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# CMOS balanced output transconductor and applications for analog VLSI

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**Abstract**

A new CMOS programmable balanced output transconductor (BOTA) is introduced. The BOTA is a useful block for continuous-time analog signal processing. A new CMOS realization based on MOS transistors operating in the saturation region is given. Application of the BOTA in realizing bandpass–lowpass–allpass–notch biquad mixed mode filter using four BOTAs and two grounded capacitors and in realizing current mode MOS-C oscillators using three or four BOTAs and two grounded capacitors are given. PSpice simulation results for the BOTA circuit and for its applications are also included. 

*Keywords:* CMOS; Transconductors

## 1. Introduction

The programmable balanced output transconductor (BOTA) is a useful building block for continuous-time analog signal processing. Based on the BOTA circuit, MOS floating and grounded resistors, balanced output integrators, MOS-C filters with balanced outputs and the active realization of passive filters with the minimum number of the BOTAs can be built [1]. Several realizations for the CMOS transconductors with a single or multiple outputs and their applications have been introduced in the literature [2–12]. The realizations given in Refs. [2–4] are based on using a differential stage with MOS transistors operating in the saturation region. The CMOS transconductors given in Refs. [5–7] are based on the use of MOS transistors operating in the nonsaturation region. The use of both a differential stage and MOS transistors operating in the nonsaturation region to realize CMOS transconductors are given in Refs. [8,9]. The application of the single output transconductor in realizing integrators, inductor, frequency dependent negative resistors are given in Ref. [10], and also in realizing filters are given in Refs. [10,11]. The application of the multiple outputs transconductor to realize tunable continuous time filters are given in Ref. [12]. A direct application of the balanced output transconductor is the implementation of voltage controlled floating resistors [13]. The BOTA realization given in Ref. [1] provides a balanced output current based on the use of a wide input range differential CMOS transconductor in cascade with a voltage-controlled MOS grounded resistor [14] and a balanced output transconductor stage.

In this paper, a new CMOS realization of a BOTA based on transistors operating in the saturation is given. The proposed BOTA can be programmed using a control voltage which allows to compensate for process parameter spreads in automatically tuned filters. The BOTA, whose symbol is shown in Fig. 1, has two input voltages and provides two balanced output currents through the two output terminals.

The application of the BOTA in realising a mixed mode biquad filter that is capable of realising bandpass, lowpass, allpass and notch responses using four BOTAs and two grounded capacitors which makes the filter suitable for VLSI is given. The application of the BOTA in realising two MOS-C oscillators using three or four BOTAs and two grounded capacitors is also given.

In Section 2, the realisation of the programmable CMOS balanced output transconductor is presented. In Section 3, the application of the BOTA in realising bandpass–lowpass–allpass–notch biquad mixed mode filter using four BOTAs and two grounded capacitors and in realising two current mode MOS-C oscillators using three or four BOTAs and two grounded capacitors are given. PSpice simulation results for the transconductor circuit indicating the linearity range and for its applications to verify the analytical results are also given.

## 2. The proposed balanced output transconductor circuit

The proposed CMOS balanced output transconductor circuit is shown in Fig. 2. The matched transistors M1–M8

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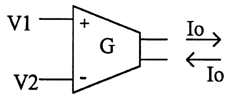



Fig. 1. The symbol of the BOTA.

are the basic transistors, and their gate voltages are the input voltages to the transconductor. The remaining transistors perform the current transfer to the output ports of the transconductor circuit. All the transistors are assumed to be operating in the saturation region with their sources connected to their substrate/bulk. The MOS drain current in the saturation region is given by:

$$I_D = \frac{K}{2}(V_{GS} - V_T)^2 \tag{1}$$

where $K = \mu_n C_{ox}(W/L)$; $(W/L)$ is the transistor aspect ratio; $\mu_n$ is the electron mobility; $C_{ox}$ is the gate oxide capacitance per unit area and $V_T$ is the threshold voltage (assumed the same for all MOS transistors).

From Fig. 2, the transconductor output current is given by:

$$I_o = (I_1 + I_4) - (I_2 + I_3) \tag{2}$$

where

$$I_1 = \frac{K}{2}(V_1 + V_{DD} - V_T)^2 \tag{3}$$

$$I_2 = \frac{K}{2}(V_2 + V_{DD} - V_T)^2 \tag{4}$$

$$I_3 = \frac{K}{2}(V_1 - V_C - V_T)^2 \tag{5}$$

$$I_4 = \frac{K}{2}(V_2 - V_C - V_T)^2 \tag{6}$$

Substituting from Eq. (3) to Eq. (6) in Eq. (2), the transconductor output current is given by

$$I_o = K(V_C + V_{DD})(V_1 - V_2) \tag{7}$$

Therefore, the proposed CMOS circuit shown in Fig. 2 operates as a balanced output transconductor with a programmable transconductance $G$ which is controlled by the control voltage $V_C$ and is given by:

$$G = K(V_C + V_{DD}) \tag{8}$$

Note that the tuning of the BOTA is achieved using the control voltage $V_C$. The performance of the proposed BOTA circuit was verified by PSpice simulations with supply voltages $\pm$ 2.5 V and using the MOSIS 2 $\mu$m technology and the transistors aspect ratios given in Table 1.

Table 1

| MOS transistors | Aspect ratio ($W/L$, $\mu$m/$\mu$m) |
|---|---|
| M1–M8 | 20/8 |
| M9–M12 | 200/4 |

The output current of the BOTA versus $V_1$ for various values of $V_2$ where $V_1$ and $V_2$ are scanned from $-1$ to 1 V with $V_C = -1.7$ V is shown in Fig. 3a. The output current of the BOTA versus $V_1$ when $V_2$ is grounded and $V_C$ as a control parameter where $V_C$ is scanned from $-1.5$ to $-2.3$ V is shown in Fig. 3b. The frequency response of the BOTA which look flat up to 10 MHz is shown in Fig. 4a,b, indicating both the amplitude and phase of the output current. PSpice results in the output-referred and input-referred noise voltage spectral densities for the BOTA when terminated by 1 kΩ are shown in Fig. 4c. The total harmonic distortion (THD) is less than 0.25% for 100 kHz 1 V peak-to-peak sinusoidal input.

