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OTA-C TRANSIMPEDANCE BIQUADS DERIVED FROM PASSIVE FILTERS

Dattaguru V. Kamath
Professor, Department of E&C Engg.,
Manipal Institute of Technology,
Manipal University, Manipal, India
dv.kamath@manipal.edu
reachdvkamath@yahoo.com

***Abstract*— This paper presents the new OTA-C transimpedance second-order continuous-time filters based on passive circuits using component substitution method. The resistor and inductor in these biquads are realized using OTA-C counterparts. The proposed biquads are attractive due to their advantageous features like ease of design, good sensitivity and orthogonal tunability of pole-Q. The biquads have been simulated using practical OTAs as well as their behavioral macro-model and the results are given to verify the theoretical analysis.**

***Index Terms*— Analog Signal Processing, Operational Transconductance Amplifier, Voltage-Mode, Transimpedance Mode, Biquad filter**

I. Introduction

The OTA-C approach [1]-[10] is one of the most preferred methods for the design of continuous-time (CT) integrated filter in analog signal processing applications. The continuous-time (CT) filters are realized in voltage-mode (VM), where the input and output variables are voltage, or current-mode (CM), where the input and the output variables are current. The continuous-time (CT) filters in transimpedance mode, where input variable is current and output variable is voltage, are useful for interfacing a current-mode circuit to a voltage-mode circuit. The transimpedance type filters are used in applications with sensors and digital-to-analog converters that provide current output signal. The transimpedance circuits are commonly used in optical receivers and receiver baseband blocks of modern radio systems.

The biquad realization is given important consideration as these are generally used as basic building block for the realization of CT filters of higher order. Several OTA-C biquad realizations either in voltage-mode [1], [2] or current-mode [1]-[10] have been reported in the literature. Few papers on active biquads in transimpedance-mode [11]-[14] have been reported in the literature.

The inverse active biquad filters are used in communication, control and instrumentation systems to correct the distortion of the signal caused by signal processing circuits. The realizations of inverse active biquads are discussed in the literature [15]-[17].

II. Proposed OTA-C Transimpedance Biquads

Currently, the continuous-time filter designs prefer devices other than op-amps such as OTAs. An OTA is a differential-input voltage controlled current source (VCCS). An ideal OTA has infinite input and output impedances and a tunable transconductance. The attractive features of OTA are controllability of its transconductance by changing the dc bias current and ability to work at higher frequencies.

The symbols of SO-OTA (single-output OTA), DO-OTA (dual-output OTA) are presented in Fig. 1. The output currents of DO-OTA are given by

$$I_o^+ = I_o^- = g_m(V_i^+ - V_i^-) \qquad 1(a)$$

where I_o^+, I_o^- are dual output currents, g_m is the transconductance of the OTA, V_i^+ and V_i^- denote non-inverting and inverting input voltages of the DO-OTA respectively.

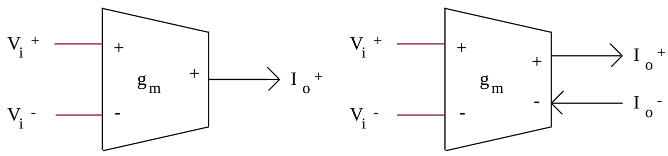


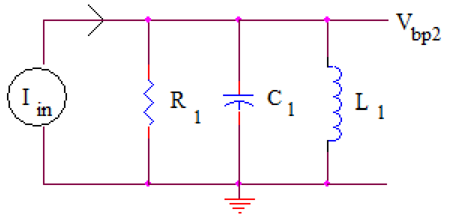
Fig. 1 Circuit symbols of (a) SO-OTA, (b) DO-OTA

Many OTA-based voltage-mode second-order continuous-time filters based on passive circuits have been reported in the literature [2], [18]-[20]. Here, we propose two passive transimpedance biquads and their inverse version. The single ended OTA-C implementation of these transimpedance biquads are implemented based on component substitution method.

