2) \tag{8}$$

where K is the transconductance parameter of each transistor of the four matched transistors M1, M2, M3 and M4. It is worth noting that the above equation is valid whether the four MOS transistors operate in the saturation or in the triode region. Thus the cell of Fig. 4 can be used as a transconductor or as a four quadrant multiplier.

Fig. 5(a) shows the output current of the cell when used as a transconductor versus V_1, when V_1 and V_2 scanned from -0.75 to $0.75\,\text{V}$, $V_{C21} = 0.2\,\text{V}$ and $K = 416.67\,\mu\text{A}/\text{V}^2$. Fig. 5(b) represents the multiplier output current vs. V_1 when V_2 is grounded and V_{C21} scanned from -0.2 to $0.2\,\text{V}$.

B. The MOS-C CFOA Integrator

Fig. 6 shows the CFOA based differential integrator. The CFOA differential integrator is a direct applica-

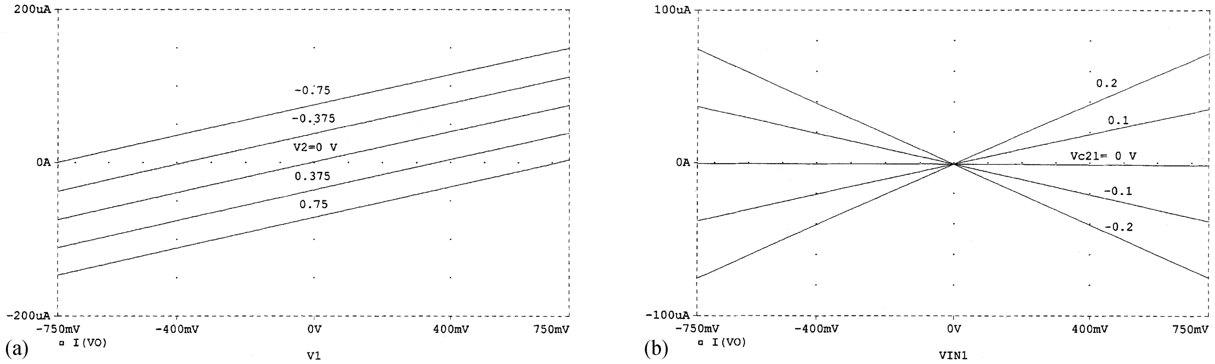

Fig. 5. (a) The output current of the transconductor cell, (b) the output current of the multiplier cell.

tion of the CFOA based transconductor/multiplier cell by connecting a capacitor C between the Z terminal and the ground. The output voltage of the integrator is taken from the O terminal and is given by:

$$V_o = \frac{1}{SCR_a}(V_1 - V_2) \tag{9}$$

where $R_a = 1/K_a(V_{C2} - V_{C1})$. The proposed CFOA differential integrator has a high input impedance since the inputs of the circuit are directly the gates of MOS transistors. PSpice simulation results for the differential integrator are shown in Fig. 7 with a square wave input of 1 V peak to peak amplitude and a frequency of 25 kHz, where R_a is adjusted to 10 kΩ and C = 1 nF.

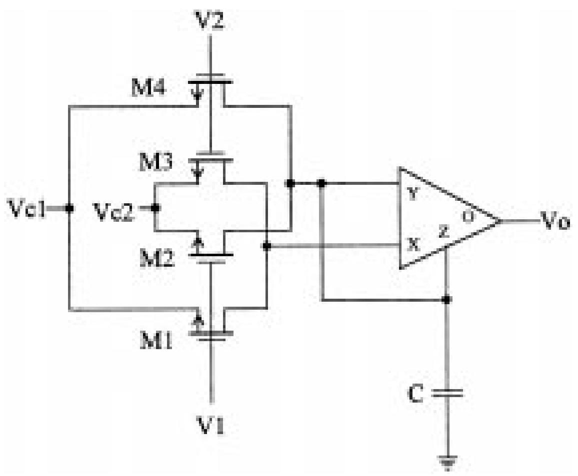

Fig. 6. The MOS-C CFOA integrator.

