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AN IMPROVED CURRENT-MODE CONTROLLED AMPLIFIER USING CURRENT CONVEYORS

BY

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Abstract. In this work, two second generation current controlled conveyors, with positive and negative current transfers, are described. They have simple structures and use only NPN bipolar transistors to operate. The electrical characteristics of these two conveyors (voltage gain, current gain, and parasitic impedances...) were determined. Current amplifiers with adjustable gain are developed based on these two conveyors. PSPICE simulation results show that the current conveyor with negative current transfer presents interesting features compared to the conveyor with positive transfer. A comparison between the performances of the proposed current controlled amplifiers and an amplifier described in a previous solution is presented. The latter confirms the improvement brought by our amplifiers at the wide range of gain adjustability, and the bandwidth observed.

Key words: current amplifier with adjustable gain; current mode circuit; second generation current controlled conveyor with negative current transfer ($CCCII^-$); second generation current controlled conveyor with positive current transfer ($CCCII^+$).

1. Introduction

The first-generation current conveyor was introduced by Smith and Sedra, (1968). Two years later, the same designers have developed the second-

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generation current conveyor (CCII) (Sedra & Smith, 1970). These circuits have become quickly the basic analog elements, of primary importance, for the design of very large circuits operating at high frequency in voltage-mode and current-mode (Sedra & Smith, 1970; Sedra *et al*., 1990; Toumazou *et al*., 1990; Wilson, 1990; Fabre, Saaid & Barthelemy, 1995; Saaid & Fabre, 1996; Toumazou *et al*., 1996; Fei, 2007).

A. Fabre introduced a new extension of conveyors which is the second generation current controlled conveyor (CCCII). This is characterized by its intrinsic resistance R_X, at the terminal X and whose value depends on the bias current (Fabre *et al*., 1995, 1996). Indeed, this advantage has extended the scope of the current conveyors in the electronics controlled at very high frequency (filters, amplifiers, oscillator, active inductor ...) (Fabre *et al*., 1995, 1996, 1997, 1998; Seguin & Fabre, 2001; Zouaoui-Abouda & Fabre, 2006; Kumngern *et al*., 2010; Abbas *et al*., 2011).

The current controlled amplifier made up with CCCIIs, has interesting characteristics: high-frequency operation, ease of control by current polarization, small area on the substrate... Moreover, this circuit does not use negative feedback and requires no additional external resistor to operate (Saaid & Fabre, 1996; Fabre *et al*., 1996).

In this article, we present two types of current conveyors namely a second generation current controlled conveyor with negative current transfer ($CCCII^-$) based on a new simplified structure, and a second generation current controlled conveyor with positive current transfer ($CCCII^+$), described in Seguin and Fabre, (2001). Both structures operate at a reduced supply voltage, and they rely only on NPN bipolar transistors to convey the signal and the CMOS transistors to bias the circuit. These transistors are from the 0.35 μm BiCMOS technology of ST, (1994).

Next, we analyze two current-mode amplifiers, one with $CCCII^-$ and the other based on $CCCII^+$s conveyors. A comparison of the characteristics of these two amplifiers with another current amplifier from Fabre *et al*., (1996) is performed.

2. Second Generation Current Controlled Conveyor

2.1. Description of Current Conveyors

The second generation current controlled conveyors are active electronic circuits which have three input-output terminals called X, Y and Z. These circuits are characterized by an intrinsic resistance R_x at the X terminal whose value is adjustable by the bias current I_0. This can be added as a fourth terminal for controlling the conveyor (Fig. 1).

The input-output variables of the conveyor CCCII are linked together by the following matrix equation (Fabre *et al*., 1996):

$$\begin{pmatrix} I_Y \\ V_X \\ I_Z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 1 & R_X & 0 \\ 0 & \pm 1 & 0 \end{pmatrix} \begin{pmatrix} V_Y \\ I_X \\ V_Z \end{pmatrix}. \quad (1)$$

In this expression, the transfer of the current I_Z/I_X is equal to +1 for the current controlled conveyor CCCII$^+$, and to –1 for the conveyor CCCII$^-$.

Furthermore, the resistance R_X is given by the following relationship:

$$R_X = \frac{V_T}{I_0}. \quad (2)$$

where V_T is the thermal voltage (≈ 26 mV at 27°C).

The most common structure of conveyors uses a mixed translinear loop and two complementary current mirrors, composed of NPN and PNP transistors (Fabre *et al.*, 1996, 1998). While the use of PNP transistors limits the frequency response of circuits (Seguin and Fabre, 2001).

