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Realisation of *n*th-order current transfer function employing ECCIIs and application examples

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In this article, a universal *n*th-order current-mode filter employing electronically tunable second-generation current conveyors (ECCIIs) and grounded passive elements is proposed. As the current gain of the ECCII can be controlled electronically by adjusting the ratio of its DC bias currents, it is possible to tune all the coefficients of the transfer function independently. SPICE simulation results using TSMC 0.35 μm CMOS process model are included to verify the theory. Furthermore, a design example of a fourth-order video band filter is given to illustrate the application of the introduced topology in analog circuit design.

Keywords: electronically tunable; current conveyor; transfer function; filter; CMOS

Introduction

It is well known that current-mode circuits have greater linearity, lower power consumption, wider bandwidth and larger dynamic range than their voltage-mode counterparts (Ferri and Guerrini 2003). As an important current-mode active device, the second-generation current conveyor (CCII) (Sedra and Smith 1970) is widely used by analogue designers for realising different types of filters (Surakampontorn and Thitimajshima 1988; Tek and Anday 1989; Chang and Chen 1991; Surakampotorn and Kumwatchara 1992; Anday and Gunes 1995; Fabre and Alami 1995; Acar and Özoğuz 1996; Papazoglou and Karybakas 1997).

In many applications, it is required to change the coefficients of the filter transfer function (TF). Then further research has been focused on current conveyors with adjustable current gain (Senani 1980; Surakampontorn and Thitimajshima 1988; Surakampotorn and Kumwatchara 1992; Fabre and Mimeche 1994; Papazoglou and Karybakas 1997; Sayın 2004; Minaei, Sayin, and Kuntman 2006a,b).

The electronically tunable current conveyor (ECCII) which has a controllable current gain was first proposed by Senani (1980) using an operational amplifier (OA) and an operational transconductance amplifier (OTA). Then the ECCII was designed and realised in both CMOS and Bipolar technology (Surakampontorn and

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Thitimajshima 1988; Surakampotorn and Kumwatchara 1992; Fabre and Mimeche 1994; Minaei et al. 2006b).

High-order filters are needed and widely used for realisation of communications systems. Several *n*th-order voltage- and current-mode TF synthesis methods and circuits are available in the literature employing active elements such as CCIIs and current differencing buffered amplifiers (CDBAs) (Tek and Anday 1989; Chang and Chen 1991; Anday and Gunes 1995; Acar and Özoğuz 1996; Acar and Özoğuz 2000). However, these circuits suffer from the lack of electronic tunability which is very important for today's modern circuit design. High-order filters employing ECCIIs seem to bring a solution to this problem (Sayın 2004; Minaei et al. 2006a). A preliminary version of this work appeared in work by Minaei et al. (2006a).

In this article, a general circuit configuration for realising *n*th-order current TF is derived using CMOS implementation of the ECCII reported in Minaei et al. (2006b). All coefficients of the current TF can be tuned independently by adjusting the current gain of the ECCIIs used in the configuration. Moreover, a second-order current-mode filter which realises low-pass, high-pass, band-pass and notch responses is derived from the proposed configuration. Furthermore, a fourth order video band filter is designed using second order low-pass and low-pass notch filters connected in cascade. Simulation results using transistor level implementation for the ECCIIs are given to confirm the theoretical analysis.

The ECCII and its CMOS implementation

The electrical symbol of a ECCII is shown in Figure 1. The terminal current–voltage relations of an ideal ECCII can be given by

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm k & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \tag{1}$$

The ECCII, like a CCII, has a unity voltage gain between its Y and X terminals but unlike a CCII has a tunable current gain $\pm k$ between its X and Z terminals. The plus and minus signs of k denote positive (ECCII+) and negative (ECCII−) type conveyors, respectively.

Recently, an improved CMOS realisation of the ECCII has been introduced (Minaei et al. 2006b). This CMOS implementation of the positive type electronically tunable current conveyor (ECCII+) is shown in Figure 2.

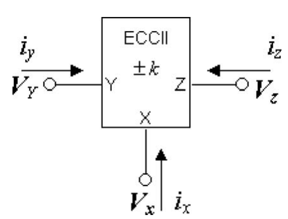

Figure 1. Electrical symbol of the ECCII.