C. *The CFOA Bandpass–Lowpass Filter*

Since the integrator is a basic building block in realizing continuous-time filters [12–14]. The CFOA based integrators are used to implement two continuous-time filters with single ended and balanced bandpass–lowpass outputs in the voltage mode. Fig. 8 shows the single ended bandpass–lowpass filter with the following voltage transfer functions:

$$\frac{V_{BP}}{V_i} = -\frac{s/R_aC_1}{D(s)}, \quad \frac{V_{LP}}{V_i} = \frac{1/R_aR_bC_1C_2}{D(s)} \tag{10}$$

and

$$D(s) = s^2 + \frac{1}{R_CC_1}s + \frac{1}{R_aR_bC_1C_2} \tag{11}$$

$$\omega_o = \frac{1}{\sqrt{R_aR_bC_1C_2}} \quad \text{and} \quad Q = R_C\sqrt{\frac{C_1}{R_aR_bC_2}} \tag{12}$$

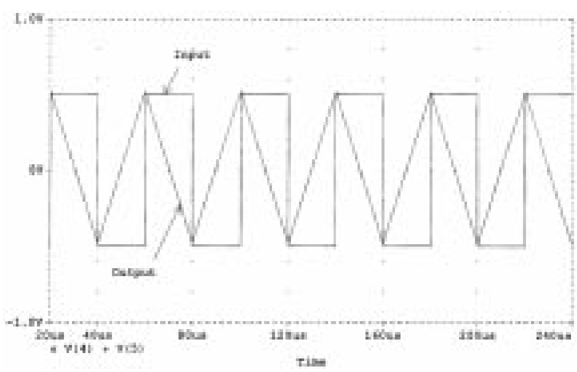

Fig. 7. The output of the integrator along with the square wave input signal.

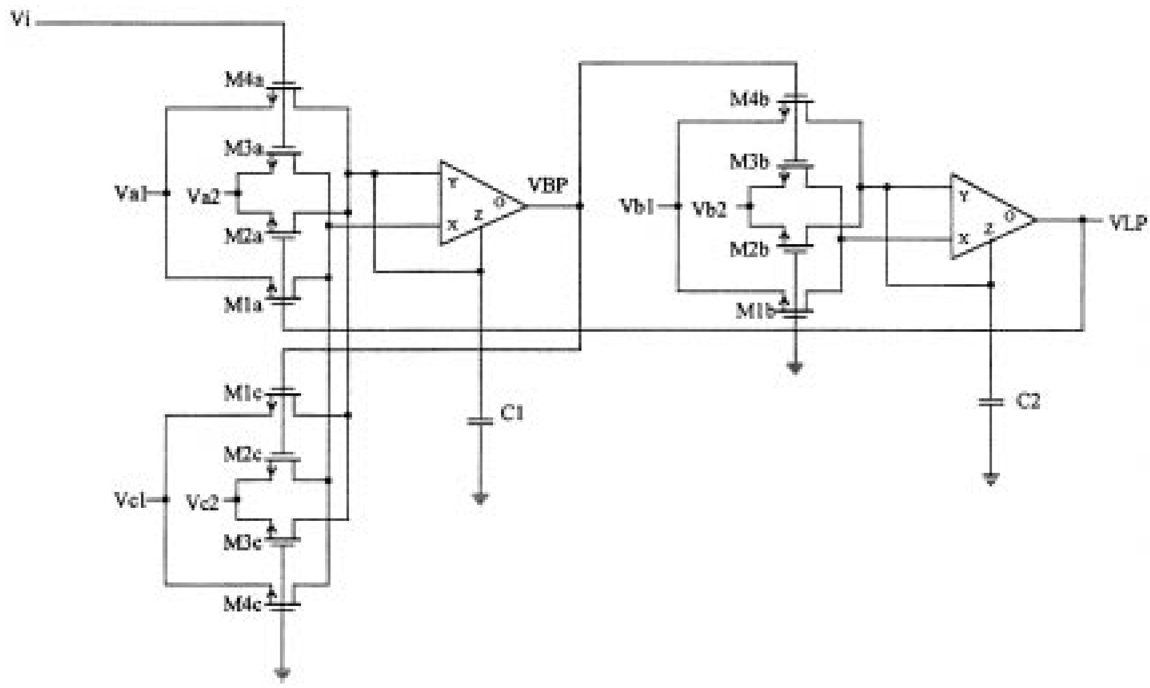

Fig. 8. The CFOA bandpass–lowpass filter.

