

GENERATION OF GROUNDED CAPACITOR ICCII-BASED BAND-PASS FILTERS

AHMED M. SOLIMAN

*Electronics and Communication Engineering Department,
Faculty of Engineering, Cairo University,
Giza 12613, Egypt
asoliman@ieee.org*

Revised 15 April 2007

A new current-mode band-pass filter using the inverting second-generation current conveyor (ICCI) is introduced. The circuit is generated from a frequency-dependent negative resistance (FDNR)-C circuit realized using ICCI+. It is observed that a voltage-mode band-pass filter using two CCII+ has similar transfer function to this current-mode filter. The adjoint network theorem is used to demonstrate the transformation between the two circuits. Two new voltage-mode grounded capacitor band-pass filters using two ICCI are also introduced. The first voltage-mode circuit is generated from the FDNR-C circuit and employs two opposite Z polarity ICCI. The second voltage-mode circuit is obtained from the first circuit by relocation of the input and a grounded terminal. Two new additional grounded capacitor and grounded resistor current-mode band-pass filters with independent control on the filter Q are also introduced. Spice simulation results with $0.35\ \mu\text{m}$ CMOS transistors model are included to demonstrate the practicality of the two ICCI– band-pass current-mode filter.

Keywords: Current conveyors; inverted current conveyors; band-pass filters.

1. Introduction

Thirty-seven years ago Sedra and Smith¹ introduced the second-generation current conveyor (CCII) which has attracted the attention of many researchers in the area of active circuits. Of course the CMOS technology was not ready at that time for the fabrication of this universal building block.

The inverting second-generation current conveyor (ICCI) was first introduced in Ref. 2 as a new block to be added to the current conveyor family.

The symbolic representation of the ICCI is shown in Fig. 1(a). The relation between terminal voltages and currents is given by²

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

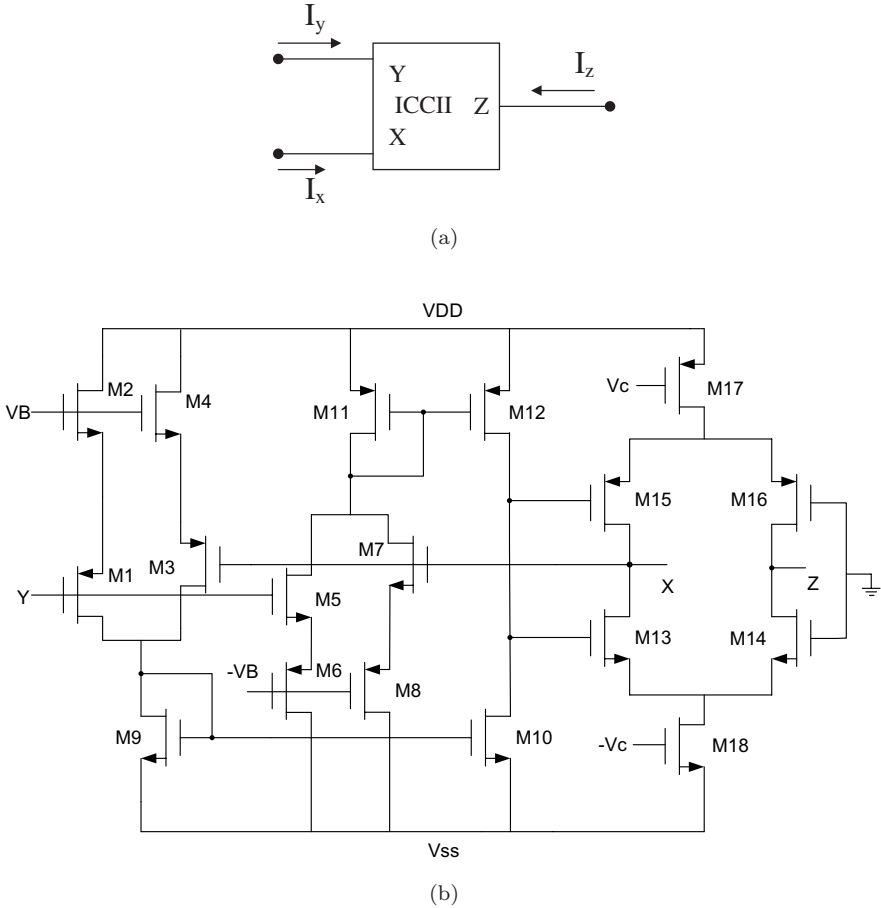


Fig. 1. (a) Symbol of the ICCII. (b) The CMOS realization of the ICCII- (Ref. 2).

