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Metamutator applications: a quadrature MOS only oscillator and transconductance/transimpedance amplifiers

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Abstract NMOS based circuit realizations of a sinusoidal quadrature oscillator, a transconductance, a transimpedance amplifier are presented. All the circuits are constructed with a voltage-mode "Metamutator" consisting of an analog adder and a subtractor which is one of its possible realizations. The most important feature of the proposed circuits is their extremely simple structures containing only twelve NMOS transistors (six for adder, six for subtractor). Another significant advantage of the proposed circuits is that no external passive element is needed for the oscillator and only one resistor is used for each amplifier circuit; a variable resistor can provide gain adjustability. The post-layout simulations of all the proposed circuits have been executed using TSMC 0.25 µm process parameters with ±1.25 V power supply voltage.

Keywords Circuit design · Active networks · Mutator · Metamutator · Oscillator · CMOS

1 Introduction

Oscillator circuits are widely used in communication circuits (e.g., GSM, DECT), instrumentation and measurement which require generation of an accurate 90° phase difference between two quadrature signals. There are many oscillator circuits available in the literature using various active elements [1–11]. For example in [1] a sinusoidal oscillator using two Current Controlled Current Differencing Transconductance Amplifiers (CCCDTAs) as active elements and two grounded capacitors is presented. Similarly, other active elements such as second generation Current Conveyors (CCIIs), Operational Transconductance Amplifiers (OTAs), Differential Voltage Current Conveyors (DVCCs) etc., have been used to construct sinusoidal oscillators [2–11]. All of the above mentioned oscillator circuits necessitate passive elements such as resistors and capacitors which increase the power consumption and the silicon area in integrated circuit (IC) fabrication.

On the other hand "the Metamutator" introduced for the first time in [12], called then "a versatile mutative 4-port," was shown to be capable of doing all kinds of mutations when two of the ports were properly terminated. Several ways of realizing memristors, memcapacitors, meminductors, gyrators, inverters etc. were presented in [12, 13].

TransImpedance amplifier is one of the most critical building blocks of the receivers. The main goal of a TransImpedance Amplifier (TIA) is to convert the current pulses produced by the photodiode or other current output sensors into voltage pulses [14, 15]. Operational amplifier circuits are usually used to implement TIA building blocks [14]. Several circuit techniques have been proposed in the literature, including capacitive peaking, inductive peaking, common gate input configuration and common drain configuration [14].

On the other hand, TransConductance Amplifier (TCA) is also one of the most significant building-blocks of analog Very Large Scale Integration (VLSI). A transconductance amplifier is an important component that is used in a variety of calibration activities requiring a known

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stable source of current. Such an amplifier ideally produces a current in a load proportional to an input voltage and maintains that current independent of the load impedance [16]. A TCA is widely used as an active element in switched-capacitor filters, data converters, sample/hold circuits, or as buffer amplifiers for driving large capacitive loads [16].

In this work, a new sinusoidal oscillator circuit using only one adder and one subtractor ADD/SUB [12] realization (each possessing six NMOS transistors) of the Metamutator is being presented. The most important and unique feature of the circuit is that no passive elements are required for its realization. If desired however, an external capacitor can be included to change the oscillation frequency. It is interesting to observe that the ADD/SUB topology of the Metamutator introduced in [12], augmented by two simple external feedback paths between its ports creates an oscillator in addition to many applications demonstrated in [12, 13].

Also, new realizations for TIA and TCA using the same Metamutator with only one additional variable resistor, which can be exploited to provide adjustable gain, are given. These realizations are applicable to any Metamutator implementation.

The paper is organized as follows. The proposed oscillator circuit and its analysis is given in Sect. 2, transconductance and transimpedance amplifier circuits and their analyses in Sect. 3. Simulation results of all the proposed circuits are presented in Sect. 4. Finally, some concluding remarks are discussed in Sect. 5.

2 Proposed oscillator circuit

The Metamutator 4-port is shown in Fig. 1 [12] and its 4-port defining relation is given with equality (1) under the assigned polarities.