The two structures of current conveyors that we present in this work are relatively simple and do not contain PNP transistors, which allows to achieve very high frequencies (Seguin and Fabre, 2001). Figs. 2 *a* and 2 *b* represent respectively the CCCII$^-$ and CCCII$^+$ conveyors proposed.

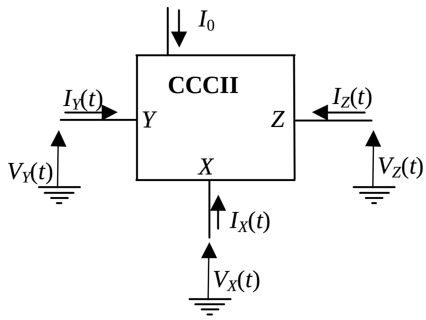
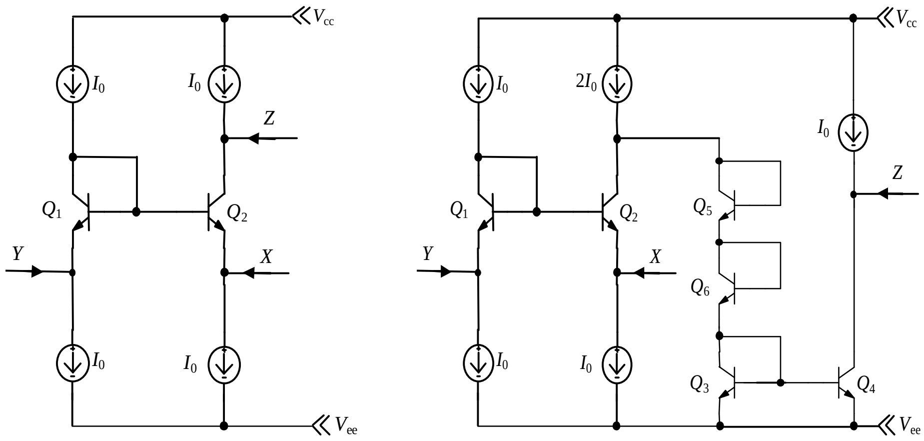


Fig. 1 – Second generation current controlled conveyor.

The CCCII$^-$ conveyor (Fig. 2 *a*) consist of only two NPN transistors, Q_1 and Q_2 to transfer the different signals. The voltage follower function, between the *Y* and *X* channels, is performed by the transistors Q_1 and Q_2, which act as two emitter followers. Between terminals *X* and *Z*, the current follower function is obtained without needing to add a current mirror circuit for extracting the output current I_Z. Polarization is provided by four current sources of the same value.

For the conveyor CCCII$^+$ (Fig. 2 *b*) a complementary current mirror Q_3–Q_4 is added to the structure of CCCII$^-$ (Fig. 2 *a*) in order to reverse the sign of the output current on port *Z*, and, also to increase the dynamic range of the voltage release. The transistors Q_5 and Q_6 connected in diode play the role of level shift between the collector voltages of Q_2 and Q_3 (Seguin & Fabre, 2001).

Furthermore, the various sources of bias current provide a current equal to I_0 in each transistor (Q_1, Q_2, Q_3 and Q_4). Indeed, the current source connected to the collector of Q_2 supplies a current value of $2I_0$ which splits into two equal parts in the transistors Q_2 and Q_3 (Seguin & Fabre, 2001).



a *b*
Fig. 2 – Schematic implementation of conveyors:
a – CCCII$^-$; *b* – CCCII$^+$.

The bias current sources of the two conveyors are, in the real case, replaced by CMOS current mirror of N and P types so as to control the value of resistance R_X by changing the bias current. The size of these transistors will be suitably chosen to enable good current bias circuits.

2.2. Simulation Results

Table 1 summarizes the main characteristics of conveyors CCCII$^-$ and CCCII$^+$ (Fig. 2) for a bias current $I_0 = 100$ µA. The voltage gain $\beta(s)$ and current gain $\alpha(s)$ are very close to the unit, which is in good agreement with theory.

The conveyor CCCII$^-$ presents a very good frequency performance with low power dissipation and a reduced number of transistors. Moreover, it operates in class AB; *i.e*, the amplitude of the current to be treated by this conveyor can exceed the value of the bias current.

In contrast, the CCCII$^+$ consumes more energy, because it uses six NPN transistors to operate. Thus, this latter operate in class A, that is to say, the amplitude of the input signal should always be strictly smaller than the current value of polarization I_0.

To compensate the offset of the conveyor CCCII$^-$ (Fig. 2 *a*), we change the value of the bias current strap side. In addition, we add a DC voltage source to the node Z to ensure the smooth operation of transistors.