The voltage at terminal X is the inversion of the voltage at terminal Y . The current at terminal Z follows the current at terminal X in magnitude. In Eq. (1), the ± 1 specifies the type of the current conveyor (ICCII+ or ICCII-). By convention, the positive sign is taken to mean that the current at the X and Z terminals are both flowing inwards to the conveyor.

The ICCII is considered to be a special case from the differential voltage current conveyor introduced in Ref. 3 with a single Y input only. This active element can be easily implemented with CMOS technology and Fig. 1(b) represents one realization of the ICCII-.²

The important advantage of the ICCII- is to obtain and design current-mode circuits from their voltage-mode counterparts using the adjoint network theorem.^{4,5} The class of circuits that are most suitable for the adjoint network theorem is the single-input single-output circuits.

In this paper, a new grounded capacitor FDNR-C circuit using a single ICCII+ is introduced. The proposed FDNR-C circuit is used as a basic building block in the generation of the current-mode band-pass filter and using two ICCII-. The same circuit will be generated from a well-known voltage-mode band-pass filter using the adjoint network theory. The FDNR-C circuit is also used to generate two new voltage-mode band-pass filters having similar transfer functions as the generated current-mode band-pass filter. Two additional new grounded capacitor and grounded resistor current-mode band-pass filters with independent control on the filter Q are also generated from the passive LRC circuit and the RCD-circuit. Spice simulation results will be included to support the theory.

2. The Generation of the Current-Mode Filter from Passive LRC Filter

Figure 2(a) represents the well-known current-mode passive LRC filter. It is possible to realize the parallel LR circuit using the ICCII+, the realization however will employ a floating capacitor, and therefore, Bruton transformation⁶ will be applied first to the LRC circuit resulting in the circuit shown in Fig. 2(b).

Figure 3 represents a grounded capacitor FDNR-C circuit using a single ICCII+. The magnitudes of C and D are given, respectively, by

$$C = C_1 + C_2, \tag{2}$$

$$D = C_1 C_2 R_2. \tag{3}$$

It is worth noting that applying the RC:CR transformation to the circuit in Fig. 3 results in a parallel LR circuit similar to the Ford-Girling op amp circuit⁷ which is also realizable using CCII-⁸ and used in several filter applications.^{9,10}

The generation method starts by using the circuit in Fig. 3 to replace the parallel C and D part in Fig. 2(b) resulting in the circuit of Fig. 4(a). Of course the current in R_1 remains as a low-pass; however, a current follower must be added to the circuit to utilize this current.

The transfer function of this low-pass current is given by

$$\frac{I_{LP}}{I_i} = \frac{1}{s^2 C_1 C_2 R_1 R_2 + s(C_1 + C_2)R_1 + 1}. \tag{4a}$$

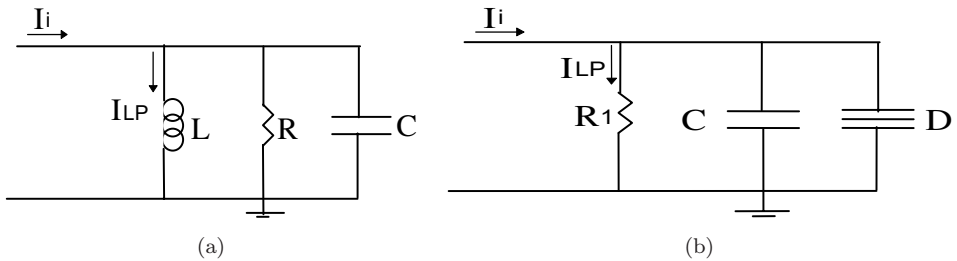


Fig. 2. (a) The LRC passive filter. (b) The RCD active filter obtained from the LRC filter.

