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Novel MOS-C oscillators using the current feedback op-amp

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Three new MOS-C oscillators using the current feedback op-amp are presented. The proposed oscillators have the advantage of independent control of the oscillation frequency and the condition of oscillation. Two of the proposed MOS-C oscillators provide two outputs in phase quadrature. The third proposed oscillator provides two outputs in the balanced form. PSpice simulation results for the proposed oscillators are given.

1. Introduction

Oscillators are key components for most communication systems, in particular, single chip communication systems and the demand for low power programmable analogue functionality on a single application specific integrated circuit (ASIC). Many oscillators are available in the literature using the conventional op-amp (Budak, 1974), whose finite gain bandwidth product affects both the condition of oscillation and the frequency of oscillation (Soliman *et al.* 1988). Recently there has been great interest in realizing sinusoidal oscillators using the current feedback op-amp (CFOA), grounded or floating resistors and capacitors (Celma *et al.* 1994, Liu and Tsay 1996, Senani and Singh 1996, Soliman 1999). The CFOA, is a very versatile building block in analogue signal processing (Soliman 1996), and is now commercially available from several manufacturers (Evans 1998, Analog Devices 1990). The CFOA has the advantages of constant bandwidth which is independent of the closed loop gain and its high slew rate which is typically around $2000\,\mathrm{V}\,\mu\mathrm{S}^{-1}$. Recently MOS-C filters using the CFOA have been introduced in the literature (Chen *et al.* 1995, Mahmoud and Soliman 1998).

In this paper, three novel MOS-C oscillators using the CFOA are presented. The proposed oscillators have the advantages of controlling the condition of oscillation through a control voltage without affecting the oscillation frequency which is controlled by another control voltage. The MOS transistor nonlinearities and their cancellation is given in § 2. The MOS-C CFOA based quadrature and balanced output oscillators are given in §§ 3 and 4 respectively. PSpice simulations of the proposed MOS-C-CFOA oscillators are also given. The CMOS CFOA circuit proposed by Mahmoud and Soliman (1999) is used in the simulations.

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2. The MOS transistor nonlinearities and their cancellation

An NMOS transistor is shown in figure 1, with its gate connected to a dc control voltage V_G. The terminal voltages V_1 and V_2 are assumed to remain below V_G by at least the threshold voltage of the transistor V_T to allow operation in the non-saturation region. The current in the non-saturation region is given by (Banu and Tsividis 1983)

$$I = K(V_G - V_T)(V_1 - V_2) + a_1(V_1^2 - V_2^2) + a_2(V_1^3 - V_2^3) + \cdots \quad (1)$$

K is the transconductance parameter of the NMOS transistor and is given by

$$K = \mu_n C_{ox}\left(\frac{W}{L}\right) \quad (2)$$

where (W/L) is the transistor aspect ratio, C_{ox} is the gate oxide capacitance per unit area and μ_n is the electron mobility.

Clearly, if one cancels the effect of the nonlinear terms, the transistor behaves like a linear resistor. Many different techniques have been proposed for eliminating the effect of the nonlinearities (Czarnul 1986, Tsividis *et al.* 1986, Sakurai *et al.* 1992). Some cancel the even nonlinearities in the current of one MOS transistor, others cancel the nonlinearities in the difference of the currents in two or four MOS transistors. The various techniques used in this paper to realize MOS-C oscillators suitable for VLSI are summarized in figure 2.

It is easily verified from the drain current of the MOS transistor in the non-saturation region given above, that the even nonlinearities are eliminated for the MOS transistor with its drain and source voltages out of phase as shown in figure 2(*a*), and the current in this case is approximately given by

$$I = 2K(V_G - V_T)V_1 \qquad \text{for } V_G - V_T \geq |V_1| \quad (3)$$

The remaining odd nonlinearities are minute for most practical purposes.

The circuit shown in figure 2(*b*) (Ismail and Fiez 1994) accomplishes in principle complete cancellation of both the even and the odd nonlinearities in the difference between the currents of M1 and M2. Since the transistors M1 and M2 have equal drain and equal source voltages, therefore the difference between the two currents is given by

$$I = I_1 - I_2 = KV_G(V_1 - V_2) \qquad \text{for } V_G - V_T \geq \max(V_1, V_2) \quad (4)$$

The circuit shown in figure 2(*c*) (Czarnul 1986) also performs a complete cancellation of the nonlinearities and the linearized current is given by

$$I = (I_1 + I_3) - (I_2 + I_4) = (I_1 - I_4) - (I_2 - I_3) = KV_G(V_1 - V_2) \quad (5)$$

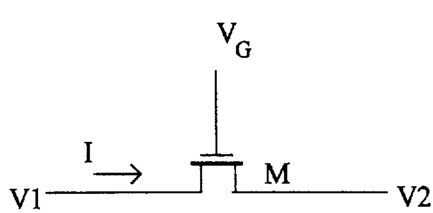


Figure 1. The symbol of NMOS transistor.