## 3. Applications of the BOTA

Fig. 5 represents a filter circuit which realizes second-order lowpass, bandpass, allpass and notch responses. The lowpass and bandpass outputs exist in the voltage and current modes; however, the allpass and notch outputs exist

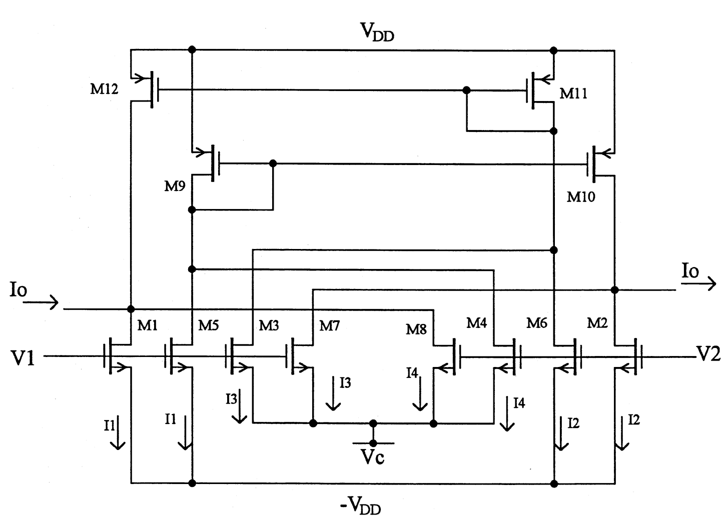



Fig. 2. The CMOS circuit of the BOTA.

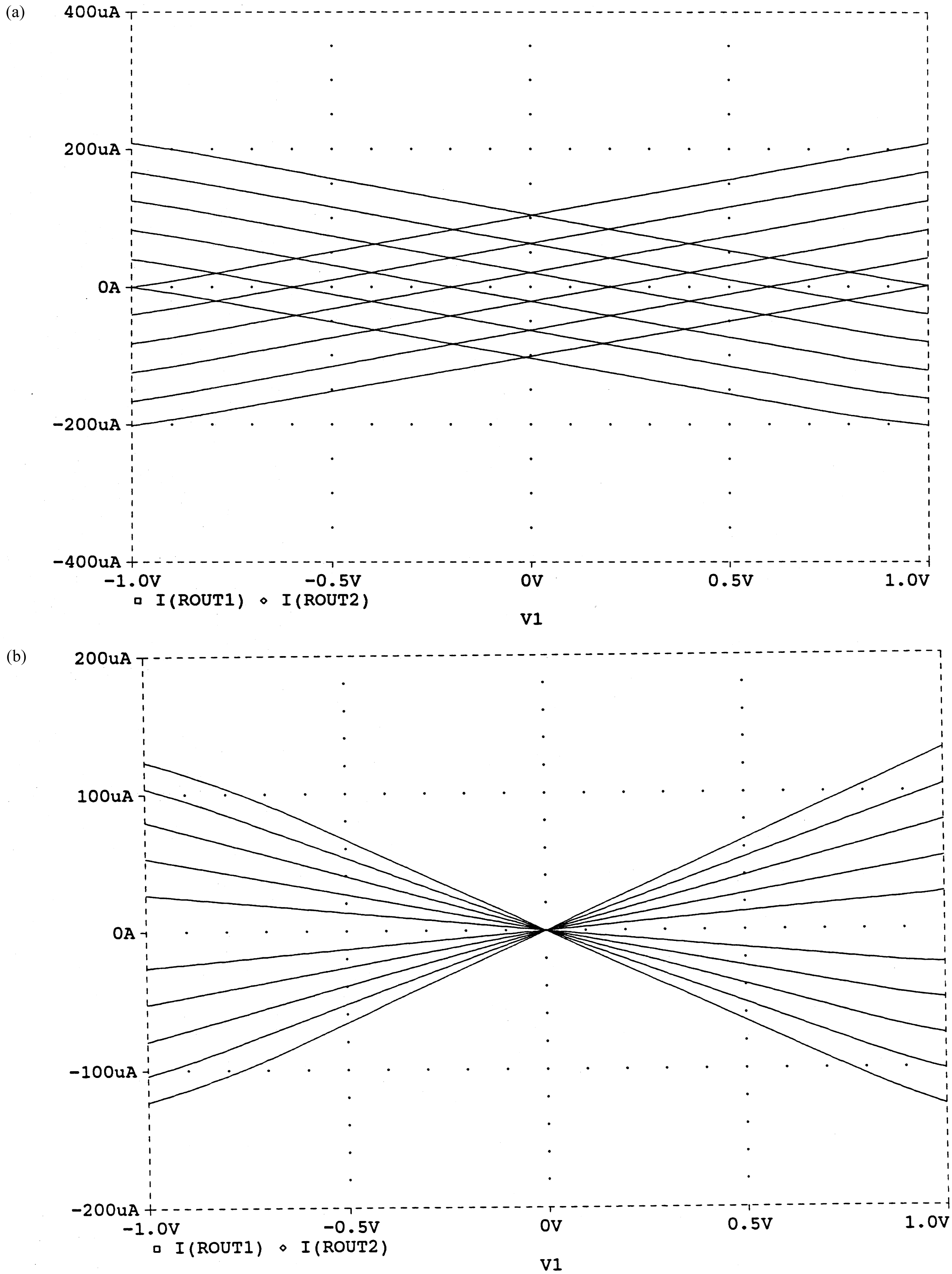
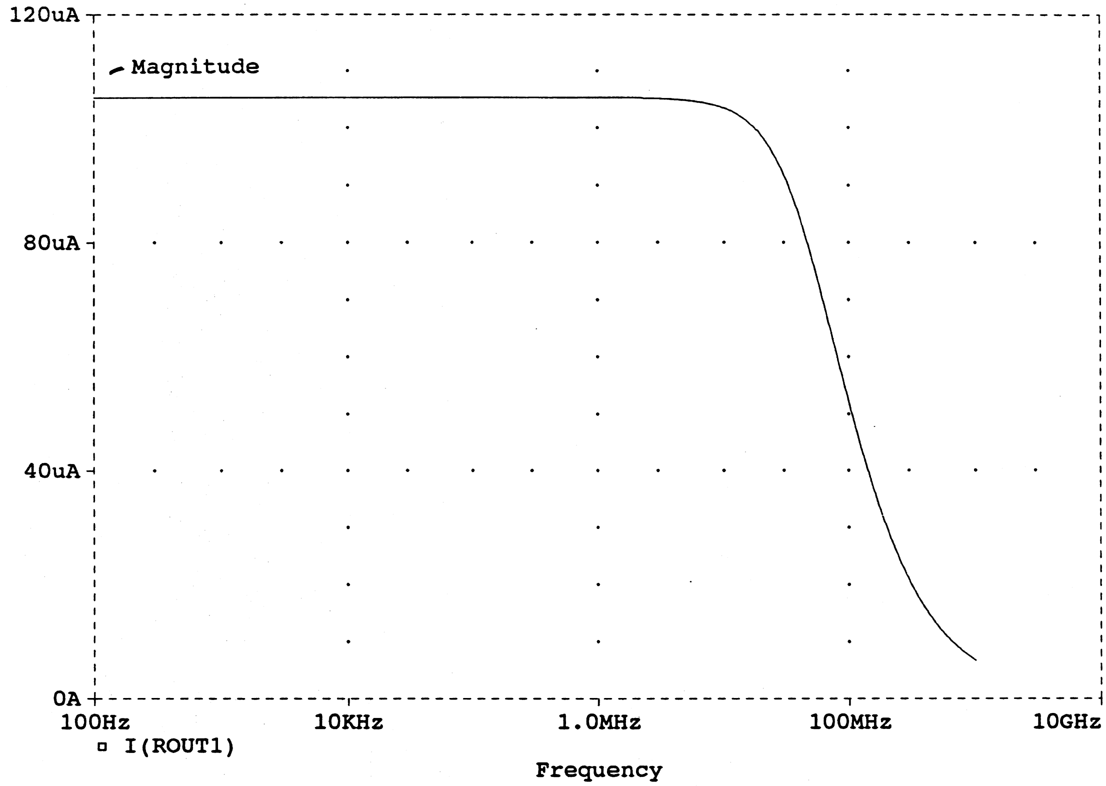