Table 1
Simulated Characteristics of CCCII Circuits at 27°C

Conveyor	$CCCII^-$	$CCCII^+$
Voltage gain $\beta(s) = V_X/V_Y$	0.973	0.9733
–3 dB Bandwidth of $\beta(s)$	27.4 GHz	23 GHz
Input impedance ($R_Y//C_Y$)	1.98 MΩ//0.31 pF	1.987 MΩ//0.28 pF
Intrinsic resistance R_X	272 Ω	272.2 Ω
Offset output voltage at X	–169.7 μV	–8.9 μV
Current gain $\alpha(s) = I_Z / I_X$	0.995	0.988
–3 dB Bandwidth of $\alpha(s)$	719.78 MHz	196.79 MHz
Output impedance ($R_Z//C_Z$)	1.43 MΩ//0.42 pF	1.43 MΩ//0.42 pF
Offset output current at Z	249 nA	116.1 nA
Supply voltage	±0.75 V	±2.2 V
Power consumption	0.3 mW	0.6 mW
Class of operation	AB	A
Number of transistors	2 NPN	6 NPN

3. Current Controlled Current Amplifiers

3.1. Description of Current Amplifiers

In this section, we present two current controlled amplifiers structures. Each one of them is made by cascading two second generation current controlled conveyors of the same type. The two conveyors of each current amplifier successively performe a current-voltage conversion and a voltage-current conversion. These conversions are based on the use of intrinsic resistances R_X of the two conveyors. So, by changing the values of bias currents, we can adjust the gain of the amplifiers without need to add any passive component.

The current gains of amplifiers, that depend only on the two bias currents of conveyors $CCCII^-$ and $CCCII^+$ are respectively:

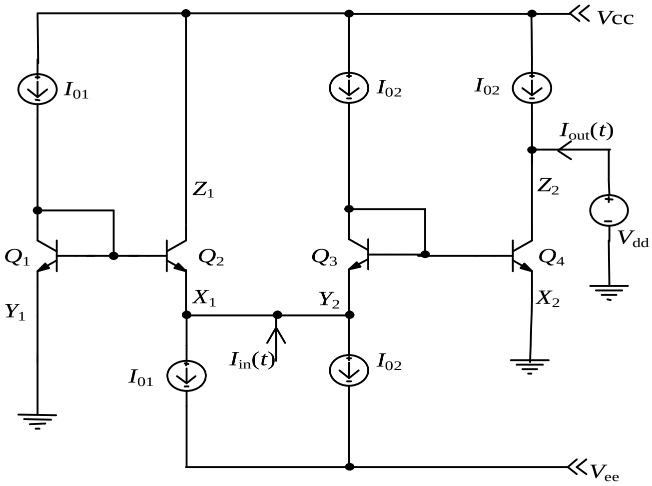
$$G_I = \frac{I_{out}(t)}{I_{in}(t)} = \frac{R_{X1}}{R_{X2}} = \frac{I_{02}}{I_{01}}. \quad (3)$$

$$G_I = \frac{I_{out}(t)}{I_{in}(t)} = -\frac{R_{X1}}{R_{X2}} = -\frac{I_{02}}{I_{01}}. \quad (4)$$

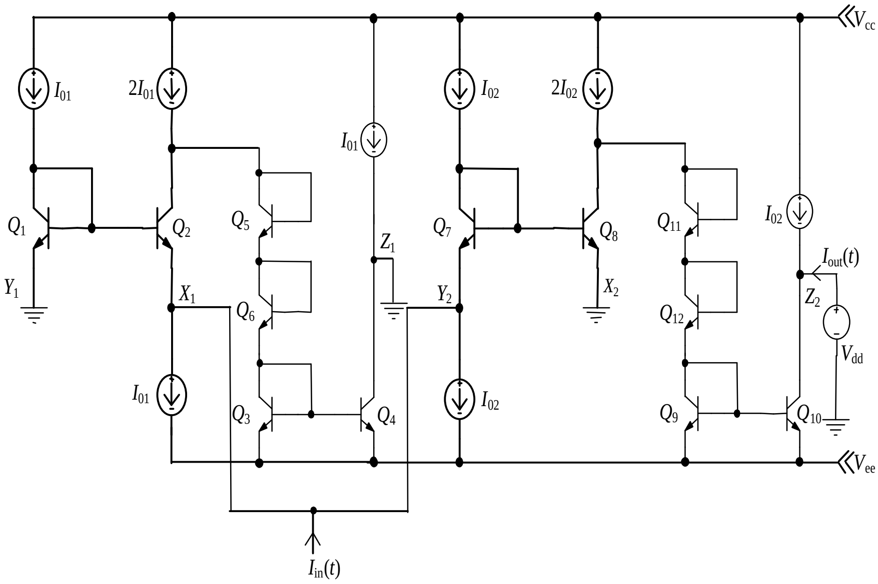
Figs. 3 *a* and 3 *b* show the electric schematics diagrams of each amplifier formed by $CCCII^-$s and $CCCII^+$s successively.