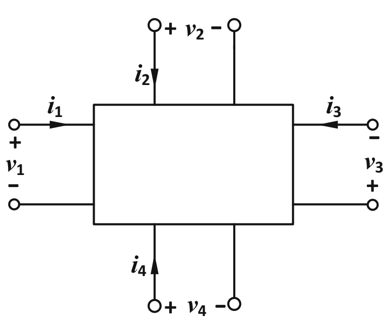

Fig. 1 Metamutator 4-port

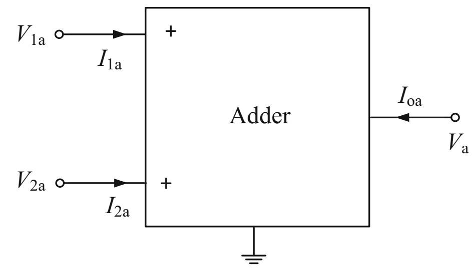

Fig. 2 Symbol of the analog adder circuit

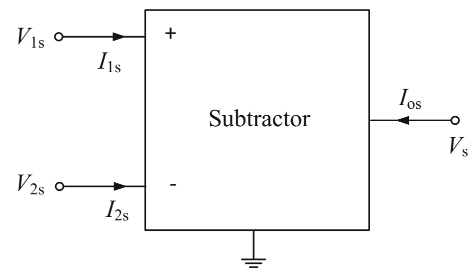

Fig. 3 Symbol of the analog subtractor circuit

$$\begin{bmatrix} I_1 \\ I_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_3 \\ I_4 \\ V_2 \\ V_1 \end{bmatrix} \quad (1)$$

In this paper the analog adder and subtractor circuits shown in Fig. 2 and Fig. 3, respectively will be used to implement the Metamutator because: the input terminals of the adder (V_{1a}, V_{2a}) and subtractor (V_{1s}, V_{2s}) exhibit high impedance while the output terminals (V_a, V_s) exhibit low impedance and this realization contains the least number of transistors (12 in total) [12, 13]. The ideal input–output relations of adder and subtractor circuits are:

$$V_{oa} = V_{1a} + V_{2a} \quad (2)$$

$$V_{os} = V_{1s} - V_{2s} \quad (3)$$

together with $I_{1a} = I_{2a} = I_{1s} = I_{2s} = 0$.

In the non-ideal case the expressions take the form:

$$V_{oa} = k_1 V_{1a} + k_2 V_{2a} \quad (4)$$

$$V_{os} = k_3 V_{1s} - k_4 V_{2s} \quad (5)$$

where k_i (i = 1, 2, 3, 4) is the non-ideality coefficient of the adder and subtractor circuits depending on the threshold voltages and aspect ratios of the transistors. A detailed analysis of the non-ideality coefficients is given in [12].

2.1 The proposed MOS only oscillator

The proposed MOS only oscillator circuit constructed with an analog adder and a subtractor is given in Fig. 4. In order

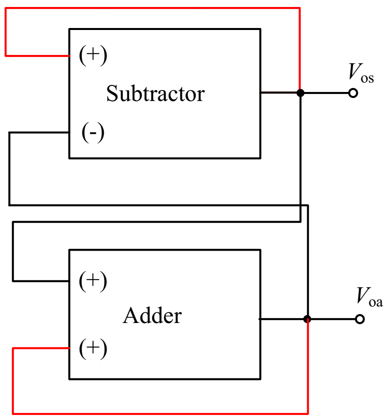

Fig. 4 Oscillator circuit

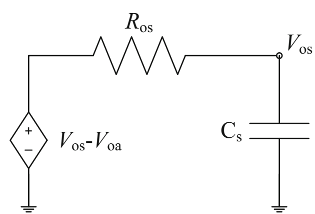

Fig. 5 Equivalent circuit of the subtractor block

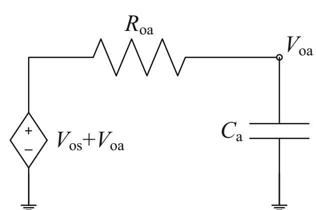

Fig. 6 Equivalent circuit of the adder block

to find the theoretical operating frequency of the oscillator, simplified equivalent circuits of the subtractor and adder blocks including the feedback connections between the ports are shown respectively in Fig. 5 and Fig. 6 where R_{os} and R_{oa} represent the output resistances and C_s and C_a are the equivalent parasitic capacitances at the output nodes of the subtractor and adder circuits. Replacing Fig. 5 and Fig. 6 in Fig. 4, the matrix state equation in (8) can be derived showing, in fact, that it is a quadrature oscillator [17].