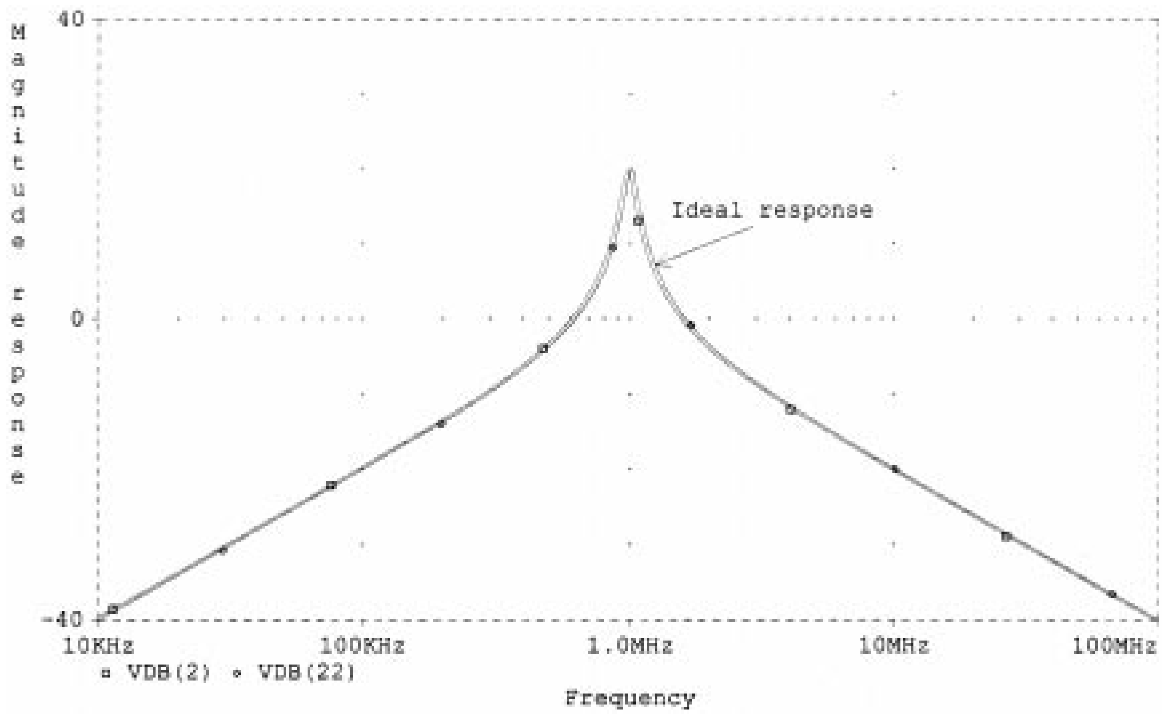

Fig. 9(a). The magnitude response of the bandpass filter.