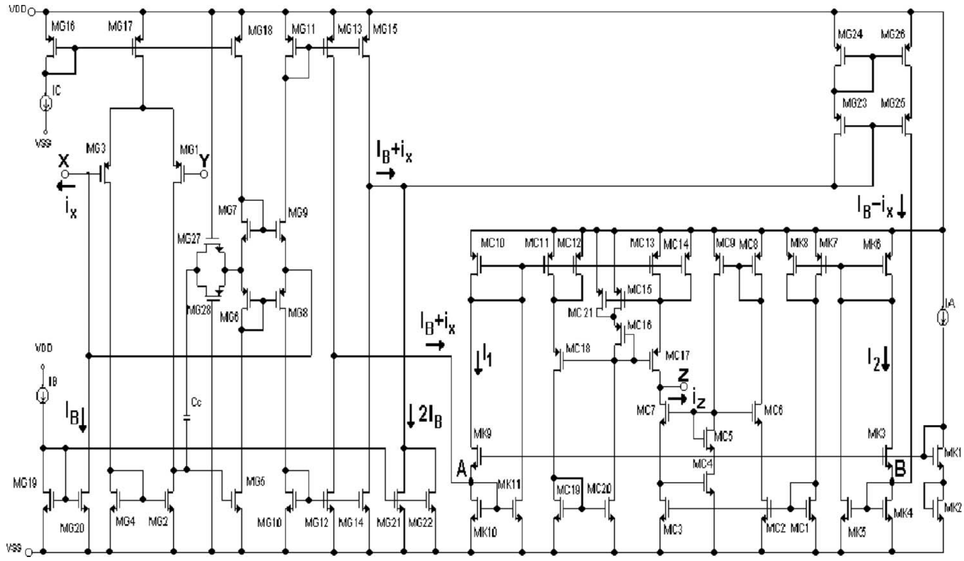

Figure 2. CMOS realisation of the ECCII+ (Minaei et al. 2006b).

The output current of the circuit i_z can be calculated as (Surakampotorn and Kumwatchara 1992; Minaei et al. 2006b)

$$i_z = nI_1 - nI_2 = n\left(\frac{I_B}{2I_A}\right) \cdot i_x = k.i_x \tag{2}$$

where $k = n\left(\frac{I_{\mathrm{B}}}{2I_{\mathrm{A}}}\right)$ is the small-signal current gain of the amplifier and can be controlled electronically by changing DC bias currents I_{A} and I_{B}. The parameter n is the current multiplication factor of the current mirrors used in the output stage of the ECCII+. From Figure 2, it can be seen that the value of parameter $n = 2$ because identical transistors (MC13, MC14) and (MK7, MK8) are used in parallel.

It should be noted that to implement a negative-type electronically tunable current conveyor (ECCII−) it is sufficient to apply the currents $I_{\mathrm{B}} + i_x$ and $I_{\mathrm{B}} - i_x$ into terminals B and A of the small-signal current amplifier, respectively.

Tunable *n*th-order current transfer function realisation

The ECCII can be used for realisation of the *n*th-order current TF (Minaei et al. 2006a). An *n*th order current TF can be expressed as

$$T(s) = \frac{I_{\mathrm{out}}}{I_{\mathrm{in}}} = \frac{a_n s^n + a_{n-1}s^{n-1} + \cdots\cdots\cdots + a_1 s + a_0}{s^n + b_{n-1}s^{n-1} + \cdots\cdots\cdots + b_1 s + b_0} \tag{3}$$

where I_{in} and I_{out} are the input and output currents, respectively. The signal flow-graph model for realising the TF $T(s)$ is shown in Figure 3. This may be easily verified using the well-known Mason gain formula.

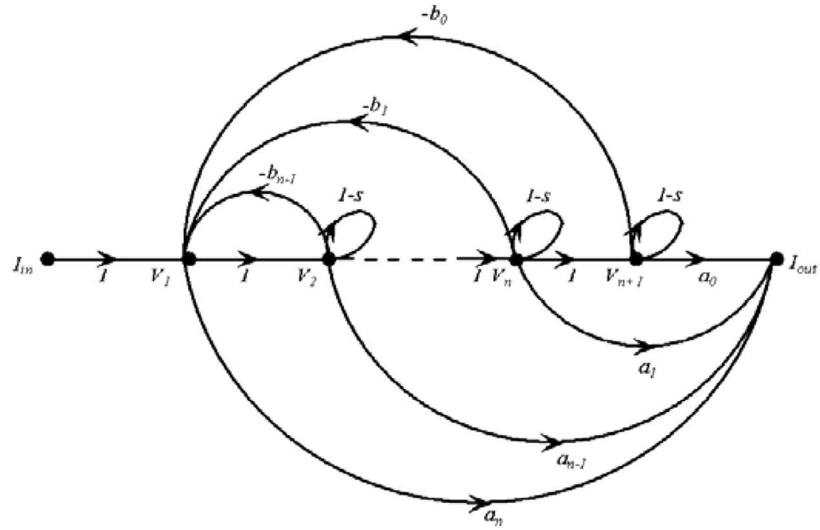

Figure 3. Signal flow-graph representing $T(s)$.