Fig. 3. (a) The $I$–$V$ characteristics of the output currents of the BOTA. (b) The $I$–$V$ characteristics of the output currents of the BOTA with $V_C$ as a parameter.

(a)




(b)

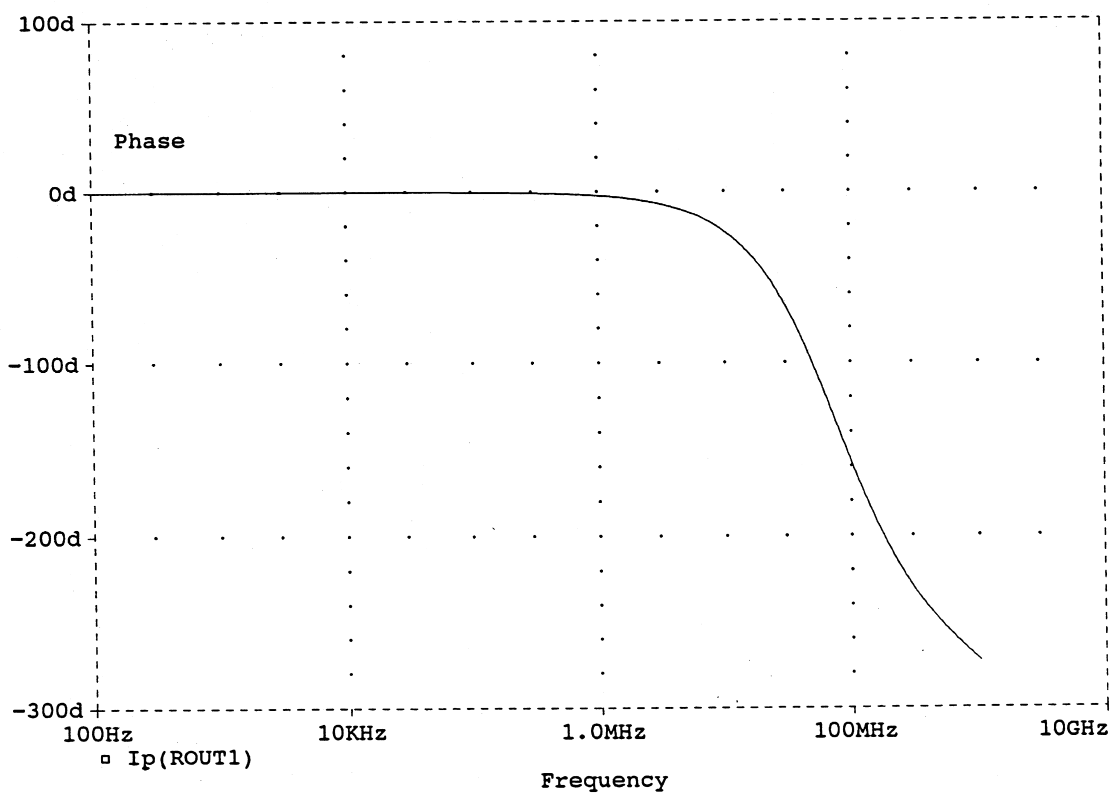



Fig. 4. The magnitude response of the proposed BOTA. (b) The phase response of the proposed BOTA. (c) The output-referred and input-referred noise voltage spectral densities for the BOTA when terminated by 1 kΩ.

(c)