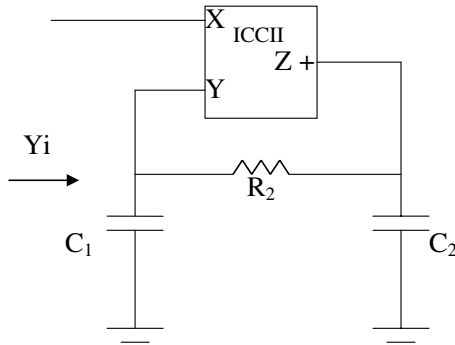
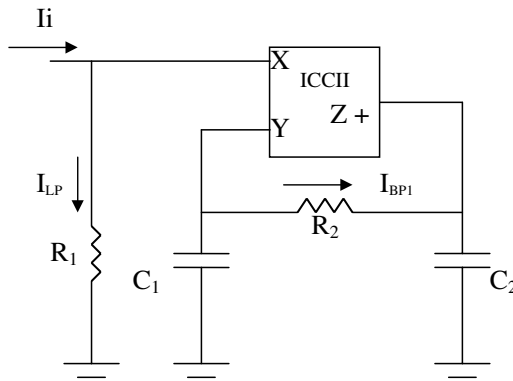
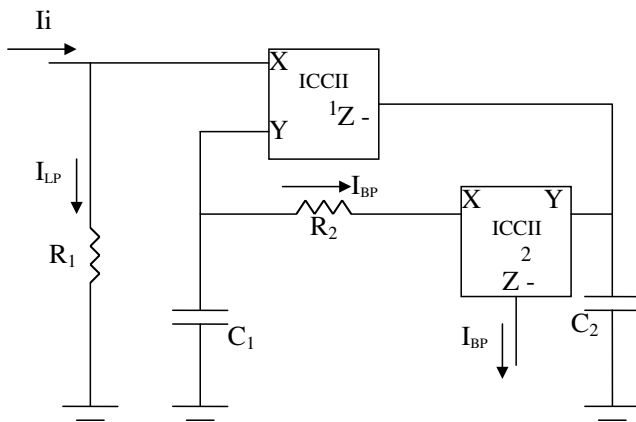


Fig. 3. FDNR-C circuit using a single ICCII+.



(a)



(b)

Fig. 4. (a) Single ICCII+ band-pass and low-pass filter. (b) The ICCII- grounded C current-mode band-pass filter.

Next, it is observed that the current in R_2 has a band-pass nature and the transfer function given by

$$\frac{I_{BP1}}{I_i} = \frac{sC_1R_1}{s^2C_1C_2R_1R_2 + s(C_1 + C_2)R_1 + 1}. \tag{4b}$$

To utilize this current an ICCII– is added in series with R_2 as shown in Fig. 4(b). In this case, however, to have a stable circuit the first ICCII+ is replaced by an ICCII–. This new current-mode band-pass filter employs two ICCII– and uses grounded capacitors. The band-pass current transfer function is given by

$$\frac{I_{BP}}{I_i} = \frac{sC_1R_1}{s^2C_1C_2R_1R_2 + sC_2R_1 + 1}. \tag{5}$$

Comparing the denominators of Eqs. (4b) and (5), it is seen that the addition of the second ICCII– serves not only to provide the band-pass current at terminal Z– but also to enhance the filter Q by reducing the coefficient of the s term.

2.1. Equal C design

For a specified ω_0 and Q the design equations based on equal C design results in a unity gain at the center frequency and in this case the design equations are given by

$$C_1 = C_2 = C, \tag{6}$$

$$R_1 = \frac{1}{Q\omega_0C}, \quad R_2 = \frac{Q}{\omega_0C}. \tag{7}$$

This design provides a high resistor ratio R_2/R_1 equal to Q^2 .

2.2. Equal RC design

To limit the resistor ratio to Q the recommended design is the equal RC design in this case and for a specified ω_0 and Q the design equations, are given by

$$C_1 = QC_2, \tag{8}$$

$$R_1 = \frac{1}{\omega_0C_1}, \quad R_2 = \frac{1}{\omega_0C_2}. \tag{9}$$

This design results in a gain at the center frequency equals to Q .