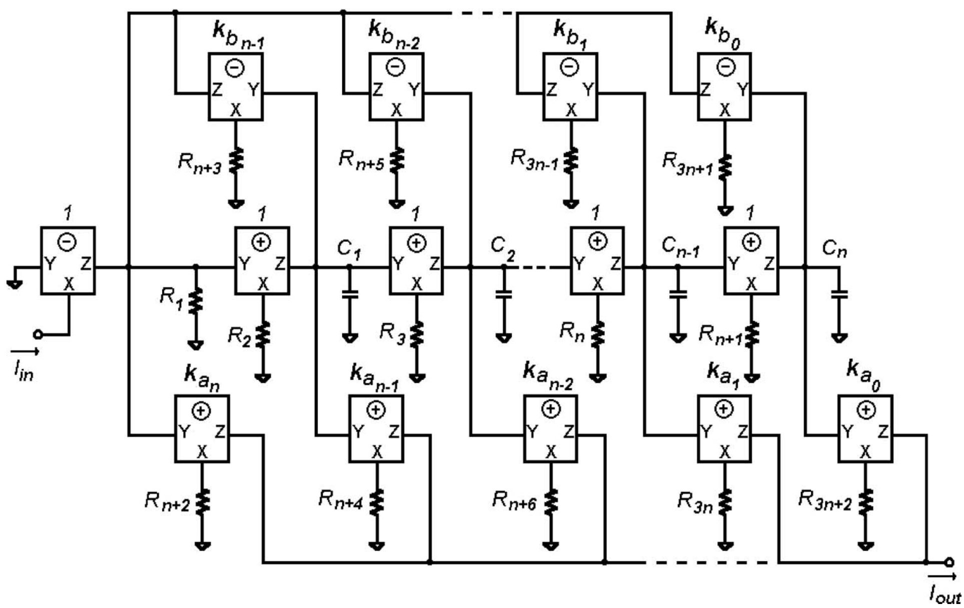

Figure 4. Implementation of the nth-order current TF using ECCII.

Using this signal flow-graph, the nth-order current TF $T(s)$ can be realised using positive and negative ECCIIs as shown in Figure 4. The circuit of Figure 4 includes $3n + 2$ ECCIIs, $3n + 2$ resistors and n grounded capacitors. All of the resistors and capacitors in the proposed circuit are grounded which is attractive for integrated circuit implementation. The current TF of the circuit can be found as

$$\frac{I_{\text{out}}}{I_{\text{in}}} = \left[k_{a_n}s^n\left(\frac{R_1}{R_{n+2}}\right) + k_{a_{n-1}}s^{n-1}\left(\frac{R_1}{R_{n+4}R_2C_1}\right) + k_{a_{n-2}}s^{n-2}\left(\frac{R_1}{R_{n+6}R_2R_3C_1C_2}\right) + .. + k_{a_0}\left(\frac{R_1}{R_{3n+2}(R_2..R_{n+1})(C_1..C_n)}\right)\right] \Bigg/ \left[s^n + k_{b_{n-1}}s^{n-1}\left(\frac{R_1}{R_{n+3}R_2C_1}\right) + k_{b_{n-2}}s^{n-2}\left(\frac{R_1}{R_{n+5}R_2R_3C_1C_2}\right) + ... + k_{b_0}\left(\frac{R_1}{R_{3n+1}(R_2.....R_{n+1})(C_1....C_n)}\right)\right] \quad (4)$$

The coefficients k_{ai} and k_{bj} ($i = 0 \ldots n$ and $j = 0 \ldots n - 1$) are the current gains of the ECCIIs, which can be controlled electronically. Each of the ECCIIs is used to adjust an individual coefficient in the current TF. It means that each coefficient can be tuned independently by adjusting the current gain of the relevant ECCII. This is the most important advantage of the proposed circuit compared with the conventional designs which makes it very attractive for analog designers.