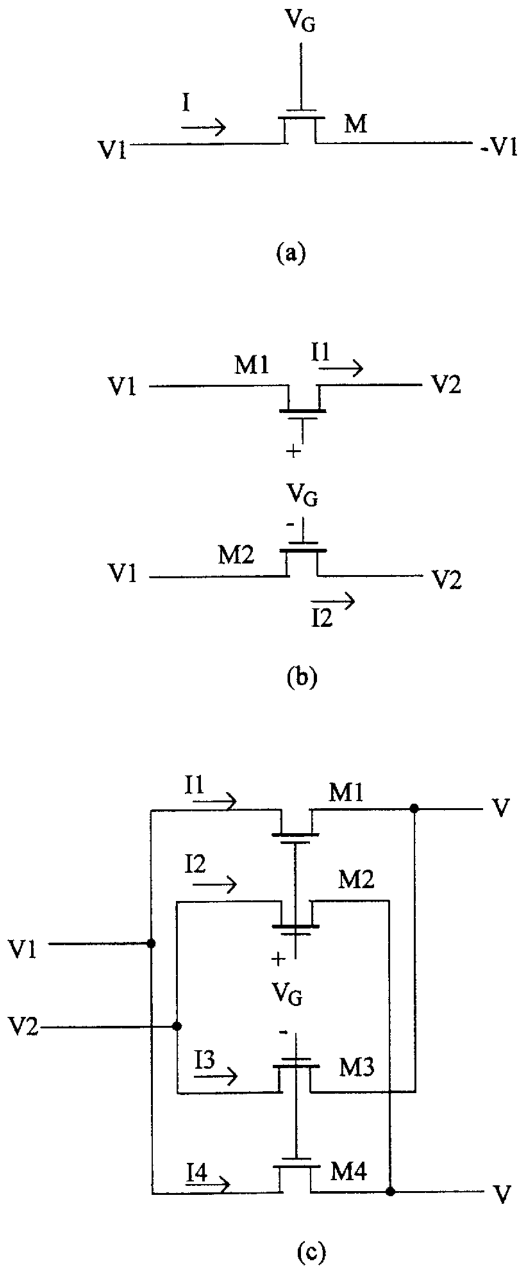


Figure 2. (*a*) An NMOS transistor with even nonlinearities' cancellation. (*b*) Two MOS transistors circuit with full nonlinearities' cancellation. (*c*) Four MOS transistors circuit with full nonlinearities' cancellation.

Based on the above MOS circuits, new MOS-C oscillators using the CFOA are proposed in the following sections. The low voltage rail to rail CMOS CFOA shown in figure 3 (Mahmoud and Soliman 1999) operating from ± 1.5 V supply voltages was used in all the simulations included in the paper.