The bias currents I_{01} and I_{02} of the two conveyors have been positioned, in the two current amplifiers, so as to optimize the structure used. In addition, we can control the current gain of circuits (Fig. 3) by varying the W and L of channel from CMOS transistors in the real case.

We note that the current amplifier made based on $CCCII^-$s (Fig. 3 *a*) uses a minimum number of NPN transistors which reduces its consumption.



a



b

Fig. 3 – Schematic implementation of current amplifiers:
a – $CCCII^-$; *b* – $CCCII^+$.

The current amplifier made with $CCCII^+$s (Fig. 3 *b*) has a large number of transistors some of which have absolutely no role; that is for example the case of the transistors which constitute the output *Z* of the first conveyor, which is connected to ground. So we can simplify the circuit by eliminating the output Z_1. This amplifier has high power consumption.

The current output (Z_2 port) of both amplifiers has very high impedance. It is however necessary to ensure that the output impedance of the input generator $I_{in}(t)$ remains high compared to R_{X1}. Moreover, to extract the output current $I_{out}(t)$ of the two amplifiers, we set the potential Z_2 in a reference voltage equal to 0.5 V (load impedance $Z_L = 0$).

3.2. Simulation Results

The theoretical and the simulated gain values for the two amplifiers (Fig. 3) are compared in Fig. 4 as a function of the current I_{02} with $I_{01} = 100$ µA and $I_{in} = 10$ µA. Furthermore, variations of the gain obtained by simulating the current amplifier described in Fabre *et al*., (1996), were represented also in the same graph.

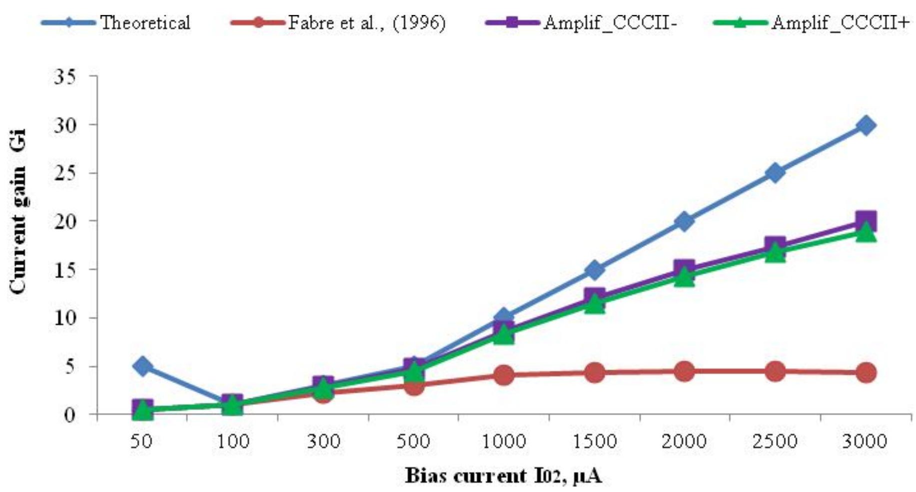


Fig. 4 – Variation of current gain G_I as a function of I_{02}, for $I_{01} = 100$µA.

The gap that appears between the theoretical and the simulated gains of the two amplifiers, comes from the difference between the theoretical and the simulated values of intrinsic resistance R_{X2} when the current I_{02} becomes important.

It is clear that the proposed current controlled amplifiers are characterized by a controlled interval of gain broader and nearest to the theoretical one than the gain of the current amplifier from the previous solution.

We explain this difference, in that, the amplifier presented in our paper is constituted by current conveyors that use many NPN and PNP transistors, and runs with ±2.5 V. In contrast our current amplifiers are formed from conveyors $CCCII^{-}$s and $CCCII^{+}$s having only NPN transistors in few number, and operate with a reduced supply voltage.

Moreover, the amplifier produced using CCCII⁻s provides values of gain better than the values presented by the amplifier realised with CCCII⁺s. For example, for I_{02} = 2 mA, the first amplifier provides a gain equal to 15 and the second amplifier has a current gain equal to 14.34, but the gain of the current amplifier of Fabre *et al.*, (1996) is equal to 4.5.