For the realisation of an nth-order filter, $3n + 2$ active elements are necessary in general form which could be considered as a large element number. Note that this large number can be reduced for special realisation purposes such as low-pass (LP), high-pass (HP), band-pass (BP), band-stop (BS) filter functions by removing the unused sections depending on the aim of the design. The remaining part is necessary for the tuning of the filter parameters independently.

Second-order filter using ECCII

Figure 5 shows the proposed circuit which realises a second-order current TF. It can be considered as a filter with low-pass, high-pass and band-pass responses at high output impedances. The sum of the LP, HP and BP responses yields the circuit TF as

$$T(s) = \frac{I_{\text{out}}}{I_{\text{in}}} = \frac{I_{\text{HP}} + I_{\text{BP}} + I_{\text{LP}}}{I_{\text{in}}} = \frac{k_{a_2}\left(\frac{R_1}{R_4}\right)s^2 + k_{a_1}\left(\frac{R_1}{R_6R_2C_1}\right)s + k_{a_0}\left(\frac{R_1}{R_8R_2R_3C_1C_2}\right)}{s^2 + k_{b_1}\left(\frac{R_1}{R_5R_2C_1}\right)s + k_{b_0}\left(\frac{R_1}{R_7R_2R_3C_1C_2}\right)} \quad (5)$$

The ω_o and Q parameters of the filter are obtained as

$$\omega_0 = \sqrt{\frac{k_{b0}R_1}{R_7R_2R_3C_1C_2}} \quad (6)$$

and

$$Q = \frac{R_5}{k_{b1}}\sqrt{\frac{k_{b0}R_2C_1}{R_1R_7R_3C_2}} \quad (7)$$

It can be seen that the parameter ω_0 can be tuned electronically by adjusting k_{b0}. By keeping the value of k_{b0} constant and varying k_{b1}, the parameter Q can also be

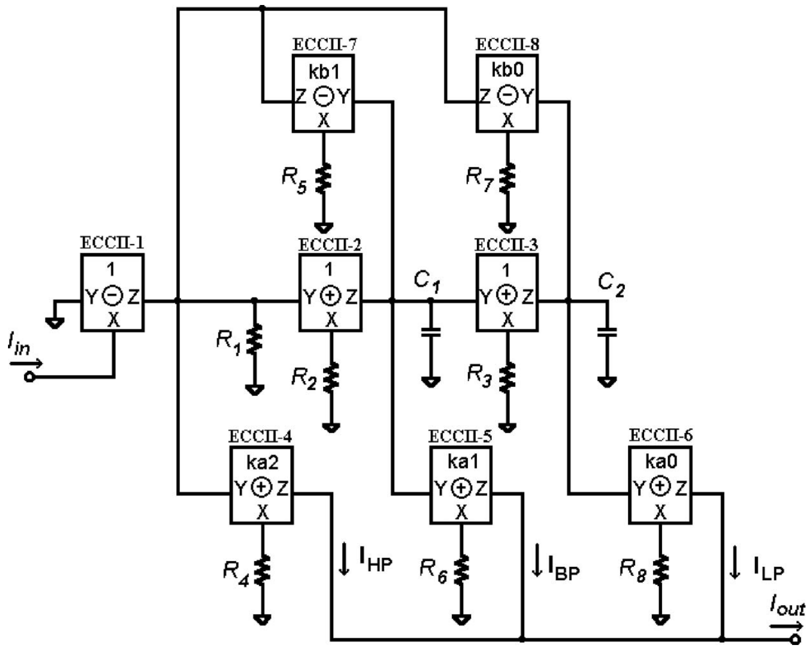

Figure 5. Second-order current-mode filter realisation.

tuned without disturbing the parameter ω_0. Also the gain factors of the HP, BP and LP responses can be tuned electronically by changing k_{a2}, k_{a1} and k_{ao}, respectively, without disturbing the parameters ω_0 and Q.

Sensitivity analysis of this filter gives:

$$S_{R_7}^{\omega_0} = S_{R_2}^{\omega_0} = S_{R_3}^{\omega_0} = S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -S_{k_{b0}}^{\omega_0} = -S_{R_1}^{\omega_0} = -\frac{1}{2}$$

$$S_{R_1}^{Q} = S_{R_7}^{Q} = S_{R_3}^{Q} = S_{C_2}^{Q} = -S_{k_{b0}}^{Q} = -S_{R_2}^{Q} = -S_{C_1}^{Q} = -\frac{1}{2}$$

$$S_{R_5}^{Q} = -S_{k_{b1}}^{Q} = 1$$

which are no more than unity in magnitude.