$$C_s \frac{dV_{os}}{dt} = \frac{V_{os} - V_{oa} - V_{os}}{R_{os}} = \frac{-V_{oa}}{R_{os}} \quad (6)$$

$$C_a \frac{dV_{oa}}{dt} = \frac{V_{os} + V_{oa} - V_{oa}}{R_{oa}} = \frac{V_{os}}{R_{oa}} \quad (7)$$

$$\frac{d}{dt}\begin{bmatrix} V_{oa} \\ V_{os} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C_a R_{oa}} \\ \frac{-1}{C_s R_{os}} & 0 \end{bmatrix} \begin{bmatrix} V_{oa} \\ V_{os} \end{bmatrix} \quad (8)$$

The eigenvalues $\lambda_{1,2}$ of the matrix in (8), are:

$$\lambda_{1,2} = \pm j\sqrt{C_s C_a R_{oa} R_{os}} \quad (9)$$

and the operating frequency of the oscillator is obtained as:

$$f = \frac{1}{2\pi\sqrt{C_s C_a R_{oa} R_{os}}} \quad (10)$$

2.2 Tunable oscillator circuit

The proposed MOS only oscillator circuit can be frequency tuned by connecting an external capacitor to either, the output node of the adder or the subtractor circuits or both. If a capacitor C_1 is connected to the output port of the adder and a capacitor C_2 is connected to the output port of the subtractor, Eq. (10) is converted to:

$$f = \frac{1}{2\pi\sqrt{(C_s + C_2)(C_a + C_1) R_{oa} R_{os}}} \quad (11)$$

As can be deduced from (11) by adding external capacitors the operation frequency of the oscillator can be tuned. The additional capacitor could be part of the silicon design; however use of a relatively large capacitor requires high silicon area and cannot be exploited for tuning the operation frequency.

3 Transconductance/transimpedance amplifier realizations

A versatile 4-port with a simple structure composed of only one adder and one subtractor and which can be considered as a Metamutator is shown in Fig. 7.

Analysis of the proposed configuration in Fig. 6 gives:

$$V_3 = V_1 - x_1 = V_1 - V_1 + V_2 = V_2 \quad (12)$$

$$V_4 = x_2 - V_2 = V_1 + V_2 - V_2 = V_1 \quad (13)$$

$$I_1 = I_3, I_2 = I_4 \quad (14)$$

The relations in (13–15) can be compactified into the matrix equation given with port relation in (1) showing in fact, that the topology of Fig. 7 realizes a Metamutator which has been used to implement elements such as memristors, memcapacitors, meminductors, gyrators etc. as discussed in [12]. Here two new applications of the 4-port Metamutator circuit in Fig. 1, namely, Transconductance/Transimpedance Amplifiers (TCA/TIA) will be introduced, their implementation being done with the Metamutator topology of Fig. 7. However, unlike the oscillator, these applications can be obtained from any implementation of 4-port in Fig. 1.