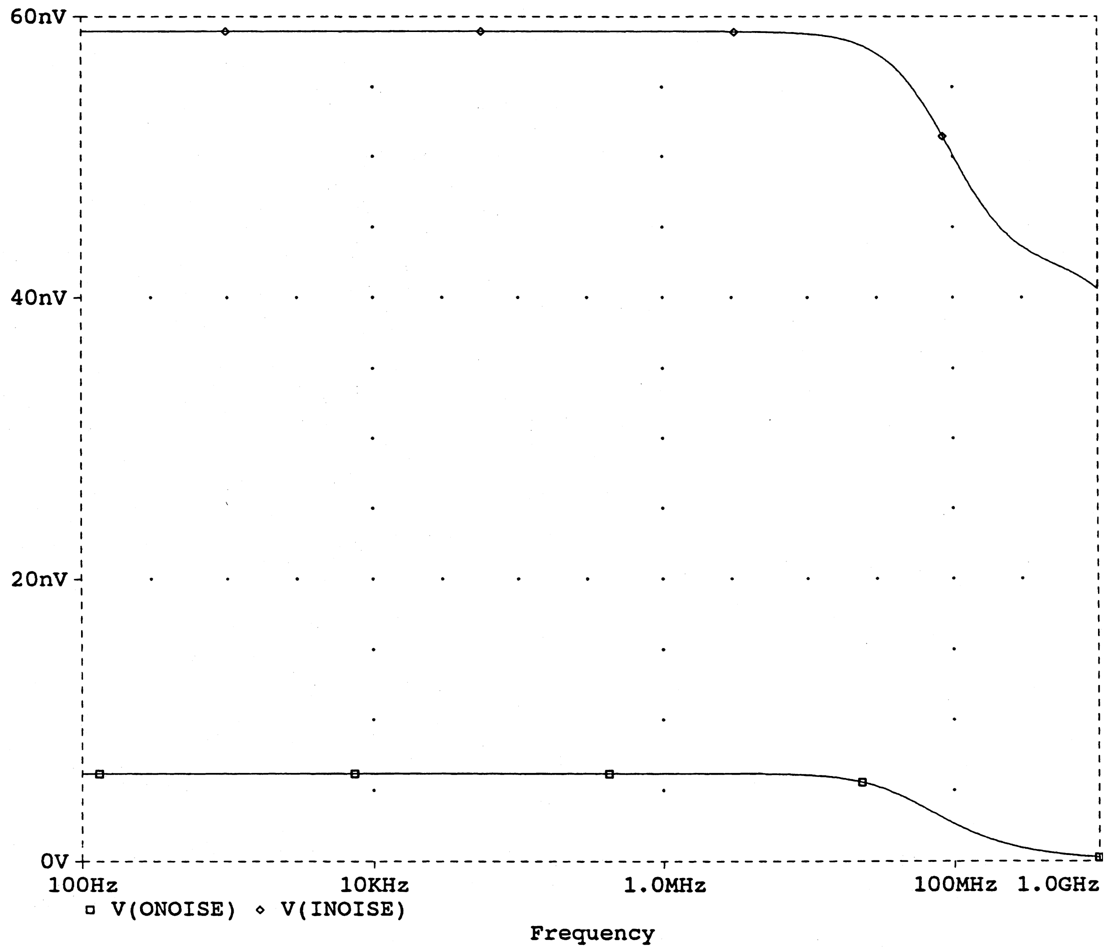



Fig. 4. *Continued.*

only in current mode. The circuit includes four BOTAs and two grounded capacitors, which makes the filter suitable for VLSI implementation. This filter is generated from the filter introduced in [15] which consists of three CCIIs, three resistors and two grounded capacitors.

By direct analysis, the following transfer functions are obtained:

$$\frac{V_{LP}}{V_i} = -\frac{\frac{G_1G_3}{C_1C_2}}{D(S)}, \quad \frac{I_{LP}}{V_i} = -\frac{\frac{G_1G_2G_3}{C_1C_2}}{D(S)} \tag{9}$$

$$\frac{V_{BP}}{V_i} = \frac{\frac{SG_3}{C_1}}{D(S)}, \quad \frac{I_{BP}}{V_i} = \frac{\frac{SG_1G_3}{C_1}}{D(S)} \tag{10}$$

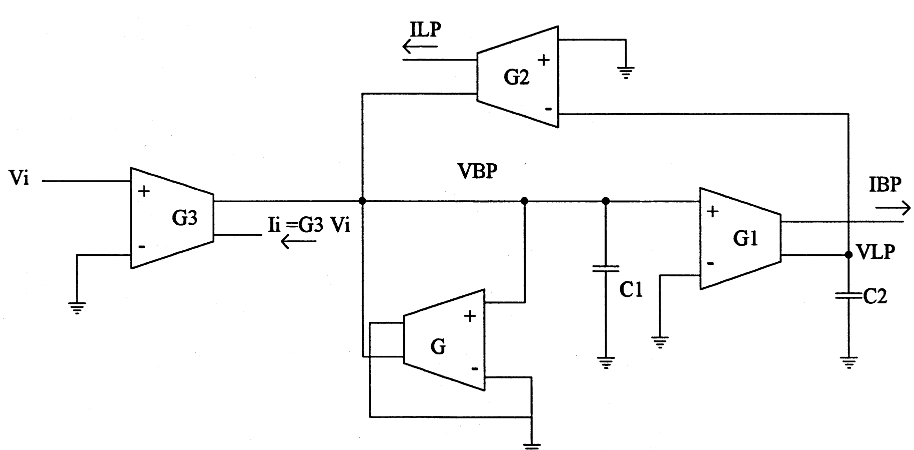



Fig. 5. The proposed BOTA-C active filter.