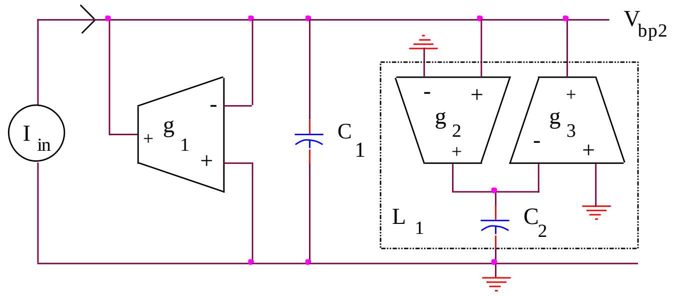
A. OTA-C Transimpedance band-pass biquad

The transfer function of passive RLC transimpedance band-pass biquad in Fig. 2(a) reported in [2] is shown to be

$$\frac{V_{bp2}}{I_{in}} = R_1 \frac{s\left(\frac{1}{R_1C_1}\right)}{s^2 + s\left(\frac{1}{R_1C_1}\right) + \frac{1}{L_1C_1}} \qquad (1a)$$



(a)



(b)

Fig. 2(a) Passive transimpedance band-pass biquad (b) OTA-C transimpedance band-pass biquad derived from (a)

The OTA-C transimpedance second-order band-pass filter circuit in Fig. 2(b) is obtained by using the passive biquad of Fig. 2(a) by replacing the resistor R_1 of value $1/g_1$ with grounded OTA simulated resistor and the inductor L_1 of value C_2/g_2g_3 realized by OTAs g_2 and g_3 and capacitor C_2. The resulting transfer function of band-pass biquad in Fig. 2(b) is given by

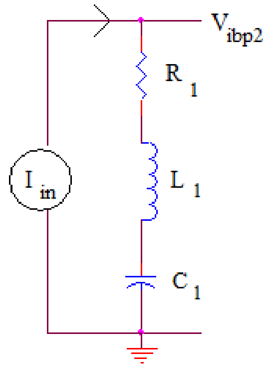
$$\frac{V_{bp2}}{I_{in}} = \left(\frac{1}{g_1}\right) \frac{s\left(\frac{g_1}{C_1}\right)}{s^2 + s\left(\frac{g_1}{C_1}\right) + \frac{g_2g_3}{C_1C_2}} \qquad (1b)$$

B. OTA-C Transimpedance inverse band-pass biquad

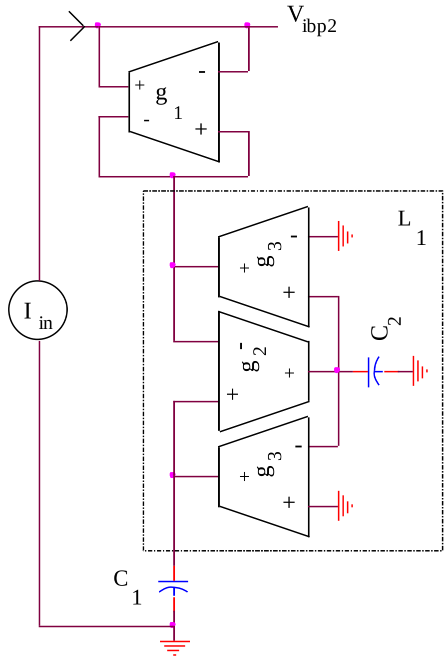
The proposed passive RLC circuit in Fig. 3(a) implements transimpedance inverse band-pass biquad, the transfer function of which is shown to be

$$\frac{V_{ibp2}}{I_{in}} = \frac{R_1\left\{s^2 + s\left(\frac{R_1}{L_1}\right) + \frac{1}{L_1C_1}\right\}}{s\left(\frac{R_1}{L_1}\right)} \qquad (2a)$$

The OTA-C transimpedance inverse band-pass biquad in Fig. 3(b) is obtained from the passive biquad of Fig. 3(a) by replacing the resistor R_1 of value $1/g_1$ with OTA simulated floating resistor and the floating inductor L_1 of value C_2/g_2g_3 is realized by OTAs of value g_2 and g_3 and capacitor C_2.