The variation of the –3dB cutoff frequencies, of our current amplifiers and those of the previous solution, are shown in Fig. 5 for a theoretical gain equal to 5, according to I_{02}.

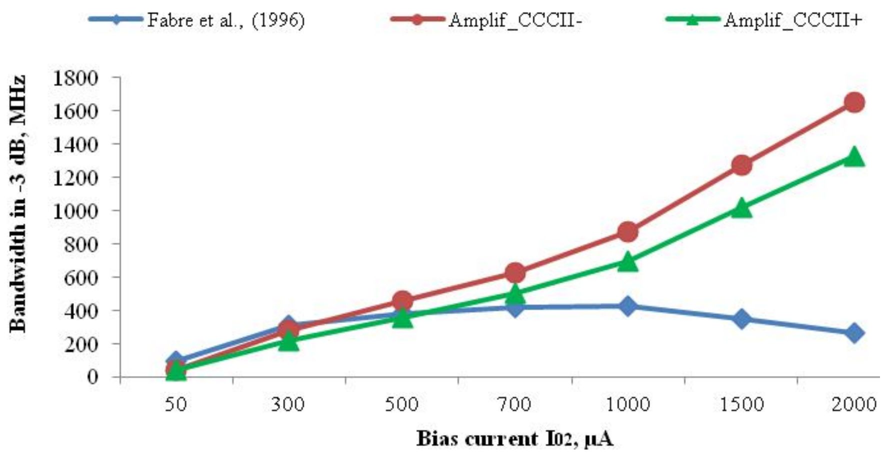


Fig. 5 – Evolution of bandwidth in –3 dB for gain equal to 5 according to I_{02}.

Table 2

Comparison of Simulated Performance of Amplifiers Circuits for I_{02}=2 mA and I_{01} = 400 µA at 27°C

Amplifier	Fig. 3 *a*	Fig. 3 *b*	Fabre *et al.*, (1996)
Number of transistors	4 NPN	12 NPN	12 PNP 14NPN
Supply voltage	±0.75V	±2.2V	±2.5V
Current gain	4.4	4.46	1.75
Bandwidth at –3dB, [GHz]	1.7	1.3	0.300
Power dissipation, [mW]	5.36	40.9	50.9

We notice that the current amplifiers made up with by CCCII⁻s and CCCII⁺s can go up to a frequency of 1.7 GHz and 1.3 GHz respectively for I_{02} = = 2 mA, while the previous version amplifier does not exceed 300 MHz.

The comparison of the characteristics of the two current amplifiers proposed and the one described in our paper are shown in Table 2, for the polarization currents I_{01} = 400 µA and I_{02} = 2 mA, and for the input current $I_{in}(t)$ equal to 10 µA. We note that the consumption of the amplifier (Fig. 3 *a*) is very low due to the reduced number of active components used and also to the low supply voltage.

4. Conclusion

In this work, we have presented a comparison between the operation of two second generation current controlled conveyors, one with positive current transfer and the other with negative transfer. Then, we have analyzed two current controlled amplifiers based on these two conveyors. These amplifiers were compared to the previous proposed solution.

Simulation results show that, the $CCCII^-$ has more interesting features than $CCCII^+$. Also, the current amplifier, consisting of two conveyors with negative transfer, presents a better control of gain as a function of bias current. This amplifier has an improved bandwidth compared to the others, it reaches 1.7 GHz for I_{02} = 2 mA, with a supply voltage less than 1 V and a low power consumption.

However, the exclusive use reduced number of NPN transistors presents low characteristics of stability to current amplifier circuits.

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UN AMPLIFICATOR ÎMBUNĂTĂȚIT CONTROLAT ÎN CURENT ŞI IMPLEMENTAT CU CONVEIOR DE CURENT

(Rezumat)

Două conveioare de curent din a doua generaţie, inversor şi neinversor, sunt descrise în această lucrare. Acestea au o structură simplă şi utilizează numai tranzistoare NPN. Pentru acestea s-au determinat caracteristicile de performanță (câştigul în tensiune, câştigul în curent, impedanţe parazite etc.). Pe baza celor două convertoare s-au proiectat ulterior amplificatoare cu câştig reglabil. Simulările PSPICE atestă proprietăți interesante pentru conveiorul inversor comparativ cu cel neinversor. O comparaţie între performanţele amplificatoarelor controlate în curent propuse în acest articol şi a unui amplificator propus anterior este prezentată în acest articol. Varianta propusă Acest din urmă se remarcă printr-un domeniu mai larg de reglare a câştigului şi benzii de frecvenţă.