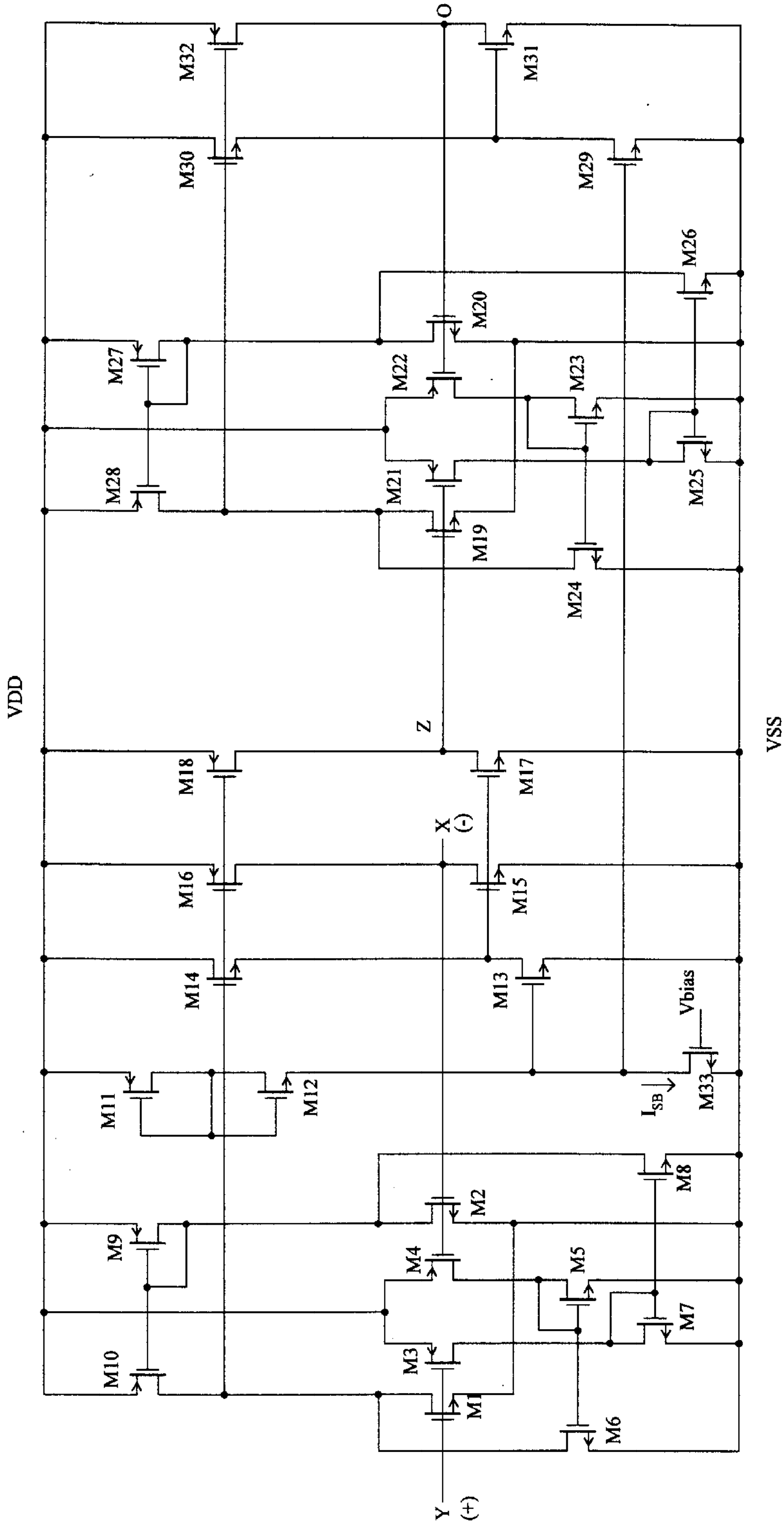


Figure 3. The low voltage rail to rail CMOS CFOA (Mahmoud and Soliman 1999).

3. The MOS-C CFOA based quadrature oscillators

Phase quadrature oscillators are very desirable in the implementation of the modulators and the demodulators in modern communication systems. In this section, two new MOS-C quadrature oscillators are proposed.

3.1. *The first proposed MOS-C oscillator*

The oscillator reported in this section is based on one of the active RC oscillators described in Soliman (1999). The CFOA MOS-C circuit is generated from the CFOA RC circuit by realizing the same state matrix equation using combinations of the MOS circuits described in figure 2 to replace the resistors properly.

Figure 4 shows the first proposed MOS-C oscillator using two CFOAs, two MOS circuits of figure 2(*b*), a MOS circuit of figure 2(*c*) and two grounded capacitors, which makes the oscillator suitable for VLSI implementation. By direct analysis, the state equations are given by

$$\frac{dV_1}{dt} = \frac{(G_1 - G_3)}{C_1} V_1 + \frac{G_3}{C_1} V_2 \tag{6}$$

$$\frac{dV_2}{dt} = -\frac{G_2}{C_2} V_1 \tag{7}$$

where

$$G_i = K_i V_{Gi} \quad (i = 1, 2 \text{ and } 3) \tag{8}$$

Thus, the condition of oscillation and the radian frequency of oscillation are given by

$$G_1 = G_3 \tag{9}$$

$$\omega_0 = \left(\frac{G_2 G_3}{C_1 C_2}\right)^{1/2} \tag{10}$$

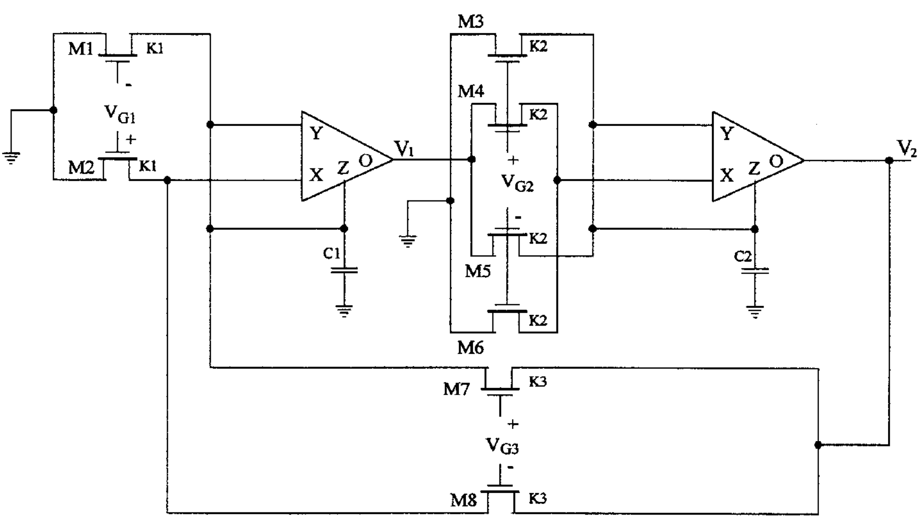


Figure 4. The first proposed MOS-C-CFOA quadrature oscillator.