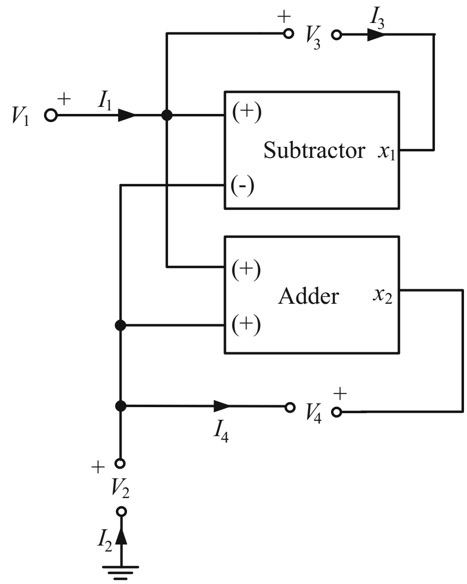

Fig. 7 Metamutator topology using adder and subtractor

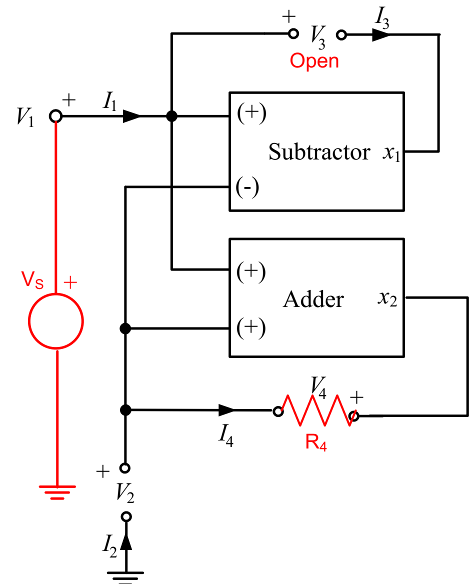

Fig. 8 TCA realization using the Metamutator

3.1 Transconductance amplifier

If, a voltage source V_s is connected to port-1, port-3 is open circuited and a resistor R_4 is connected to port-4 of Fig. 1, the equations (15) and (16) result from (1), showing that the resulting 2-port is a TCA. These interconnections are reproduced in Fig. 8 for the Adder/Subtractor implementation of the Metamutor.

$$V_4 = V_1 = V_s = -R_4 I_4 = -R_4 I_2 \tag{15}$$

$$I_2 = \frac{-V_s}{R_4} \tag{16}$$

3.2 Transimpedance amplifier

In the proposed circuit of Fig. 7, if a current source I_s is connected to port-1 and a resistor R_3 is connected to port-3 and port-4 is open circuit as shown in Fig. 8, then,

$$V_2 = V_3 = R_3 I_3 = R_3 I_S \tag{17}$$

is obtained using 4-port description (1).

The TIA with $V_{out} = R_3 I_S$ can be used to drive a device with zero input current, like the gate of MOS transistor. Otherwise, a buffer has to be connected to port-2 as shown in Fig. 9.

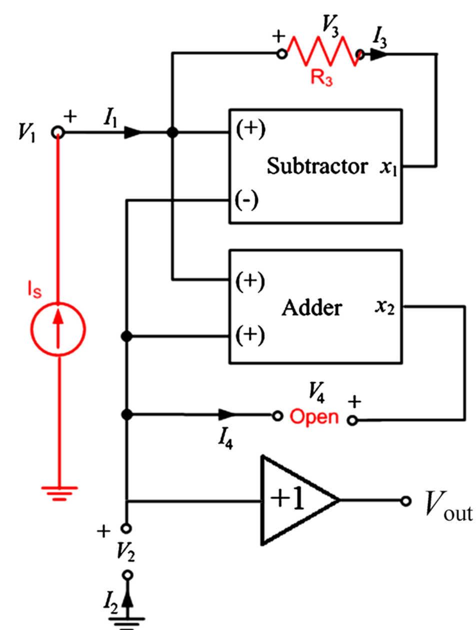

Fig. 9 TIA realization using the Metamutator

4 Simulation results of the applications

4.1 Oscillator circuit

The schematic of the proposed oscillator circuit is shown in Fig. 10; in this figure. V_{1s}, V_{2s} show the inputs of the subtractor and V_{1a} and V_{2a} show the inputs of the adder circuit. Dimensions of the MOS transistors in Fig. 10 are given in Table 1. The output resistances of the subtractor and adder blocks are found from expressions (18) and (19):