(a)



(b)

Fig. 3(a) Passive transimpedance inverse band-pass biquad (b) OTA-C transimpedance invere band-pass biquad derived from (a)

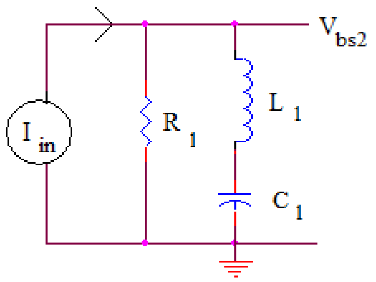
The transfer function of OTA-C transimpedance inverse band-pass biquad in Fig. 3(b) is shown to be

$$\frac{V_{ibp2}}{I_{in}} = \frac{1}{g_1}\frac{\left\{s^2 + s\left(\frac{g_2 g_3}{g_1 C_2}\right) + \frac{g_2 g_3}{C_1 C_2}\right\}}{s\left(\frac{g_2 g_3}{g_1 C_2}\right)} \qquad (2b)$$

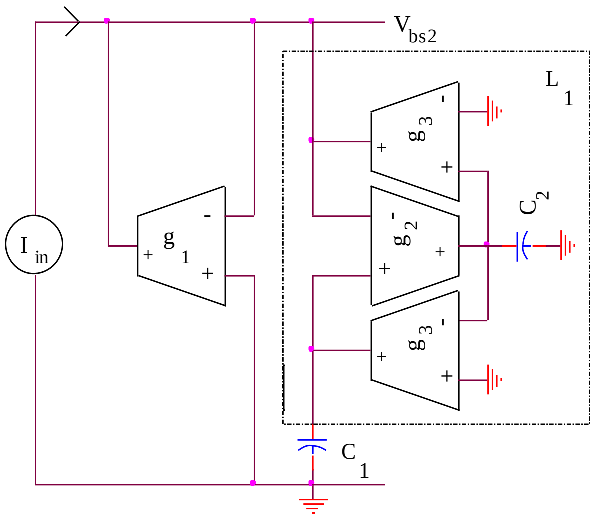
C. OTA-C Transimpedance band-stop biquad

The transfer function of proposed passive RLC transimpedance band-stop biquad in Fig. 4(a) is shown to be

$$\frac{V_{bs2}}{I_{in}} = R_1 \frac{\left\{s^2 + \frac{1}{L_1 C_1}\right\}}{s^2 + s\left(\frac{R_1}{L_1}\right) + \frac{1}{L_1 C_1}} \qquad (3a)$$



(a)



(b)

Fig. 4(a) Passive transimpedance band-stop biquad (b) OTA-C transimpedance band-stop biquad derived from (a)

The OTA-C transimpedance band-stop biquad in Fig. 4(b) is obtained from the passive biquad of Fig. 4(a) by replacing the resistor R_1 of value $1/g_1$ with OTA simulated grounded resistor and the floating inductor L_1 of value C_2/g_2g_3 is realized by OTAs of value g_2 and g_3 and capacitor C_2. The transfer function of OTA-C transimpedance band-stop biquad in Fig. 4(b) is shown to be

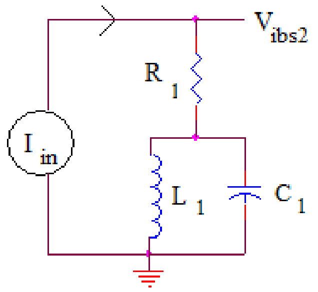
$$\frac{V_{bs2}}{I_{in}} = \left(\frac{1}{g_1}\right)\frac{s^2 + \frac{g_2 g_3}{C_1 C_2}}{s^2 + s\left(\frac{g_2 g_3}{g_1 C_2}\right) + \frac{g_2 g_3}{C_1 C_2}} \qquad (3b)$$