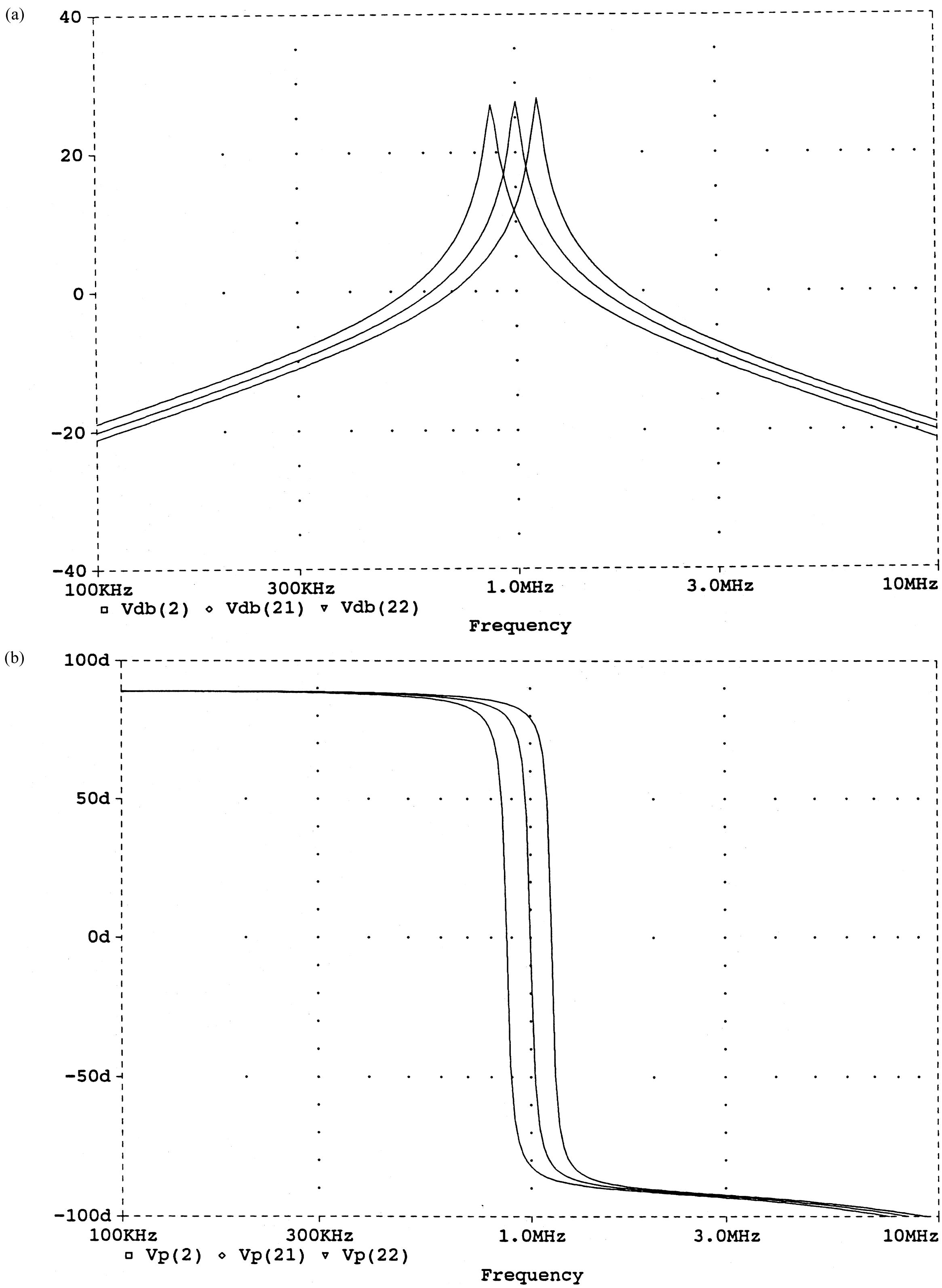



Fig. 6. The magnitude response of the voltage mode bandpass output. (b) The phase response of the voltage mode bandpass output.

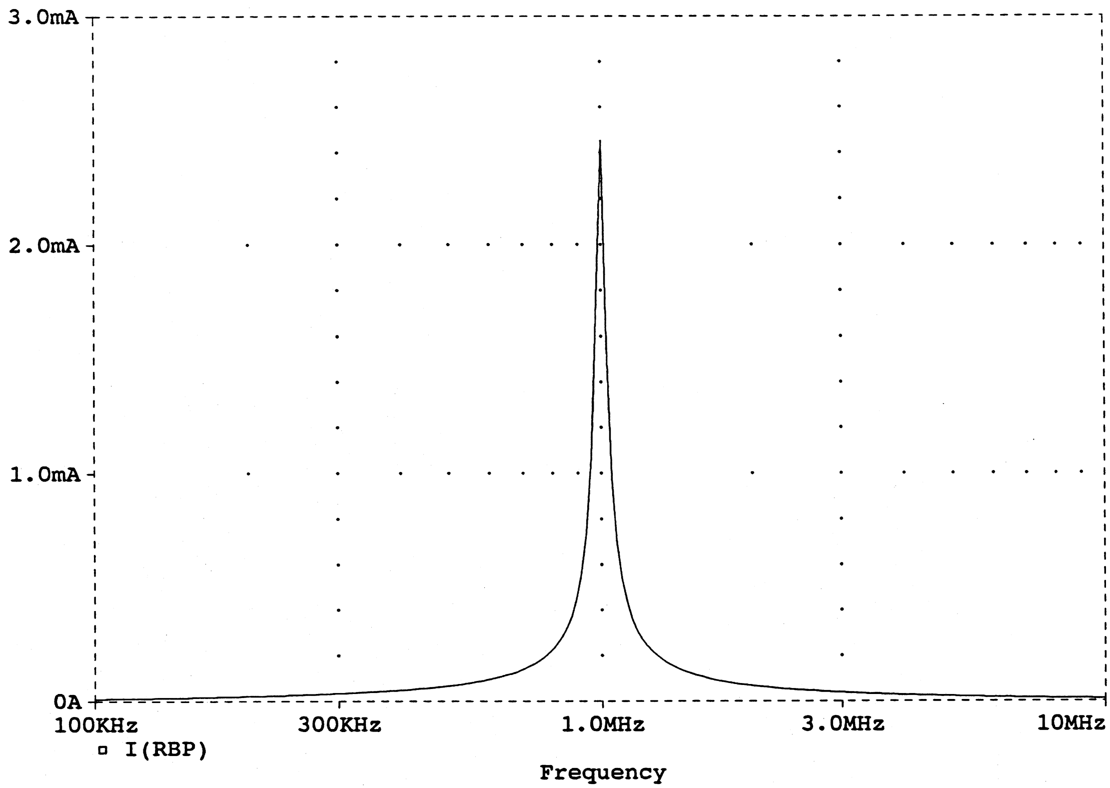



Fig. 7. The bandpass current mode output.

where

$$D(S) = S^2 + S\,\frac{G}{C_1} + \frac{G_1G_2}{C_1C_2} \tag{11}$$

From the above equation, the $\omega_o$ and $Q$ of the filter are given by:

$$\omega_o = \sqrt{\frac{G_1G_2}{C_1C_2}}, \quad Q = \frac{1}{G}\sqrt{\frac{G_1G_2C_1}{C_2}} \tag{12}$$

Note that, notch and allpass responses can be obtained by combining $I_{BP}$ and $I_i$ ($I_i$ is the output current of the transconductor $G_3$) as shown from the following analysis:

$$\frac{I_o}{V_i} = \frac{I_{BP} - I_i}{V_i} = -G_3\,\frac{S^2 + \left(\frac{G - G_1}{C_1}\right)S + \frac{G_1G_2}{C_1C_2}}{S^2 + \frac{G}{C_1}S + \frac{G_1G_2}{C_1C_2}} \tag{13}$$

For a notch response, the necessary condition is $G_1 = G$ and for an allpass response, the necessary condition is $G_1 = 2G$.

PSpice simulates for the circuit of Fig. 5 with $C_1 = C_2 =$ 15.92 pF, and $G_1 = G_2 = G_3 = 20G = K(V_C + V_{DD})$ $\mu$A $V^{-1}$ to obtain a bandpass filter with electronically tunable center frequency around $f_o = 1$ MHz, $Q = 20$, and $|T_{VBP}(\omega_o)| = 20$ is shown in Fig. 6a,b, indicating both the magnitude and phase of the voltage mode output of the bandpass filter. The center frequency is controlled by scanning the control voltage $V_C$ from −1.6 to −1.8 V with 0.1 V step and with the transconductance parameter $K = 125$ $\mu$A $V^{-2}$. Fig. 7 shows the bandpass output current for $V_C = -1.7$ V.