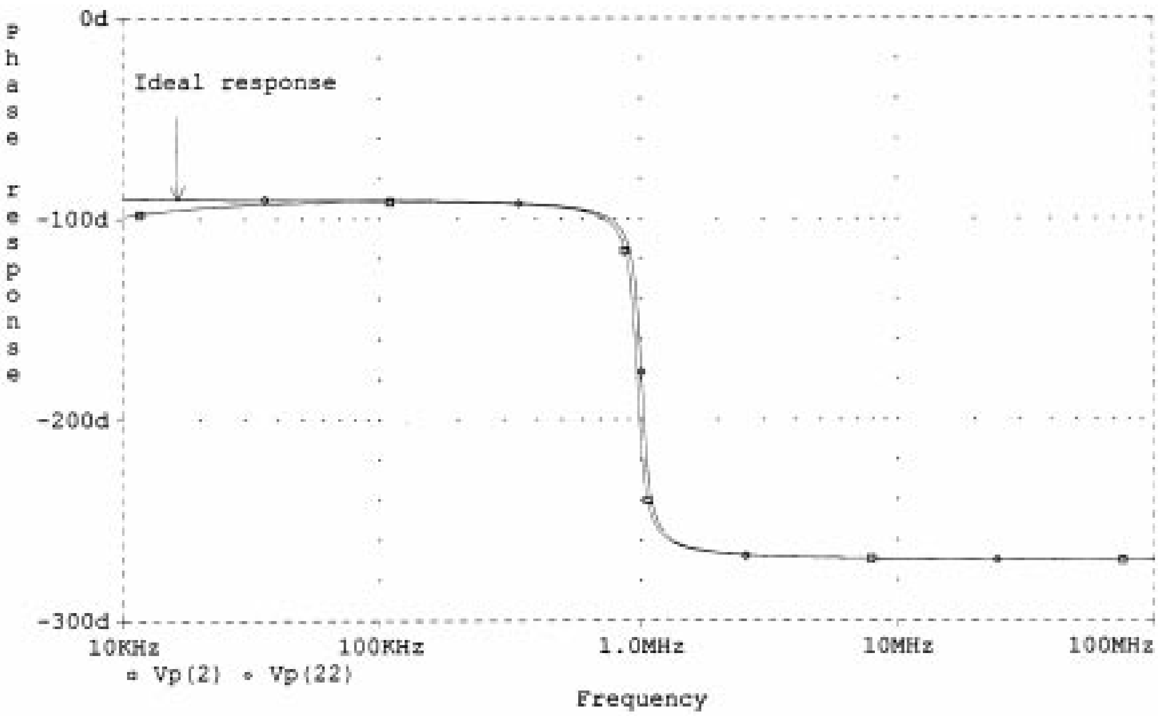

Fig. 9(b). The phase response of the bandpass filter.

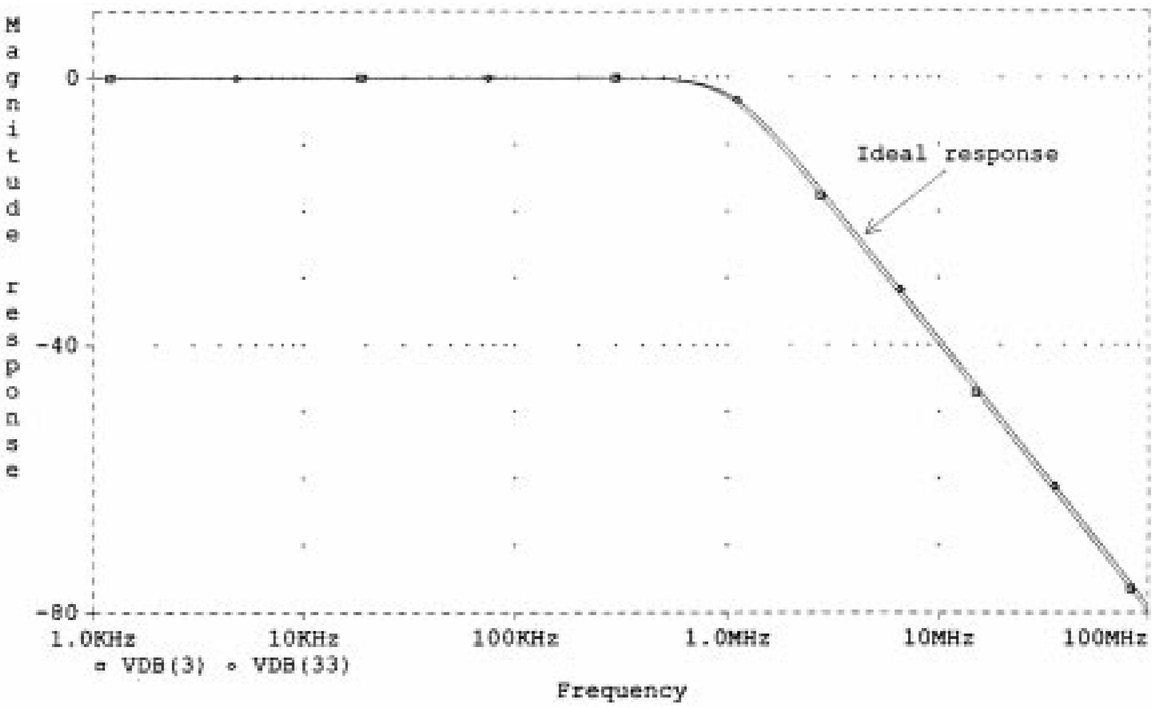

Fig. 9(c). The magnitude response of the lowpass filter.