$$R_{os} \cong \frac{1}{g_{m3s}} \tag{18}$$

and

$$R_{oa} \cong \frac{1}{g_{m5a}} \tag{19}$$

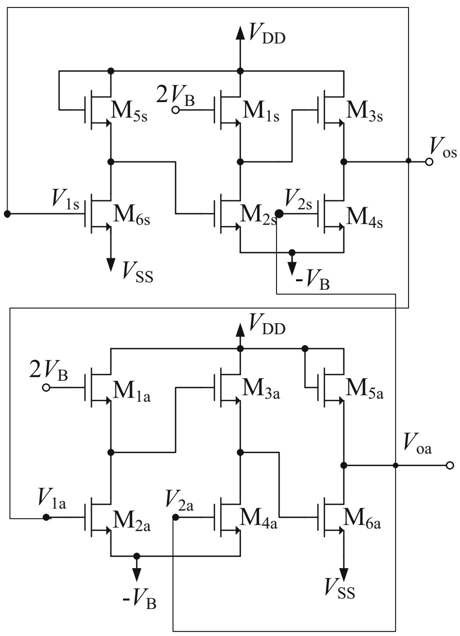

Fig. 10 The schematic of proposed oscillator circuit

Table 1 Dimensions of MOS transistors for oscillator circuit

Transistors	W (μm)	L (μm)
M_{1a}, M_{2a}, M_{3a}, M_{4a}	1	0.5
M_{5a}, M_{6a}	30	0.5
M_{1s}, M_{2s}, M_{5s}, M_{6s}	1	0.5
M_{3s}, M_{4s}	30	0.5

here g_{m3s} and g_{m5a} are the transconductances of the transistors M_{3s} and M_{5a} respectively.

From TSMC 0.25 μm process parameters with ±1.25 V power supply voltage, the output resistors in Fig. 10 are calculated as: $R_{os} = 2.2\ k\Omega$ and $R_{oa} = 2\ k\Omega$ from expressions (18) and (19). The parasitic capacitors $C_s = 73$ fF and $C_a = 71$ fF are obtained from the post-layout simulation. Using these capacitor and resistor values, operating frequency is found as 1050 MHz from equality (10). The area of the metamutator circuit is found to be 30 μm × 26 μm while its power consumption is 5.4 mW.

To test the proposed circuit, its resulting equivalent circuit including an amplitude stabilization as shown in Fig. 11, is used.

The time-domain simulation results with above mentioned passive element values are shown in Fig. 12. As it can be seen from the figure, the output voltages V_2 and V_4 are in 90 degree phase difference, i.e. they are orthogonal, thus it works as a quadrature oscillator. Moreover the diagram of V_4 versus V_2 is given in Fig. 13 which confirms that the outputs are quadrate.

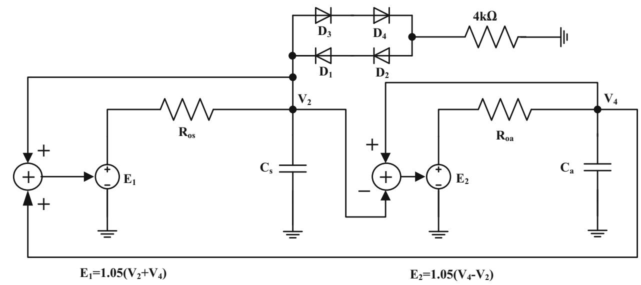

Fig. 11 Equivalent circuit for the simulation of the oscillator

The output waveform resulting from the post layout simulation of the circuit in Fig. 10 is given in Fig. 14.

The post layout simulation results of the oscillator circuit show oscillations at 1000 MHz; so, the theoretical and simulation results are in a very good agreement.

To see the effect of the external capacitors they are selected as $C_1 = 60$ fF and $C_2 = 0$. Theoretical operating frequency of the tuned oscillator is obtained as 750 MHz from expression (11). Post layout simulation result of the tuned oscillator show oscillations at 770 MHz as shown in Fig. 15. Thus theoretical and simulation results are again in a good agreement.

To further see the effects of the external capacitors several larger values have been used and perfect oscillations have been observed; for example for $C_1 = 10$ nF and $C_2 = 10$ nF, $f_{theoretical} = 7.5$ kHz and $f_{simulated} = 8.5$ kHz have been obtained.

In fact the capacitors C_1 and C_2, being externally connected, to tune the oscillation frequency, are not expected to modify much the behavior of the Metamutator IC.