Therefore, the transconductance G_1 controls the condition of oscillation without affecting ω_0 which is controlled by G_2 without affecting the condition of oscillation.

PSpice simulation results for the first proposed MOS-C CFOA oscillator using the model parameters listed in table 1, where, $C_1 = C_2 = 10\,\text{pF}$ and $G_1 = G_2 = G_3 = 62.88\,\mu\text{A V}^{-1}$ ($K_1 = K_2 = K_3 = 62.88\,\mu\text{A V}^{-2}$ and $V_{G1} = V_{G2} = V_{G3} = 1\,\text{V}$) to obtain an oscillation frequency f_0 of 1 MHz.

Figure 5 represents the two output waveforms and the frequency spectrum. The THD in the output waveforms V_1 and V_2 are 2.93% and 3.766% respectively. It is clear that the two outputs of the oscillator are in phase quadrature.

3.2. *The second proposed MOS-C oscillator*

Figure 6 shows the second proposed MOS-C oscillator using two CFOAs, two MOS circuits of figure 2(*b*), two MOS circuit of figure 2(*c*) and two grounded capacitors. By direct analysis, the state equations are given by

$$\frac{\mathrm{d}V_1}{\mathrm{d}t} = \frac{G_1}{C_1} V_2 \tag{11}$$

$$\frac{\mathrm{d}V_2}{\mathrm{d}t} = -\frac{G_2}{C_2} V_1 + \frac{(G_3 - G_4)}{C_2} V_2 \tag{12}$$

Thus, the condition of oscillation and the radian frequency of oscillation are given by

$$G_3 = G_4 \tag{13}$$

$$\omega_0 = \left(\frac{G_1 G_2}{C_1 C_2}\right)^{1/2} \tag{14}$$

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

PSpice simulation results for the second proposed MOS-C CFOA oscillator using the model parameters listed in table 1, where, $C_1 = C_2 = 10\,\text{pF}$ and $G_1 = G_2 = G_3 = G_4 = 62.88\,\mu\text{A V}^{-1}$ ($K_1 = K_2 = K_3 = K_4 = 62.88\,\mu\text{A V}^{-2}$ and $V_{G1} = V_{G2} = V_{G3} = V_{G4} = 1\,\text{V}$) to obtain an oscillation frequency f_0 of 1 MHz. Figure 7 represents the two output waveforms and the frequency spectrum. The THD in the output waveforms V_1 and V_2 are 2.866% and 2.99% respectively.

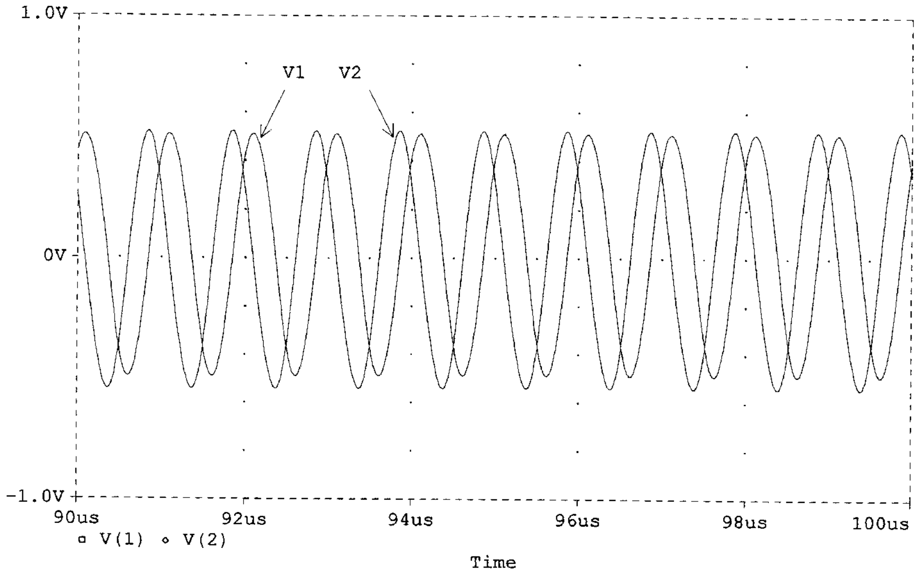
4. The MOS-C CFOA based balanced output oscillator

A balanced output active MOS-C filter using the CFOA has been reported in the literature (Mohmoud and Soliman 1998). A MOS-C oscillator based on modification of this filter circuit is introduced in this section.