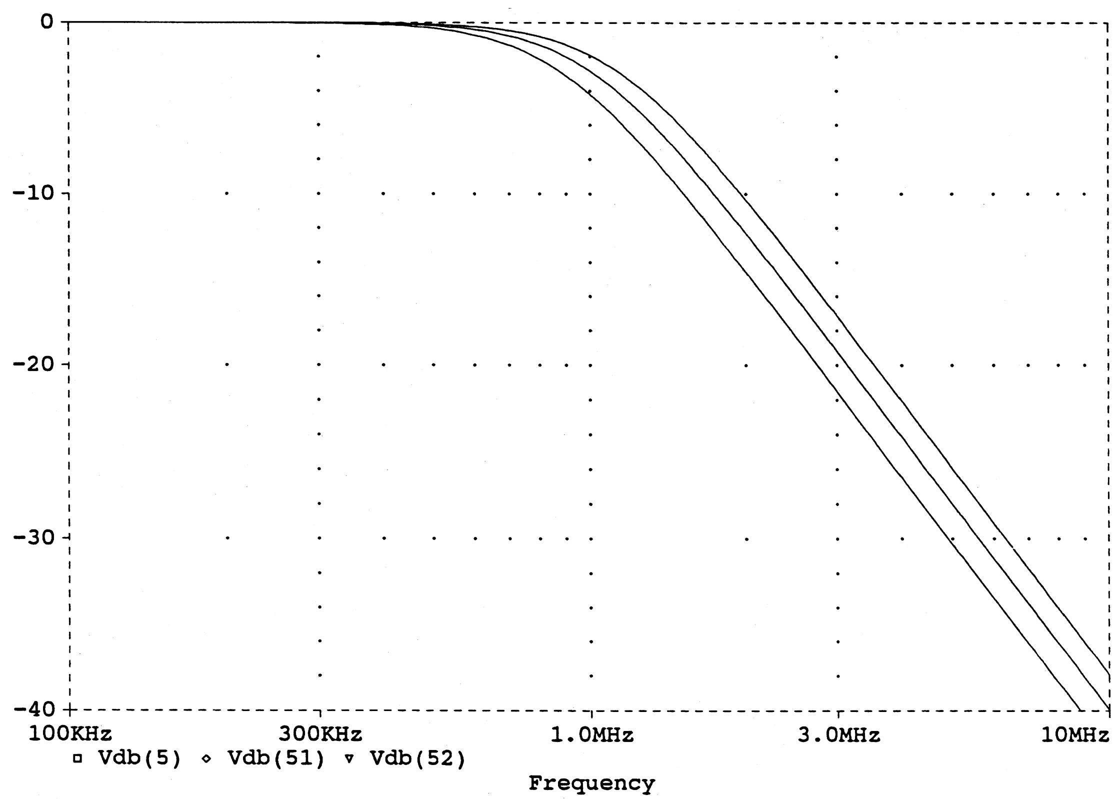
Simulation results for the same circuit with $C_1 = C_2 =$ 15.92 pF, $G_1 = G_2 = G_3 = 0.707G = K(V_C + V_{DD})$ $\mu$A $V^{-1}$ to obtain a maximally flat lowpass response designed for a DC gain of 1 and with a tunable $f_o$ around 1 MHz is shown in Fig. 8a,b, indicating both the amplitude and the phase of the voltage mode lowpass filter. The cutoff frequency is controlled by scanning the control voltage $V_C$ from −1.6 to −1.8 V with 0.1 V step and with the transconductance parameter $K = 125$ $\mu$A $V^{-2}$. Fig. 9 shows the lowpass output current with $V_C = -1.7$ V.

Simulation results are performed also for the circuit of Fig. 5 to obtain notch characteristics shown in Fig. 10a, with equal $C = 15.92$ pF and equal $G = 100$ $\mu$A $V^{-1}$ design where the notch response is obtained when the bandpass output $I_{BP}$ is added to $I_i$.

Simulation results are also performed for the proposed filter to provide the allpass characteristics shown in Fig. 10b with equal $C = 15.92$ pF and $G_1 = G_2 = G_3 = 2G = 100$ $\mu$A $V^{-1}$.

Fig. 11 represents the first BOTA-C oscillator using three BOTAs and two grounded capacitors which makes the oscillator suitable for VLSI. The condition of oscillation and the radian frequency of oscillation are

(a)




(b)

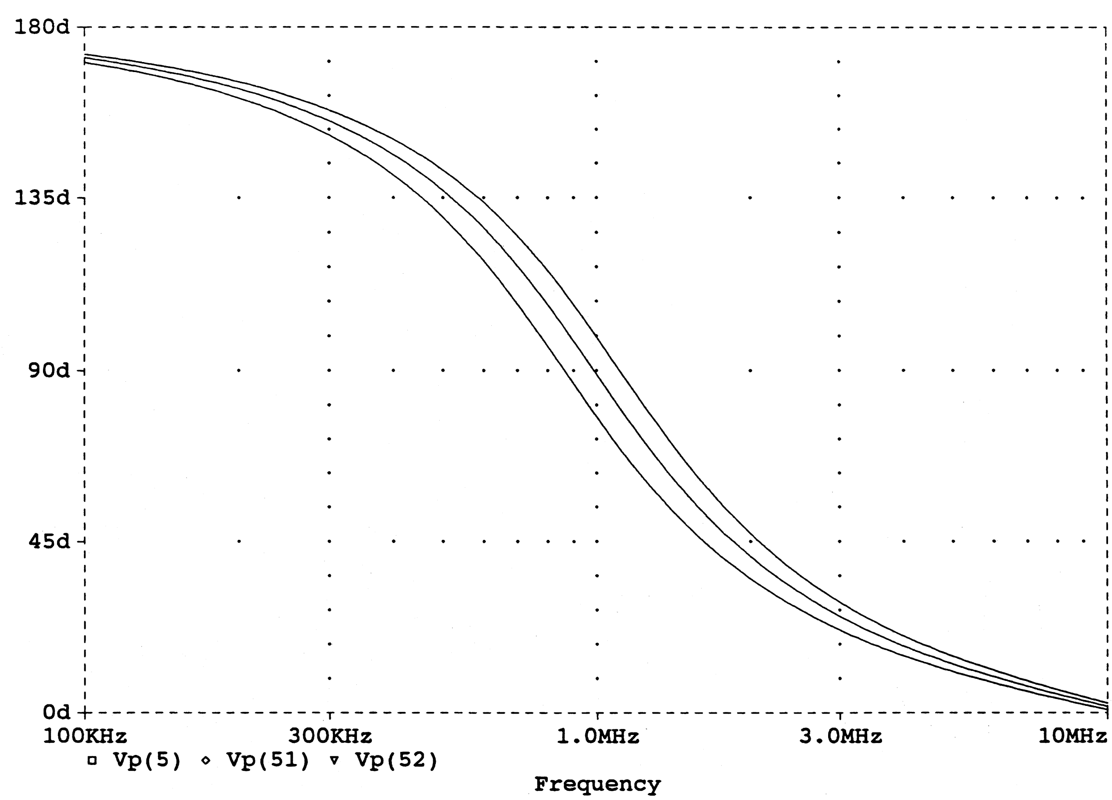



Fig. 8. The magnitude response of the voltage model lowpass output. (b) The phase response of the voltage model lowpass output.