D. OTA-C Transimpedance inverse band-stop biquad

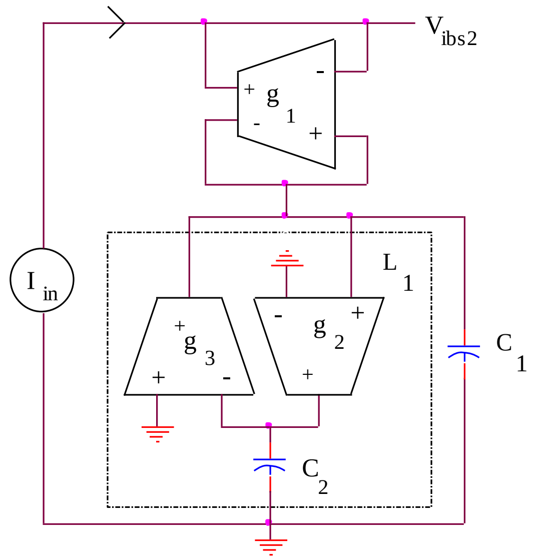
The transfer function of proposed passive RLC transimpedance inverse band-stop biquad in Fig. 5(a) is shown to be

$$\frac{V_{ibs2}}{I_{in}} = \frac{R_1\left\{s^2 + s\left(\frac{1}{R_1 C_1}\right) + \frac{1}{L_1 C_1}\right\}}{s^2 + \frac{1}{L_1 C_1}} \qquad (4a)$$

The OTA-C transimpedance inverse band-stop biquad in Fig. 5(b) is obtained from the passive biquad of Fig. 5(a) by replacing the resistor R_1 of value $1/g_1$ with OTA simulated floating resistor and the grounding inductor L_1 of value C_2/g_2g_3 is realized by OTAs g_2 and g_3 and capacitor C_2.



(a)



(b)

Fig. 5(a) Passive transimpedance inverse band-stop biquad (b) OTA-C transimpedance inverse band-stop biquad derived from (a)

The transfer function of OTA-C transimpedance inverse band-stop biquad in Fig. 5(b) is shown to be

$$\frac{V_{ibs2}}{I_{in}} = \left(\frac{1}{g_1}\right)\frac{\left\{s^2 + s\left(\frac{g_1}{C_1}\right) + \frac{g_2 g_3}{C_1 C_2}\right\}}{\left\{s^2 + \frac{g_2 g_3}{C_1 C_2}\right\}} \qquad (4b)$$

III. SUMMARY OF PROPOSED TRANSIMPEDANCE BIQUADS

The proposed OTA-C transimpedance biquads use only grounded capacitors and hence are attractive. The proposed biquads exhibit features like orthogonal tunability of pole-Q. The routine sensitivity analysis reveals that sensitivities of proposed biquad parameters (ω_o and Q_o) to the transconductance and capacitance values are less than unity.

To the best knowledge of the author there is only little work reported on the realization of OTA-C transimpedance biquads [5]. Alternately transimpedance biquads using other devices like OTRA, Opamp have been reported. In Table I, the proposed OTA-based transimpedance biquads are compared with the transimpedance biquads reported in the literature that use OTA, OTRA and Opamp.