Simulation results and application example

The performance of the proposed ECCII-based filter topology is verified using SPICE simulation program. The MOS transistors are simulated using TSMC 0.35 μm CMOS process model parameters ($V_{\mathrm{THN}} = 0.62$ V, $V_{\mathrm{THP}} = -0.58$ V, $\mu_{\mathrm{N}} = 460.5$ cm^2/V-s, $\mu_{\mathrm{P}} = 100$ cm^2/V-s, $T_{\mathrm{OX}} = 10$ nm). The dimensions of the MOS transistors are listed in Table 1. The voltage supply used for the ECCII is ± 1.5 V. The biasing currents are selected as $I_{\mathrm{A}} = I_{\mathrm{B}} = 50$ μA which results in a current gain of unity for the ECCII. Also the biasing current $I_{\mathrm{C}} = 100$ μA and compensation capacitor $C_{\mathrm{C}} = 0.2$ pF are selected.

The second-order current-mode filter of Figure 5 is simulated. The passive elements have been selected as: $R_5 = R_6 = 5.65$ kΩ, $R_i = 8$ kΩ ($i = 1 \ldots 4, 7, 8$), $C_1 = C_2 = 20$ pF to obtain LP, BP and HP responses with a natural pole frequency of $f_o = 1$ MHz and a pole quality factor of $Q = 0.707$. The simulation and ideal responses of the filter are shown in Figure 6. By adjusting the biasing current I_B of the ECCIIs, the tunability of the gain, quality factor and natural pole frequency of the filter are tested. For example, different values of 25 μA, 50 μA and 100 μA are selected for the biasing current I_B which results in a LP response current gain coefficient (k_{a0}) of 0.5, 1 and 2, respectively. The frequency response of the LP filter for different values of k_{a0} is shown in Figure 7.

Table 1. Transistor dimensions of the ECCII circuit shown in Figure 2.

Transistor	W/L (μm)
MG1, MG3, MG5 MG23-26	21/0.7
MG2, MG4	7/0.7
MG6, MG8, MG16, MG18, MG27, MG28	28/0.7
MG17	4.9/0.7
MG7, MG9, MC10-MC18, MC21	35/0.7
MG10, MG12, MG14, MG19-MG22	10.5/1.4
MG11, MG13, MG15, MK6-MK8	28/1.4
MK1- MK5, MK9- MK11	14/1.4
MC1-MC9, MC19, MC20	14/0.7

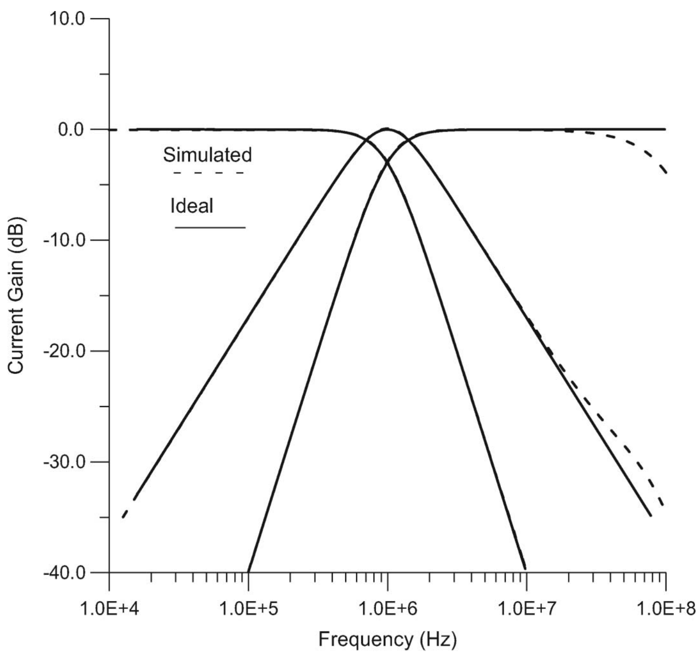

Figure 6. Simulated and ideal LP, BP, HP filter responses; $Q = 0.707$, $f_o = 995$ kHz $\approx$ 1 MHz, $R_5 = R_6 = 5.65$ kΩ, $R_i = 8$ kΩ (other resistance values), $C_i = 20$ pF, $k_i = 1$ (gain of the current conveyors).