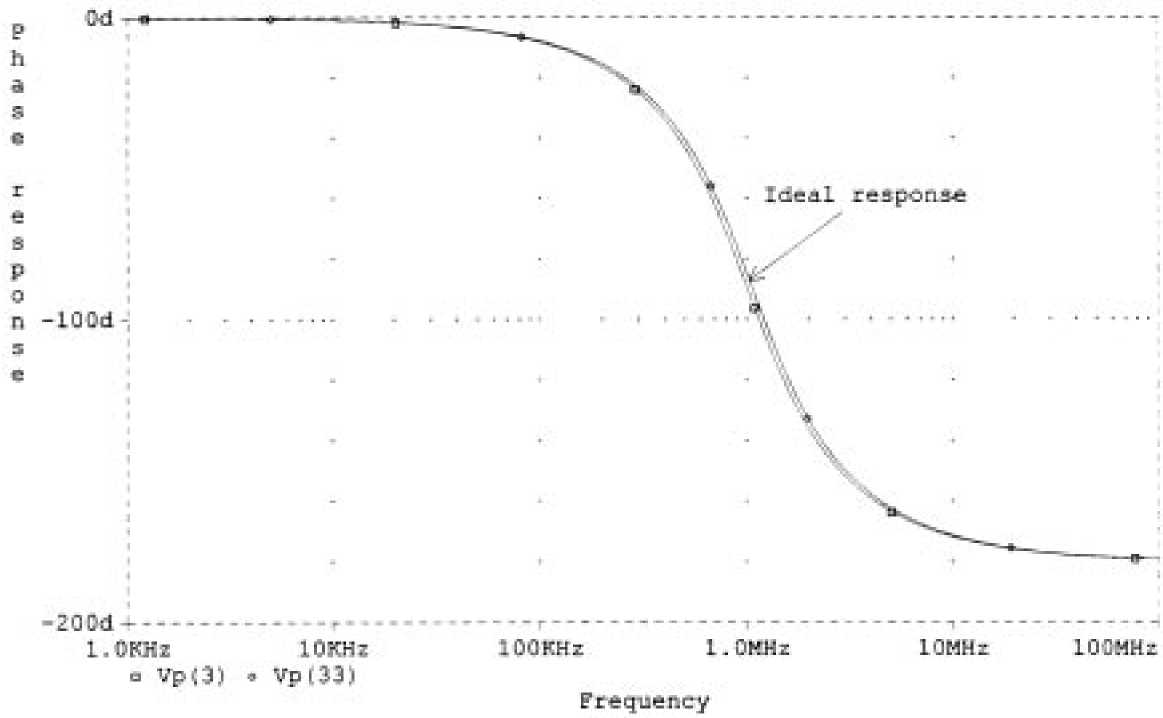

Fig. 9(d). The phase response of the lowpass filter.