TABLE I COMPARISION OF VARIOUS TRANSIMPEDANCE BIQUADS

Author /Reference	No. of active devices	No. of capacitors (grounded/ floating)	Orthogonal Tunability of pole-Q
Transimpedance band-pass/ band-stop biquad (Fig. 5 in [11])	3 OTRAs 10 MOS based resistors	2 floating	Yes
Transimpedance band-pass biquad (Refer Circuit1 i.e., Fig. 1 in [14])	2 OTAs 2 OPAMPs	No	No
Transimpedance band-pass/ band-stop biquad (Refer Circuit2 i.e., Fig. 2 in [14])	1 OTA 2 OPAMPs	No	No
Transimpedance band-pass/ band-stop biquad (Refer Circuit3 i.e., Fig. 3 in [14])	2 OTAs 2 OPAMPs	No	No
Transimpedance band-pass/ band-stop biquad (Refer Universal biquad1 i.e., Fig. 4 in [5])	2 SO-OTAs 2 DO-OTAs	1 grounded 1 floating	Yes
Transimpedance band-pass biquad (Refer Universal biquad2 i.e., Fig. 5 in [5])	2 SO-OTAs 2 DO-OTAs	2 grounded	Yes
OTA-C Transimpedance band-pass biquad (Fig. 2(b)) in this paper	3 SO-OTAs	2 grounded	Yes
OTA-C Transimpedance inverse band-pass biquad (Fig. 3(b)) in this paper	3 SO-OTAs 1 DO-OTA	2 grounded	Yes
OTA-C Transimpedance band-stop biquad (Fig. 4(b)) in this paper	4 SO-OTAs	2 grounded	Yes
OTA-C Transimpedance inverse band-stop biquad (Fig. 5(b)) in	2 SO-OTAs 1 DO-OTA	2 grounded	Yes

this paper			

IV. Simulation Results

The proposed OTA-C transimpedance biquads have been simulated using PSPICE simulator using Level 3 0.5 µm MOSIS model parameters and device dimensions (W = 4 µm and L = 2 µm) and supply voltages V_{dd} = +2V,V_{ss} = -2V [3]-[10]. The proposed OTA-C transimpedance biquads were also simulated using behavioral macro model of OTA (i.e., voltage controlled current source (VCCS) with infinite output resistance and zero output capacitance) to obtain the ideal characteristics. The schematic circuit of DO-OTA used in our simulation is presented in Fig. 6.

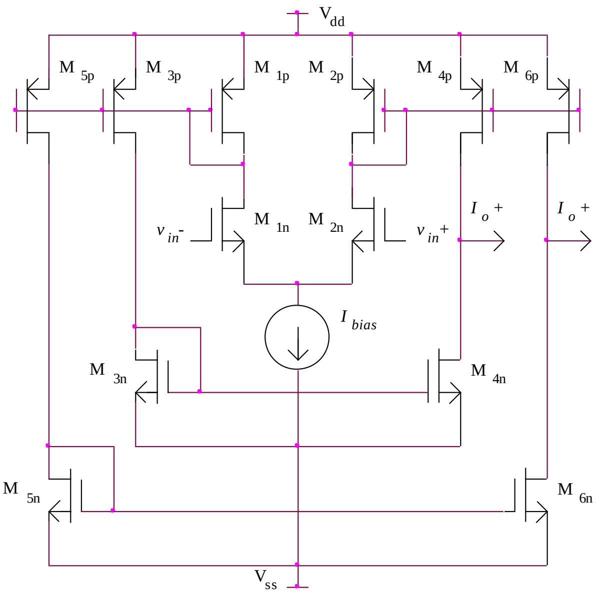
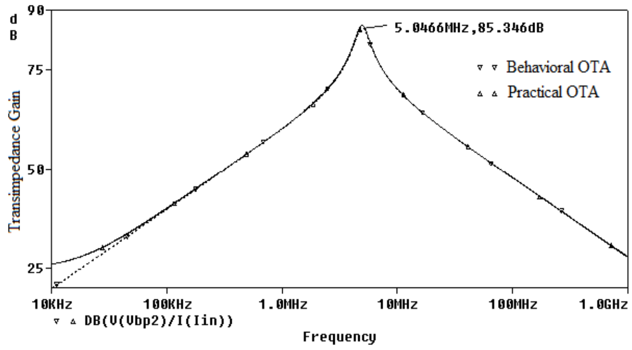