Figure 8 shows the tunability of the quality factor (Q) of the BP response by changing k_{b1}. Different biasing currents $I_B = 25\ \mu A$, $50\ \mu A$ and $100\ \mu A$ are selected for the ECCII-5 and ECCII-7 with $R_5 = R_6 = 11.3\ k\Omega$ which result in $k_{a1} = k_{b1}$ 0.5, 1, and 2, and $Q = 2.828$, 1.414, 0.707, respectively.

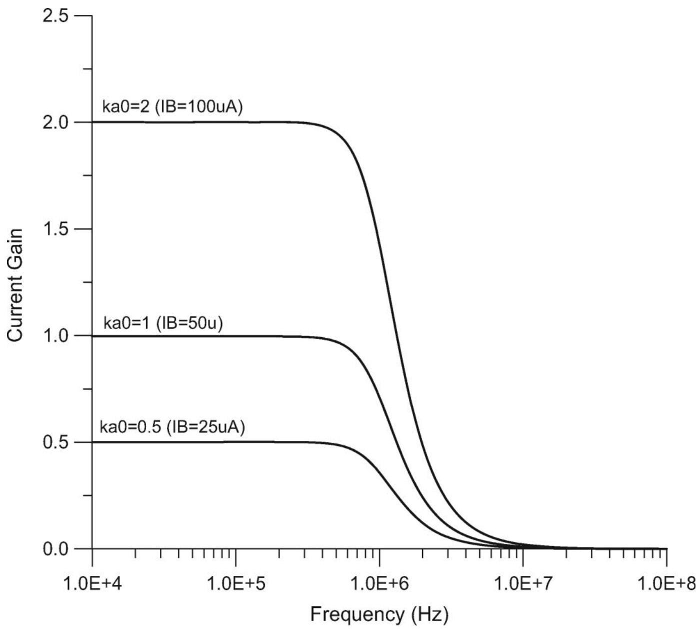

Figure 7. Tuning of the gain for LP response (gain = 0.5, 1, 2).

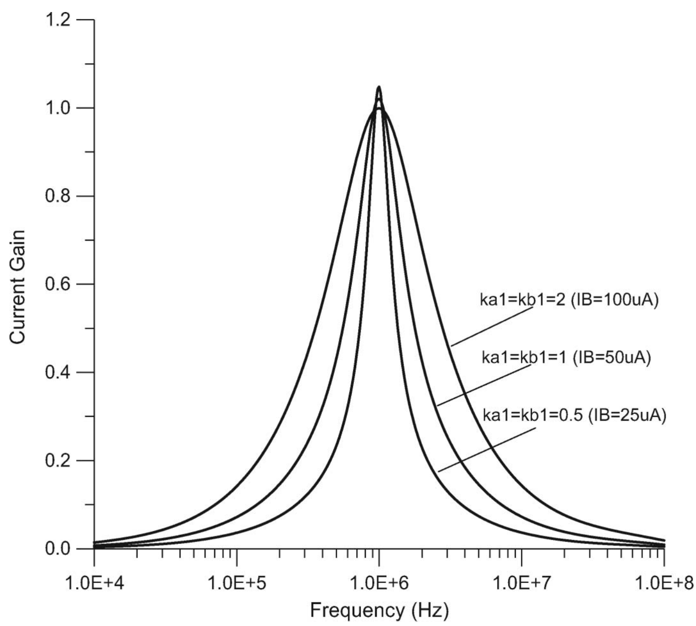

Figure 8. Tuning of the quality factor of BP response ($Q = 0.707$, 1.414, 2.828).

Finally, the tunability of the pole natural frequency of the BP response is tested by selecting different values for k_{b0}. Different biasing currents of $I_B = 25\ \mu A$, $50\ \mu A$ and $100\ \mu A$ are selected for the ECCII-8 which result in $k_{b0} = 0.5$, 1 and 2, and $f_o = 0.707$ MHz, 1 MHz, 1.41 MHz, respectively, as shown in Figure 9. It can be easily observed that the simulation results are in good agreement with the theoretical values.