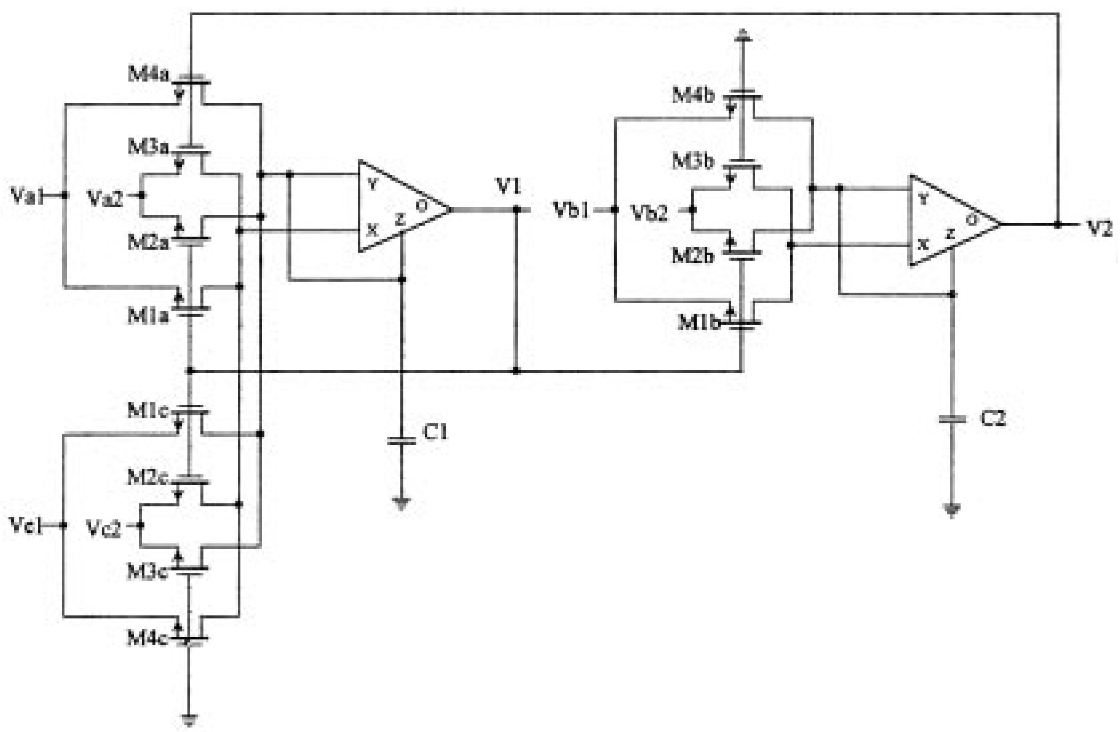

Fig. 10. The MOS-C CFOA oscillator.

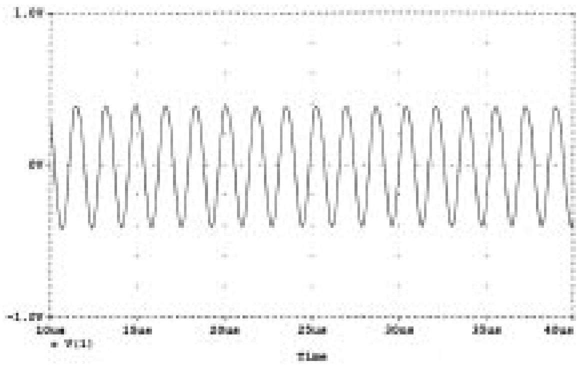

Fig. 11(a). The voltage waveform V_1 of the oscillator.

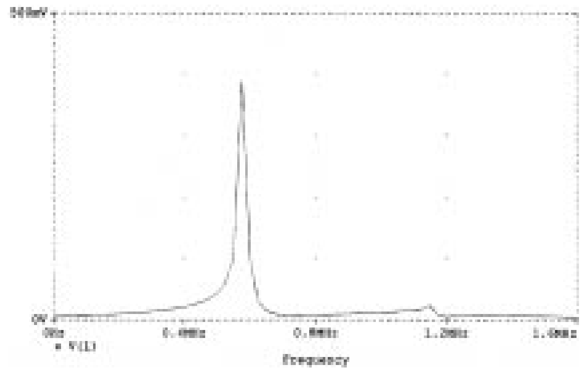

Fig. 11(b). The frequency spectrum of the oscillator.

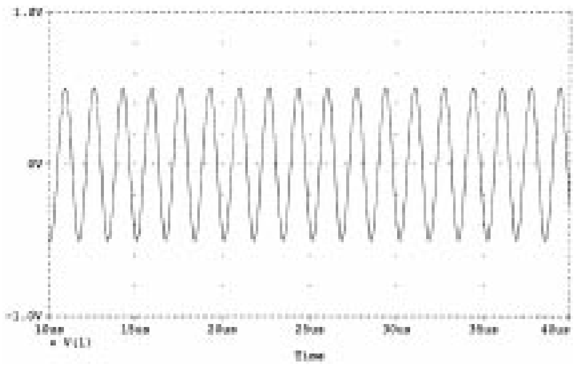

Fig. 11(c). The voltage waveform V_1 of the oscillator using ideal CFOA.