Figure 6: Schematic circuit of CMOS DO-OTA

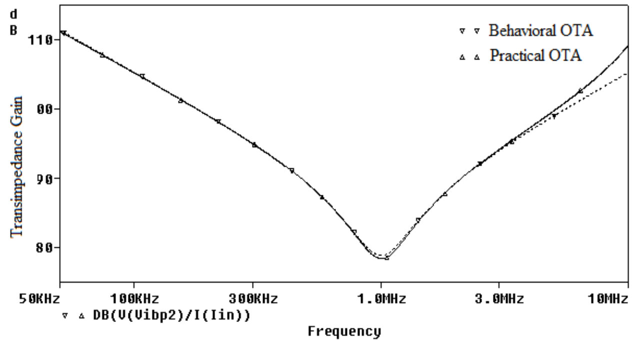
The transimpedance-mode OTA based band-pass biquad of Fig. 2(b) has been simulated using $g_{m1} = 53.9\ \mu S$ ($I_{bias1} = 10\ \mu A$), $g_{m2} = g_{m3} = 206\ \mu S$ ($I_{bias2,3} = 200\ \mu A$), $C_1 = C_2 = 6.557\ pF$ designed for a pole frequency of 5 MHz, pole-Q of Q_o = 3.82, centre-frequency gain of 85.36 dB and the resulting amplitude response is shown in Fig. 7.



∇ …. using behavioral OTA, Δ __ using Tsukutani OTA

Fig. 7 Amplitude response of OTA based Transimpedance-mode Band-pass Biquad of Fig. 2(b)

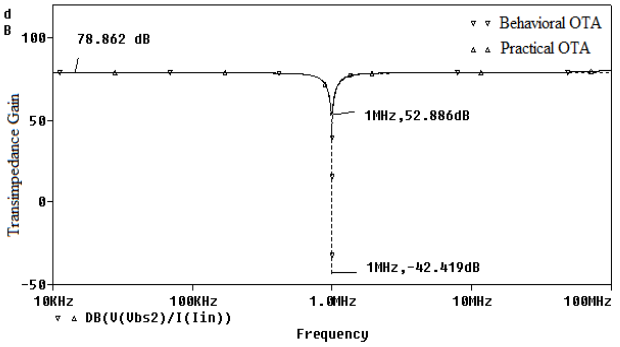
The transimpedance-mode OTA based inverse band-pass biquad of Fig. 3(b) has been simulated using $g_{m1} = 114\ \mu S$ ($I_{bias1} = 50\ \mu A$), $g_{m2} = g_{m3} = 53.9\ \mu S$ ($I_{bias2} = I_{bias3} = 10\ \mu A$), $C_1 = C_2 =$ 8.578 pF designed for a pole frequency of 1 MHz, pole-Q of Q_o = 2.115, centre-frequency gain of 78.86 dB and the resulting amplitude response is shown in Fig. 8.



∇ …. using behavioral OTA, Δ __ using Tsukutani OTA

Fig. 8 Amplitude response of OTA based Transimpedance-mode Inverse Band-pass Biquad of Fig. 3(b)

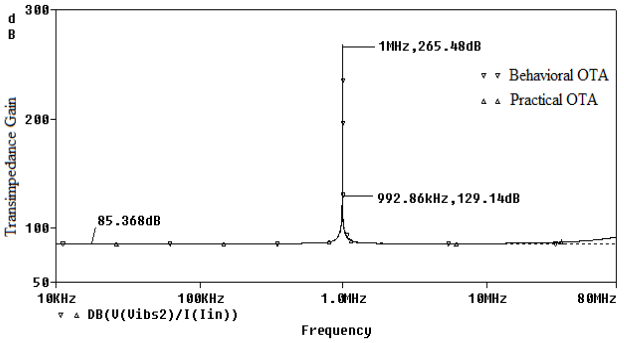
The transimpedance-mode OTA based band-stop biquad of Fig. 4(b) has been simulated using $g_{m1} = 114\ \mu S$ ($I_{bias1} = 50\ \mu A$), $g_{m2} = g_{m3} = 53.9\ \mu S$ ($I_{bias2,3} = 10\ \mu A$), $C_1 = C_2 =$ 8.578 pF designed for a pole frequency of 1 MHz, pole-Q of Q_o = 2.115, pass-band gain of 78.86 dB and the resulting amplitude response is shown in Fig. 9.