In the following, a design example of a fourth-order video band filter is given to illustrate the possibilities in analog circuit design provided by the topology introduced. The TF of the filter is

$$H(s) = H\frac{s^2 + w_{Z1}^2}{s^2 + \frac{w_{P1}}{Q_{P1}}s + w_{P1}^2}\,\frac{w_{P2}^2}{s^2 + \frac{w_{P2}}{Q_{P2}}s + w_{P2}^2} \tag{8}$$

where $H = w_{P1}^2/w_{Z1}^2 \approx 2$, $f_{P1} = 3.46$ MHz, $Q_{P1} = 3.42$, $f_{Z1} = 4.83$ MHz, $f_{P2} = 2.65$ MHz, $Q_{P2} = 0.675$. This TF is realised by cascading an LP notch filter with an LP section. The filter is constructed by cascading of two sections illustrated in Figure 5 and choosing adequate biasing of ECCIIs. The element values are chosen as $R_5 = 2.7$ kΩ, $R_i = 4$ kΩ (other resistance values) $C_i = 15$ pF, $k_i = 1$ (gain of the current conveyors) for the LP section and $R_5 = 7.9$ kΩ, $R_4 = 4.6$ kΩ, $R_i = 2.3$ kΩ (other resistance values), $C_i = 20$ pF, $k_i = 1$ (gain of the current conveyors) for the LP notch section. Simulated filter frequency response is illustrated in Figure 10. It can be easily observed from Figure 10 that the filter response is in good agreement with the ideal frequency response. Large signal behaviour of the filter is investigated by observing the dependence of the output total harmonic distortion (THD) upon the input signal level. The result is illustrated in Figure 11 which shows that THD

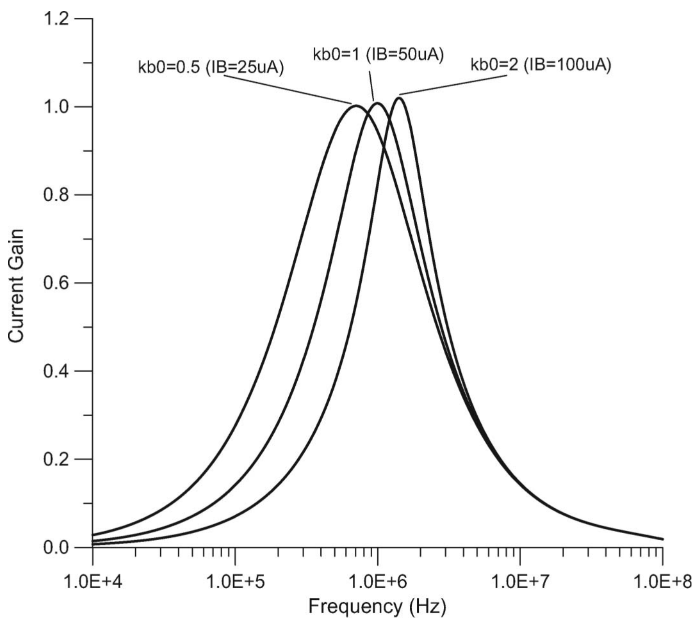

Figure 9. Tuning of the natural frequency of BP response ($f_o = 0.707$ MHz, 1 MHz, 1.41 MHz).

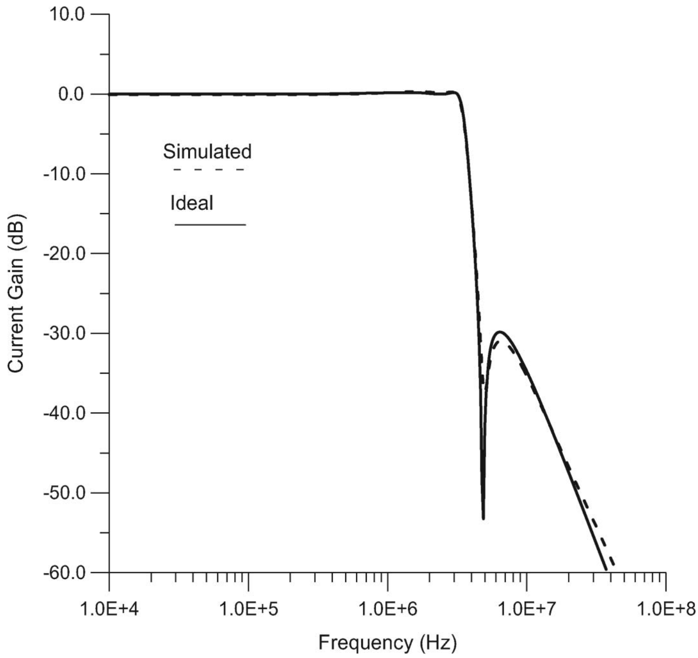

Figure 10. Simulated and ideal 4th order filter responses.