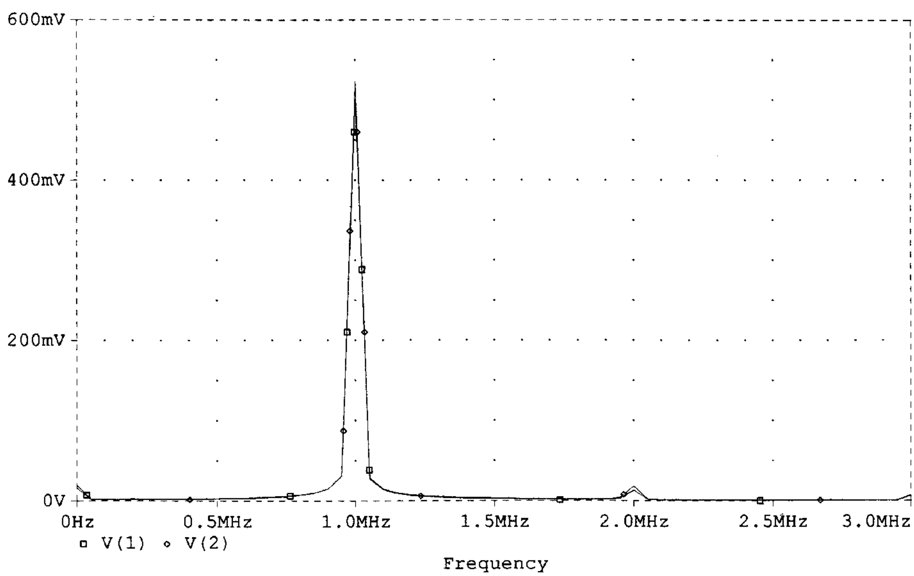
Figure 8 shows the balanced output MOS-C oscillator using four CFOAs, a MOS circuit of figure 2(*a*), four MOS circuits of figure 2(*b*) and two grounded capacitors. By direct analysis, the state equations are given by

$$\frac{\mathrm{d}V_1}{\mathrm{d}t} = \frac{(G_3 - G_1)}{C_1} V_1 - \frac{G_3}{C_1} V_2 \tag{15}$$

$$\frac{\mathrm{d}V_2}{\mathrm{d}t} = \frac{G_2}{C_2} V_1 \tag{16}$$



(a)



(b)

Figure 5. (*a*) The voltage waveforms V_1 and V_2 of the oscillator of figure 4. (*b*) The frequency spectrum of the oscillator of figure 4.

where

$$G_i = K_i V_{Gi} \quad (i = 1 \text{ and } 3) \tag{17}$$

$$G_2 = 2K_2(V_{G2} - V_T) \tag{18}$$

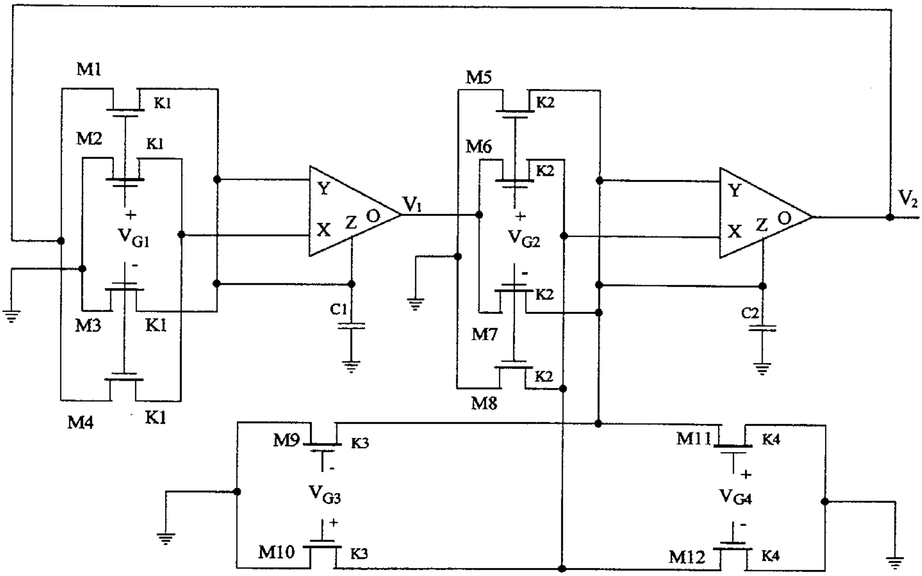


Figure 6. The second proposed MOS-C-CFOA quadrature oscillator.