∇ …. using behavioral OTA, Δ __ using Tsukutani OTA

Fig. 9 Amplitude response of OTA based Transimpedance-mode Band-stop Biquad of Fig. 4(b)

The transimpedance-mode OTA based inverse band-stop biquad of Fig. 5(b) has been simulated using $g_{m1} = 53.9\ \mu S$ ($I_{bias1} = 10\ \mu A$), $g_{m2} = g_{m3} = 206\ \mu S$ ($I_{bias2,3} = 200\ \mu A$), $C_1 = C_2 = 32.79\ pF$ designed for a pole frequency of 1 MHz, pole-Q of Q_o = 3.82, centre-frequency gain of 85.36 dB and the resulting amplitude response is shown in Fig. 10.



∇ …. using behavioral OTA, Δ __ using Tsukutani OTA

Fig. 10 Amplitude response of OTA based Transimpedance-mode Inverse Band-stop Biquad of Fig. 5(b)

The stability of the proposed inverse biquads is studied by transient analysis. The responses of the inverse band-pass biquad of Fig. 3(b) to an input current with the 10µA amplitude at frequency 1 MHz ($g_{m1} = 114\ \mu S$, $g_{m2} = g_{m3} = 53.9\ \mu S$, $C_1 = C_2 =$ 8.578 pF) obtained using behavioral OTA macro model are given in Fig. 11 (a) and (b).

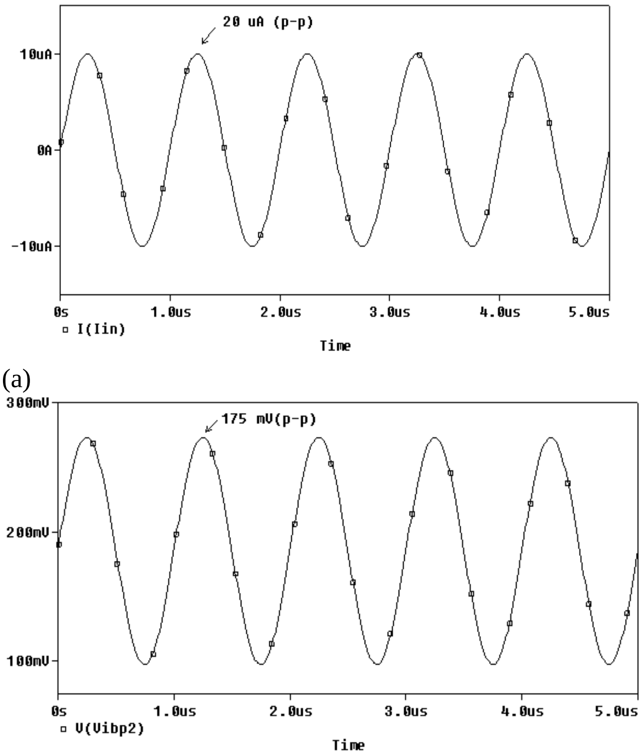


Fig. 11. Transient analysis: input and output waveforms of the OTA based Transimpedance-mode Inverse Band-pass Biquad of Fig. 3(b)

V. conclusion

In this paper, OTA-based transimpedance-mode band-pass and band-reject biquads and their inverse circuits based on passive filter circuits have been proposed. The circuits use only grounded capacitors and hence are suitable for monolithic integrated circuit implementation. All the biquads exhibit low sensitivity to component tolerances and provide independent tuning of pole-frequency and pole-Q. The simulation results obtained are in good agreement with theory. The realization of OTA-C voltage-mode and current-mode biquads, in addition to transimpedance-mode, using passive RLC circuits will be the subject of future work.

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