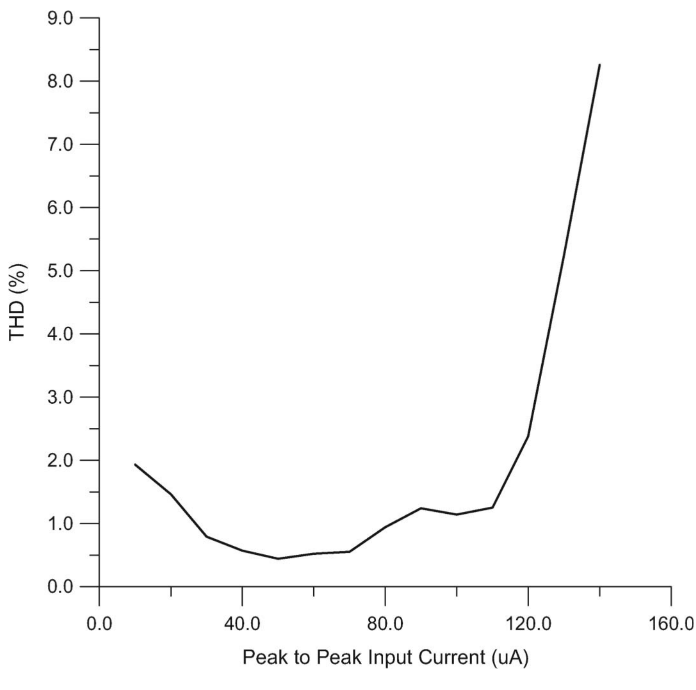

Figure 11. THD values of the filter versus input peak-to-peak current at 3 MHz frequency.

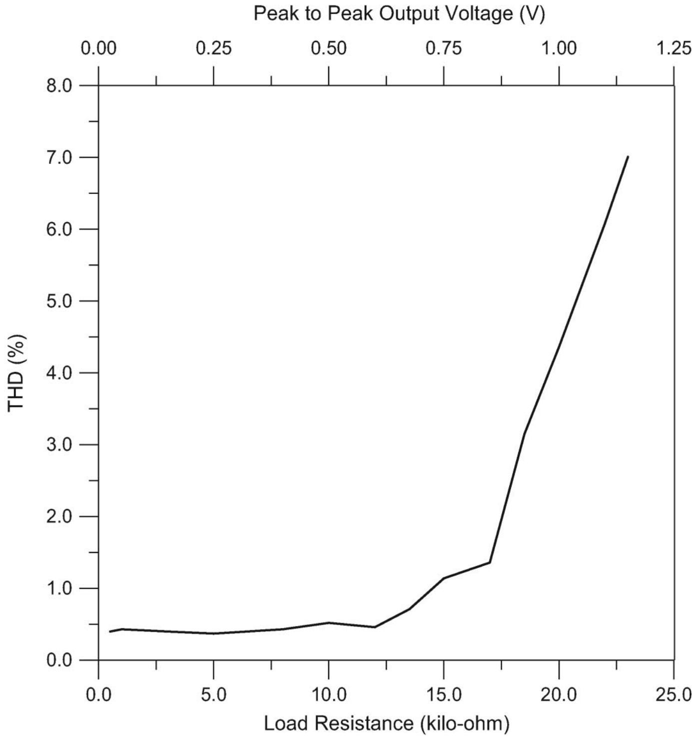

Figure 12. THD values of the filter versus output peak-to-peak voltage and load resistance for 50 μA peak-to-peak input current at 3 MHz frequency.

remains at reasonable levels (THD $< 2\%$) if the peak-to-peak input current level is lower than 120 μA. Figure 12 illustrates the dependence of THD on the load resistance and output peak-to-peak voltage for 50 μA peak-to-peak input current at 3 MHz frequency. The output voltage can be calculated as $V_O = I_{out} \times R_L$.

It can be observed that the THD remains lower than 1.5% for a load resistance of 17 kΩ which yields 0.85 V output voltage range.

Note that the TF of Equation (8) can be also realised directly as a fourth order elliptic filter by rearranging Equation (4) and choosing adequate biasing for ECCIIs. However, this causes some problems in adjusting the quality factors and pole frequencies of both sections if they are expressed in a combined form. Therefore, both sections are realised separately as second-order sections and the overall filter is constructed by cascading these two sections.

Conclusion

In this article, an nth-order current TF realisation using ECCIIs is presented. All of the coefficients in the TF can be adjusted independently. Moreover, all the passive elements are grounded, which is important in integrated circuit implementation. As an application, a fourth-order video band filter using two cascaded second-order filters is presented. The theoretical results are verified by SPICE simulations and shown to be in good agreement.

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