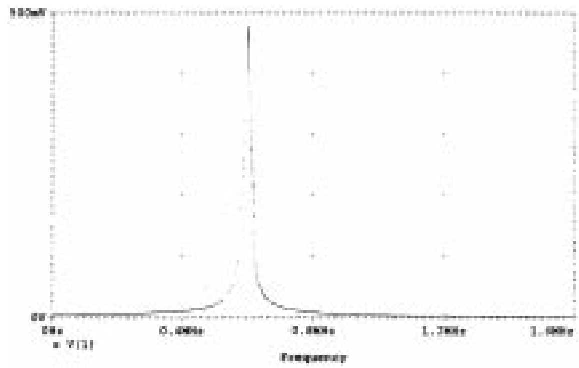

Fig. 11(d). The frequency spectrum of the oscillator using ideal CFOA.

It is seen that the resistor R_C controls the Q of the filter without affecting ω_o of the filter.

PSpice simulation results for the filter circuit shown in Fig. 8 with $C_1 = C_2 = 25\,\text{pF}$, $R_a = R_b = 6.32\,\text{k}\Omega (K = 416.67\,\mu\text{A}/\text{V}^2$ and $V_{a21} = V_{b21} = 0.38\,\text{V})$ and $R_c = 10\,Ra$. Where $\text{Kc} = 83.33\,\mu\text{A}/\text{V}^2$ and $V_{C21} = 0.19\,\text{V}$ to obtain a bandpass filter with center frequency of $f_o = 1\text{MHz}$ and $Q = |T_{BP}(\omega_o)| = 10$ is shown in Figs. 9(a) and 9(b) indicating both the magnitude and the phase of the bandpass output. Simulation results for the same circuit but with $R_C = 4.47\,\text{k}\Omega$ to obtain a maximally flat lowpass response designed for DC gain of 1 and with $f_o = 1\,\text{MHz}$ is shown in Figs. 9(c) and 9(d) indicating both the magnitude and the phase of the lowpass output where $\text{Kc} = 416.67\,\mu\text{A}/\text{V}^2$ and V_{C21} is 0.54 V.

D. The MOS-C CFOA Oscillator

Oscillators are key components for most communication systems and there is demand for low power programmable analog functionality on a single ASIC. In this section, a new MOS-C CFOA voltage oscillator is introduced. The proposed oscillator has the advantage of controlling the condition of oscillation by using the control voltage of one of the MOS transconductor without affecting the oscillation frequency which is controlled by another transconductor. Fig. 10 represents the proposed oscillator using three of the four MOS transconductor cells and two grounded capacitors which makes the oscillator suitable for VLSI. The condition of oscillation and the radian frequency of oscillation are given by:

$$R_a = R_c, \quad \omega_o = \frac{1}{\sqrt{R_a R_b C_1 C_2}} \tag{13}$$

Therefore the transconductance formed from M1c to M4c controls the condition of oscillation through its control voltage without affecting the oscillation frequency.

PSpice simulation results for the proposed oscillator using $C_1 = C_2 = 25\,\text{pF}$, R_a, R_b, and R_c equal to $11\,\text{k}\Omega$. Taking $K = 168.257\,\mu\text{A/V}^2$ and $V_{C12} = 0.54\,\text{V}$ to obtain a frequency of oscillation of 575 kHz. The oscillator output waveform of V_1 is shown in Fig. 11(a) and its spectrum shown in Fig. 11(b). The oscillator output waveform of V_1 using ideal CFOA is shown in Fig. 11(c) and its spectrum shown in Fig. 11(d).

4. Conclusions

Low voltage rail to rail CMOS–CFOA circuit is presented. The proposed circuit operates as a class AB. The circuit is suitable for low voltage, low power applications. The proposed CFOA circuit employs no compensation capacitors and are characterized by the ability to achieve high gain with low loss of bandwidth. Applications of the CFOA in analog signal processing have been discussed. It is interesting to note that in all applications, tuning can be achieved via a control voltage. PSpice simulation results for all applications are given to confirm the analytical results.

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He has held visiting academic appointments at San Francisco State University, Florida Atlantic University and the American University in Cairo and was a visiting scholar at Bochum University, Germany (Summer 1985) and with the Technical University of Wien, Austria (Summer 1987).

In 1977, Dr. Soliman was decorated with the First Class Science Medal, from the President of Egypt, for his services to the field of Engineering and Engineering Education.