Thus, the condition of oscillation and the radian frequency of oscillation are given by

$$G_1 = G_3 \tag{19}$$

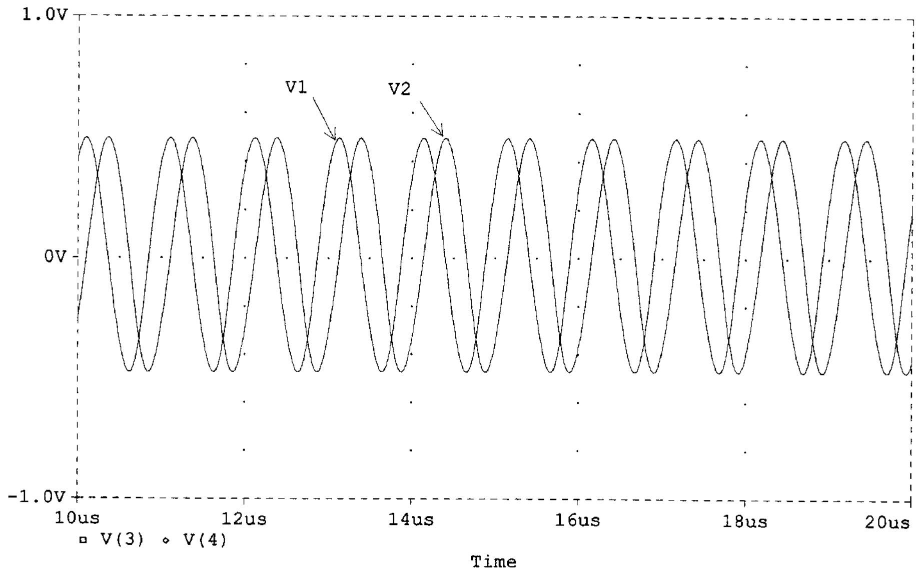
$$\omega_0 = \left(\frac{G_2 G_3}{C_1 C_2}\right)^{1/2} \tag{20}$$

Therefore, the transconductance G_1 controls the condition of oscillation without affecting ω_0 which is controlled by G_2 without affecting the condition of oscillation.

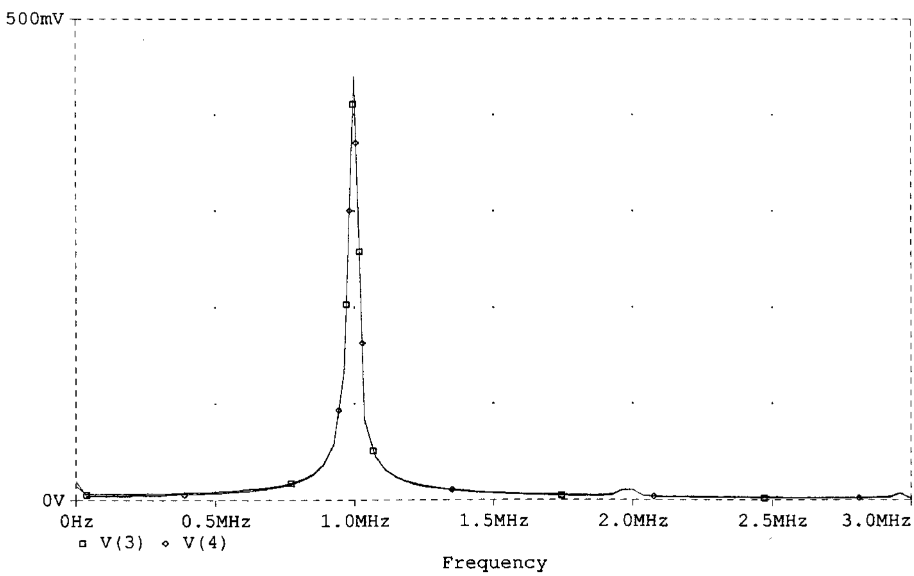
PSpice simulation results for the balanced output MOS-C CFOA oscillator using the model parameters listed in table 1, where, $C_1 = C_2 = 24\,\text{pF}$, $G_1 = G_3 = 62.88\,\mu\text{A V}^{-1}$ $(K_1 = K_3 = 62.88\,\mu\text{A V}^{-2}$ and $V_{G1} = V_{G3} = 1\,\text{V})$ and