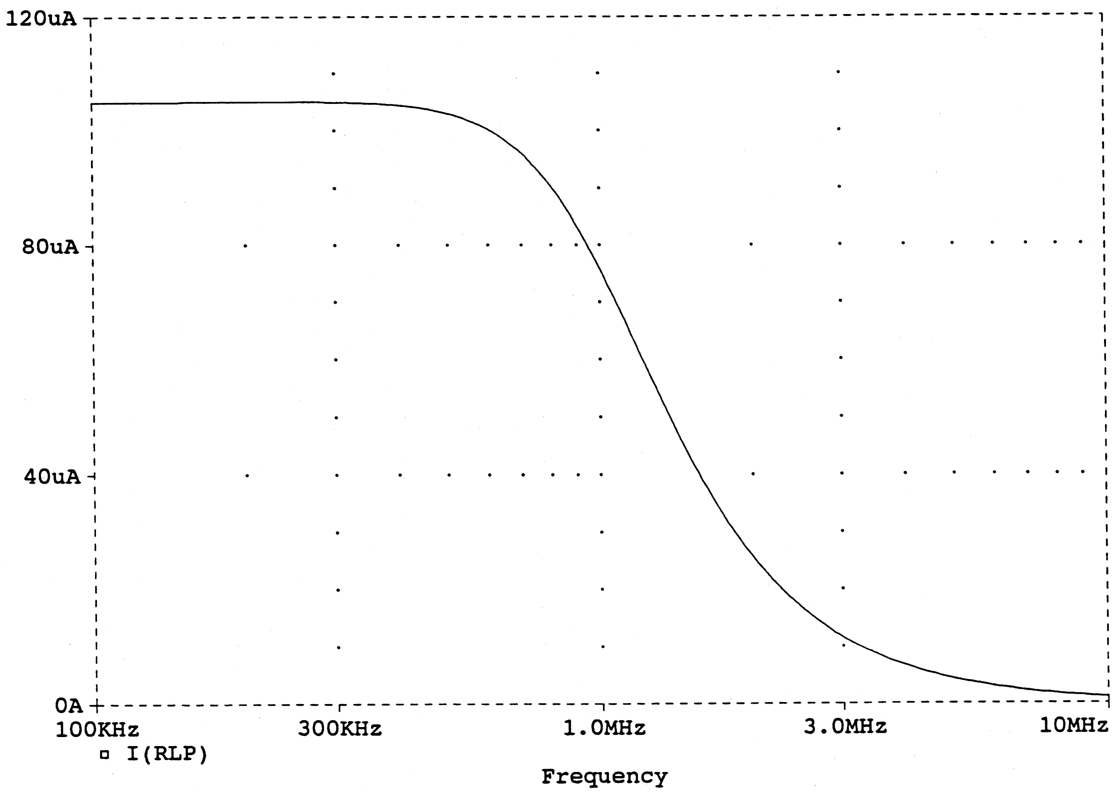



Fig. 9. The lowpass current mode output.

given by

$$G_1 = G_3 \tag{14}$$

$$\omega_o = \sqrt{\frac{G_2 G_3}{C_1 C_2}} \tag{15}$$

Therefore, the transconductance $G_1$ controls the condition of oscillation without affecting $\omega_o$ which is controlled by $G_2$ without affecting the condition of oscillation.

PSpice simulation for the proposed BOTA-C oscillator using equal $C = 25$ pF and equal $G = 25\ \mu\text{A V}^{-1}$ to obtain a radian frequency $\omega_o$ of 1 Mrad/s was carried out. From the simulations the oscillation frequency $f_{osc}$ was obtained as 163.553 kHz thus the percentage error in $f_{osc}$ is 2.76%. The THD in the output waveforms $I_{o1}$ and $I_{o2}$ is 1.55% and 2.075%, respectively.

Fig. 12 represents the second BOTA-C oscillator using four BOTAs and two grounded capacitors. The condition of oscillation and the radian frequency of oscillation are given by:

$$G_3 = G_4 \tag{16}$$

$$\omega_o = \sqrt{\frac{G_1 G_2}{C_1 C_2}} \tag{17}$$

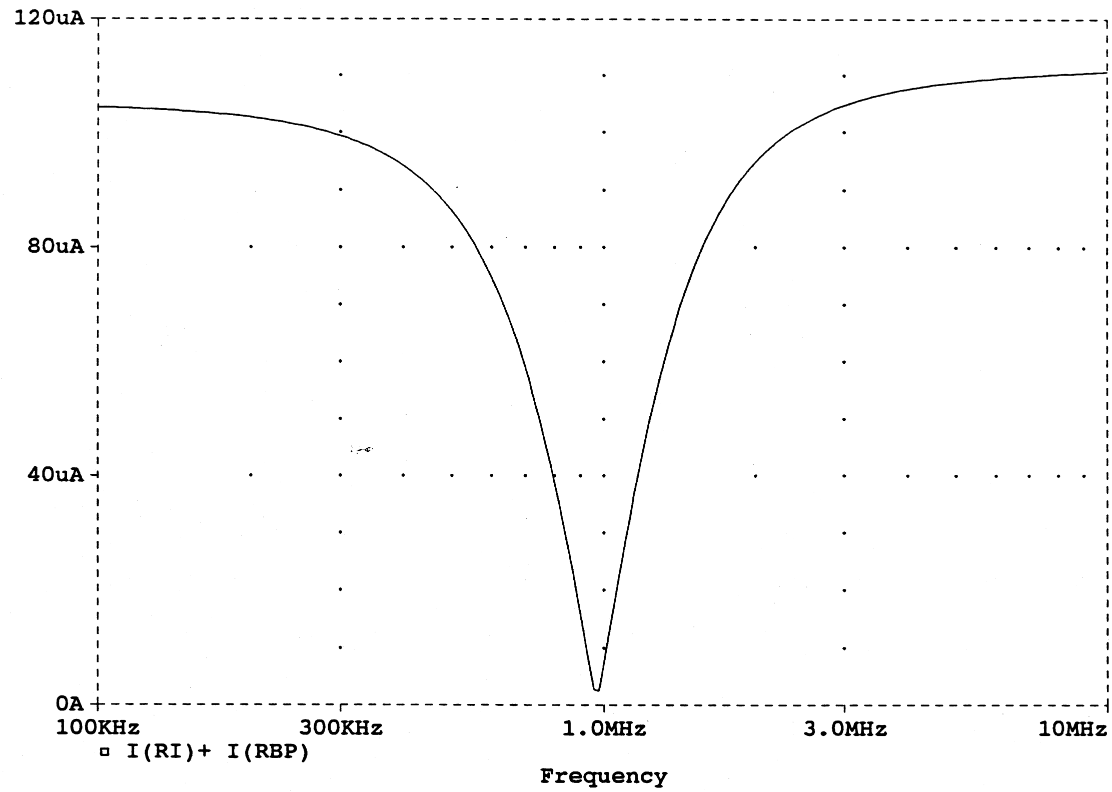
It is seen that the condition of oscillation can be controlled either by $G_3$ or $G_4$ without affecting the frequency which can be independently controlled either by $G_1$ or $G_2$.