4.2 Transconductance amplifier circuit

For simulating the transconductance amplifier a resistor of value $R_4 = 1\ k\Omega$ has been chosen. The resulting DC characteristic of the transconductance amplifier is shown in

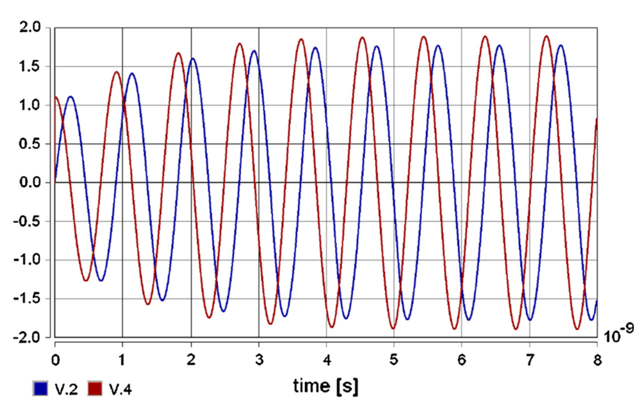

Fig. 12 Time-domain response of the proposed oscillator

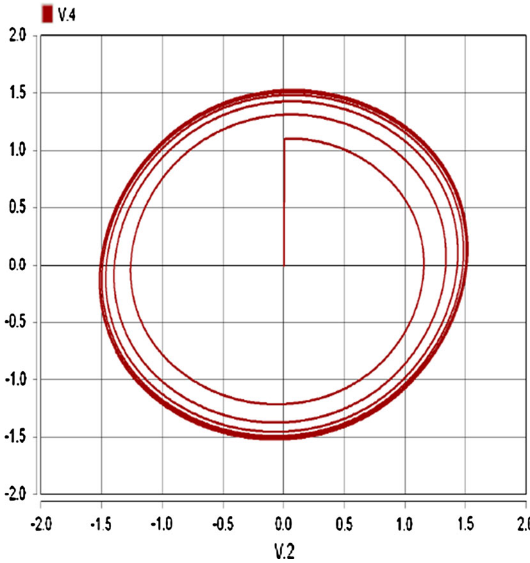

Fig. 13 V_2 versus V_4 diagram of the oscillator circuit

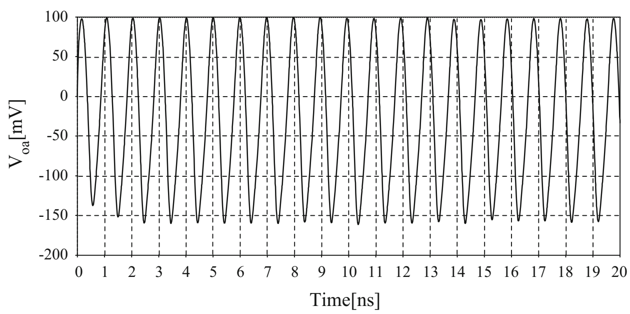

Fig. 14 Simulation result of the oscillator circuit

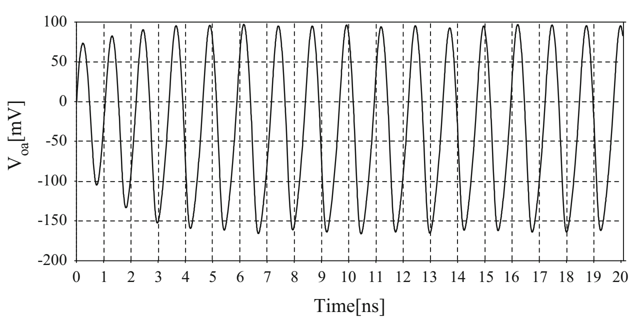

Fig. 15 Simulation result of the oscillator with external capacitor

Fig. 16 where TSMC 0.25 μm process parameters with ±1.25 V power supply voltage have been used. The AC characteristic of the amplifier is shown for three different R_4 values in Fig. 17. The 3-dB frequency is obtained as 157 MHz as implied by the Figure.