MODEL	NENH	NMOS	LEVEL= 3	PHI= 0.600000	TOX= 2.6400E-08
XJ= 0.200000U	TPG= 1	VTO= 0.9573	DELTA= 2.8320E+ 00		LD= 4.9090E-08
KP= 8.3843E-05	UO= 641.0	THETA= 9.4100E-02			RSH= 6.8510E+ 01
GAMMA= 0.7792	NSUB= 3.1290E+ 16	NFS= 1.98E+ 12			VMAX= 1.7240E+ 05
ETA= 1.3650E-01	KAPPA= 3.3040E-03	CGDO= 9.6315E-11			CGSO= 9.6315E-11
CGBO= 2.2662E-10	CJ= 5.1113E-04	MJ= 0.4670			CJSW= 3.7279E-10
MJSW= 0.286904 PB= 0.800000					
.MODEL	PENH	PMOS	LEVEL= 3	PHI= 0.600000	TOX= 2.6400E-08
XJ= 0.200000U	TPG= -1	VTO= -0.8406	DELTA= 2.9950E-Ol		LD= 1.2370E-09
KP= 2.5454E-05	UO= 194.6	THETA= 7.6950E-02			RSH= 3.1440E+ 02
GAMMA= 0.5768	NSUB= 1.7150E+ 16	NFS= 3.46E+ 12			VMAX= 1.0930E+ 05
ETA= 3.0470E-02	KAPPA= 4.4120E+ 00				CGDO= 2.4270E-12
CGSO= 2.4270E-12	CGBO= 2.7364E-10	CJ= 3.8950E-04			MJ= 0.4794
CJSW= 3.8646E-10	MJSW= 0.358053	PB= 0.850000			

Table 1. Model parameters set for 1.2 μm CMOS technology (obtained through MOSIS).



(a)



(b)

Figure 7. (*a*) The voltage waveforms V_1 and V_2 of the oscillator of figure 6. (*b*) The frequency spectrum of the oscillator of figure 6.

$G_2 = 362.2\,\mu A\,V^{-1}$ ($K_2 = 62.88\,\mu A\,V^{-2}$ and $V_{G2} = 5\,V$) to obtain an oscillation frequency f_0 of 1 MHz. Figure 9 represents the two balanced output waveforms and the frequency spectrum. The THD in each of the output waveforms V_1 and V_2 is less than 0.06%.

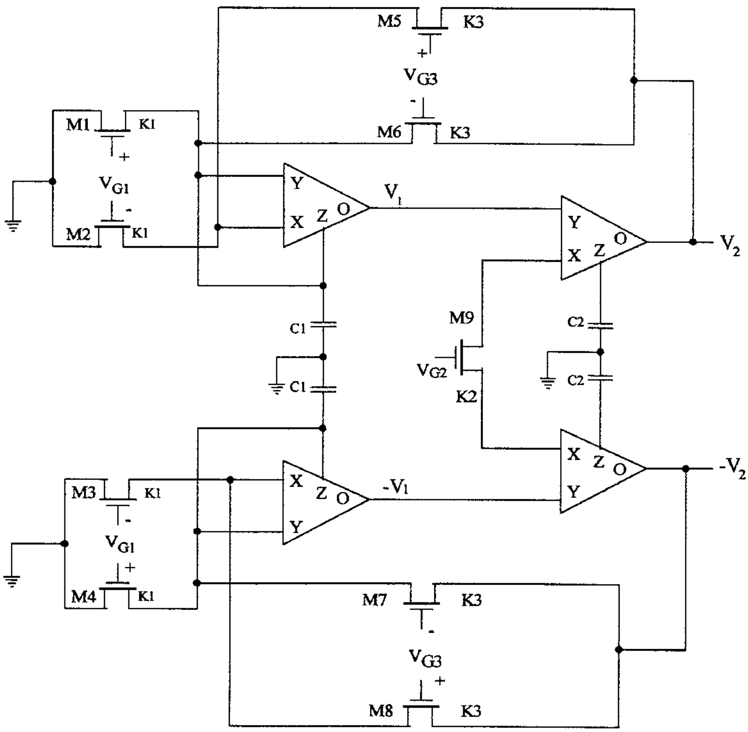
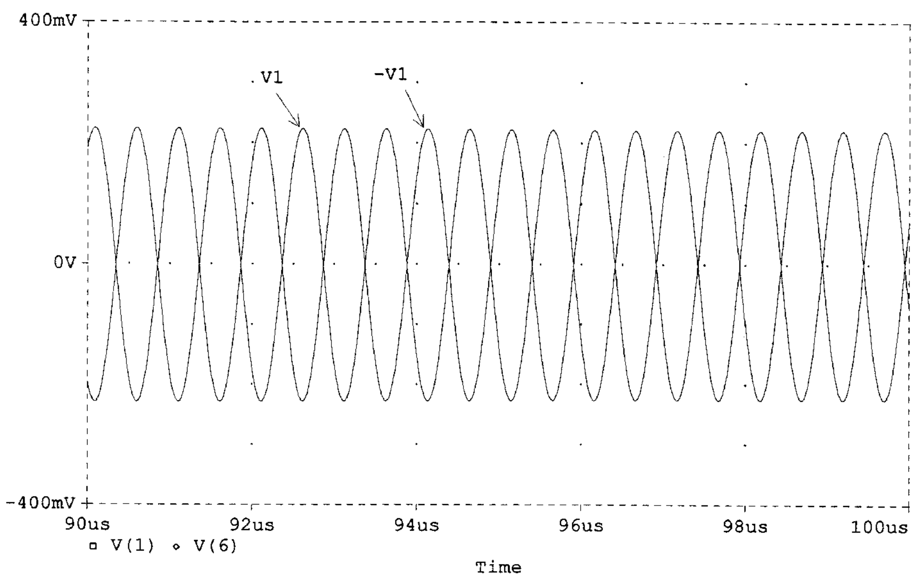
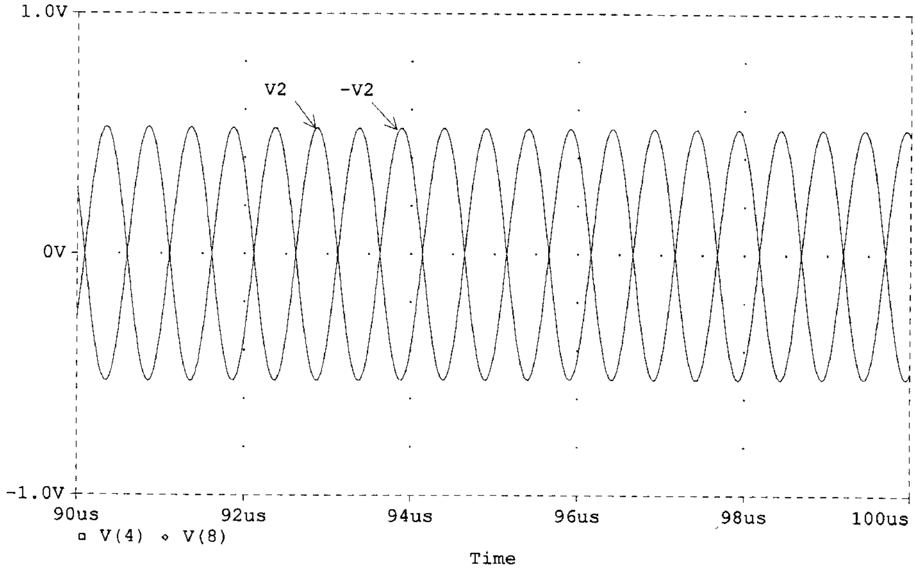