PSpice simulation for the second proposed BOTA-C oscillator using equal $C = 25$ pF and equal $G = 25\ \mu\text{A V}^{-1}$ to obtain a radian frequency $\omega_o$ of 1 Mrad/s was carried out. From the simulations the oscillation frequency $f_{osc}$ was obtained as 163.112 kHz thus the percentage error in $f_{osc}$ is 2.49%. The THD in the output waveforms $I_{o1}$ and $I_{o2}$ is 3.0034%, respectively.

## 4. Conclusions

A new CMOS programmable balanced output transconductor has been proposed. Application of the BOTA in realizing a second-order active filter is given. This filter provides the following advantages: realization of lowpass, bandpass, allpass and notch characteristics, low passive and active sensitivities, suitable for VLSI implementation by using only grounded capacitors, and the control of the $Q$ and the filter's gain are independent of $\omega_o$. Application of the BOTA in realizing current mode MOS-C oscillators using three of four BOTAs and two grounded capacitors is also given. PSpice simulation results for the proposed CMOS BOTA and for its applications which confirm the analytical results are included.

(a)

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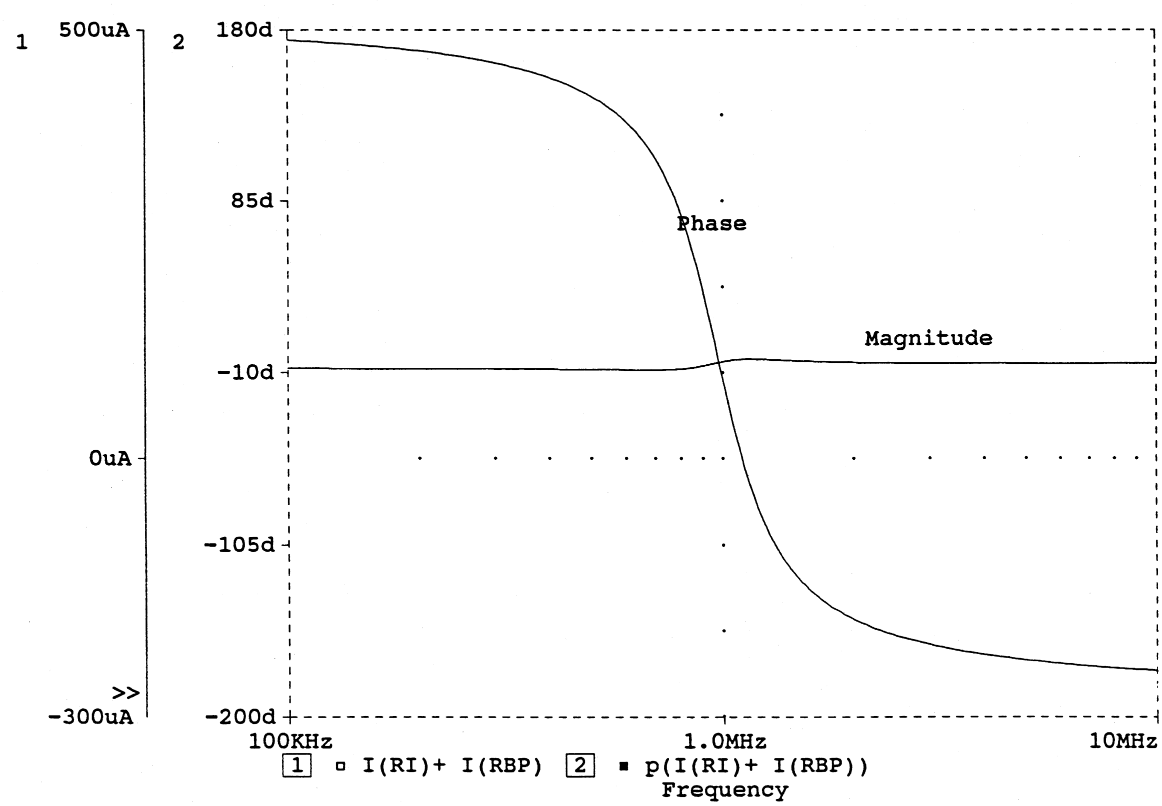


Fig. 10. The magnitude response of the current mode notch output. (b) The magnitude and phase responses of the current mode allpass output.

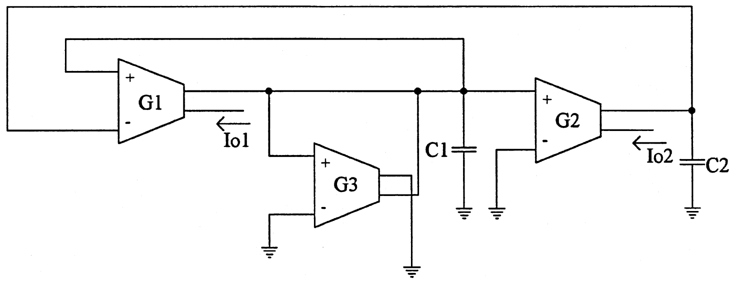


Fig. 11. The first proposed current mode BOTA-C oscillator.

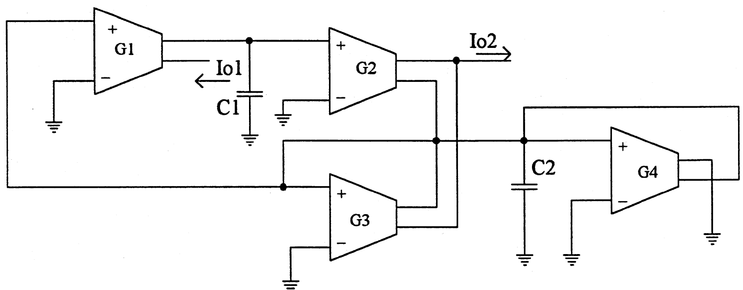


Fig. 12. The second proposed current mode BOTA-C oscillator.

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