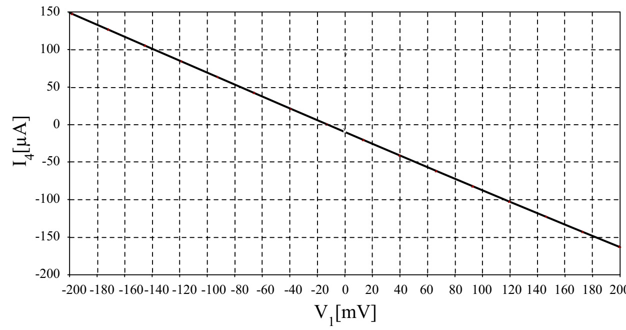

Fig. 16 DC characteristic of the transconductance amplifier

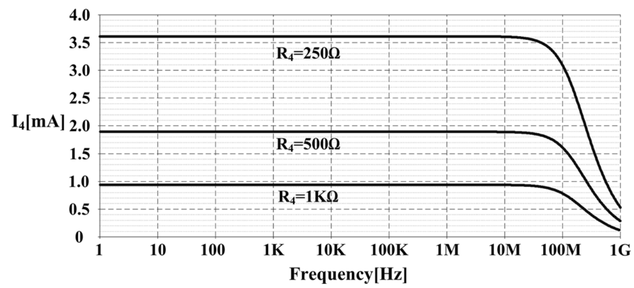

Fig. 17 AC response of the transconductance amplifier

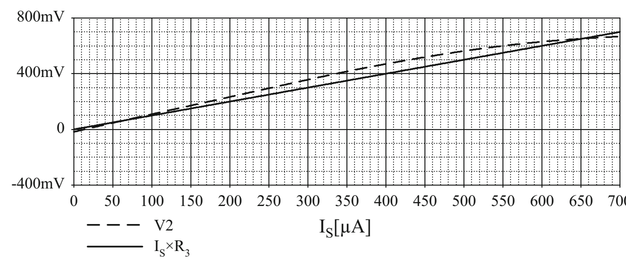

Fig. 18 DC response of the transimpedance amplifier

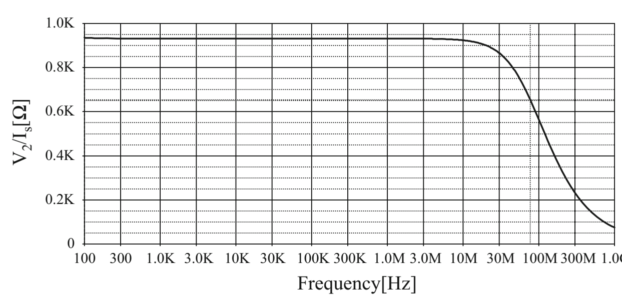

Fig. 19 AC response of the transimpedance amplifier

4.3 Transimpedance amplifier circuit

For the simulation of the TIA, using the same technology parameters, a resistor of $R_3 = 1\ k\Omega$ has been chosen. Theoretical and simulation plots of the TIA DC characteristic are given in Fig. 18, showing good agreement. The frequency response of the TIA is given in Fig. 19; the 3-dB frequency is approximately found to be 78 MHz.

5 Conclusions

In this paper using the recently introduced Metamutator 4-port, new NMOS realizations with a minimal number of transistors (6 for the adder, 6 for the subtractor) for a quadrature oscillator, transconductance and transimpedance amplifiers have been presented. The quadrature oscillator necessitates that the Metamutator be built with an adder and a subtractor block as their internal circuitry is being exploited.

On the other hand, the other two applications can be achieved with any 4-port realization with defining relation as given by (1). With the applications introduced here, in addition to previously demonstrated ones such as mutator, inverter, gyrator, filter etc. circuits [12, 13] and with its hidden existence in many circuits (three published, two recently discovered) the universality of the Metamutator 4-port is being clearly established.

By connecting an external capacitor to the output of the adder or the subtractor circuit or both the oscillation frequency of the quadrature oscillator can be tuned. The gains of the amplifiers can be adjusted with variable resistors for TCA and TIA realizations. All post-layout simulations of the proposed circuits are done with SPICE using TSMC 0.25 μm process technology parameters. Finally, comparisons of SPICE simulated versus theoretical values are also presented which show a very good agreement.

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