Figure 8. The balanced output MOS-C-CFOA oscillator.

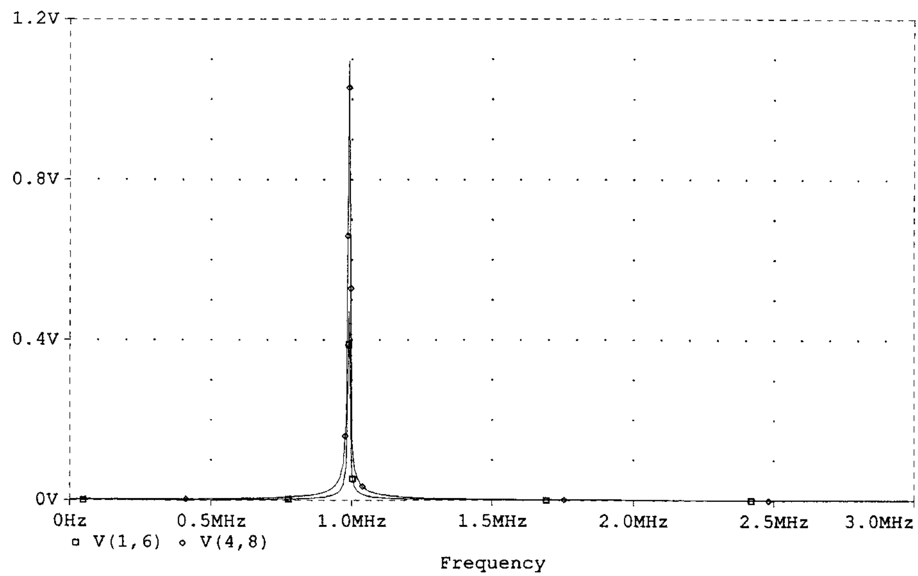


(a)

Figure 9. (*a*) The voltage waveforms V_1 and $-V_1$ of the oscillator of figure 8. (*b*) The voltage waveforms V_2 and $-V_2$ of the oscillator of figure 8. (*c*) The frequency spectrum of the oscillator of figure 8.



(b)



(c)

Figure 9. (*Continued*)

5. Conclusions

New MOS-C quadrature and balanced output oscillators using the CFOA have been proposed. The proposed oscillators have the advantage of independent control of the oscillation frequency and the condition of oscillation. PSpice simulation results for the proposed oscillators which confirm the analytical results are given. It is has been shown that the balanced output oscillator has the lowest THD among the three proposed oscillators.

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