3. The Generation of the Current-Mode Band-Pass Filter Using the Adjoint Network Theorem

The proposed current-mode band-pass filter has similar transfer function equation as in the voltage-mode band-pass filter given in Ref. 11. The filter given in Ref. 11 is classified as insensitive filter and employs two CCII+ as shown in Fig. 5. This observation of the similarity of the two transfer functions, results in trying to know how they can be generated from each other. Since the proposed filter realizes a current transfer band-pass response and the filter in Ref. 11 realizes a voltage transfer

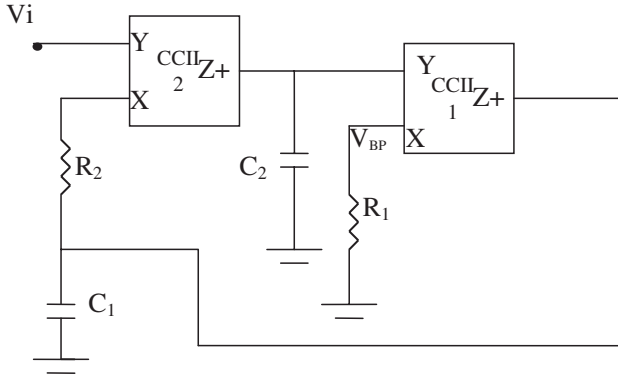


Fig. 5. The grounded C voltage-mode CCII+ band-pass filter (Ref. 11).

band-pass response this leads directly to consider the adjoint network theorem^{4,5} as a vehicle to illustrate the generation of one from the other. It is found that the proposed filter can be obtained from Fig. 5 using the adjoint network theorem as explained next. In Ref. 11 the band-pass voltage output was defined at the Y terminal of the CCII+ given number 1 here. Due to the voltage following action of the CCII+ the output will be taken at port X of the same CCII+. Injecting the input current at this port and replacing the CCII+ by its singular model consisting of a nullator and a current mirror.² Applying the adjoint network theorem and replacing the nullator by a norator and the current mirror by a voltage mirror² the circuit in Fig. 6 is obtained with the output current at the same node of the original input voltage. It is easily seen that the circuit in Fig. 6 is identical to that obtained from the passive filter and shown here in Fig. 4(b). On the other hand, if the adjoint network theorem is applied to the circuit shown in Fig. 4(b) the voltage-mode circuit in Fig. 5 and using two-CCII+ is obtained. Therefore, this paper also

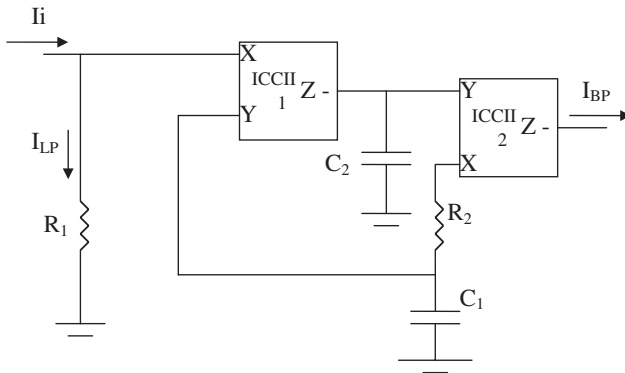


Fig. 6. The ICCII- grounded C current-mode band-pass obtained from Fig. 5 using adjoint network theorem.

serves as a method of generating the circuit of Fig. 5 from the passive LRC filter through a sequence of transformations. It is worth noting that in Ref. 11 nothing was mentioned about the origin of the two CCII+ voltage-mode band-pass filter in Fig. 5.

4. Generation of Voltage-Mode Band-Pass Filters Using ICCII

The FDNR-C circuit in Fig. 3 is used here to generate new voltage-mode band-pass filters. Adding the resistor R_1 at port X of the ICCII+ of Fig. 3 and injecting V_i at the other terminal of R_1 results in a band-pass current flowing in R_2 , to convert this current to a band-pass voltage a second ICCII is added to the circuit as shown in Fig. 7(a). The voltage transfer function is given by

$$\frac{V_{BP}}{V_i} = \frac{-sC_1R_2}{s^2C_1C_2R_1R_2 + sC_1R_1 + 1} \tag{10}$$

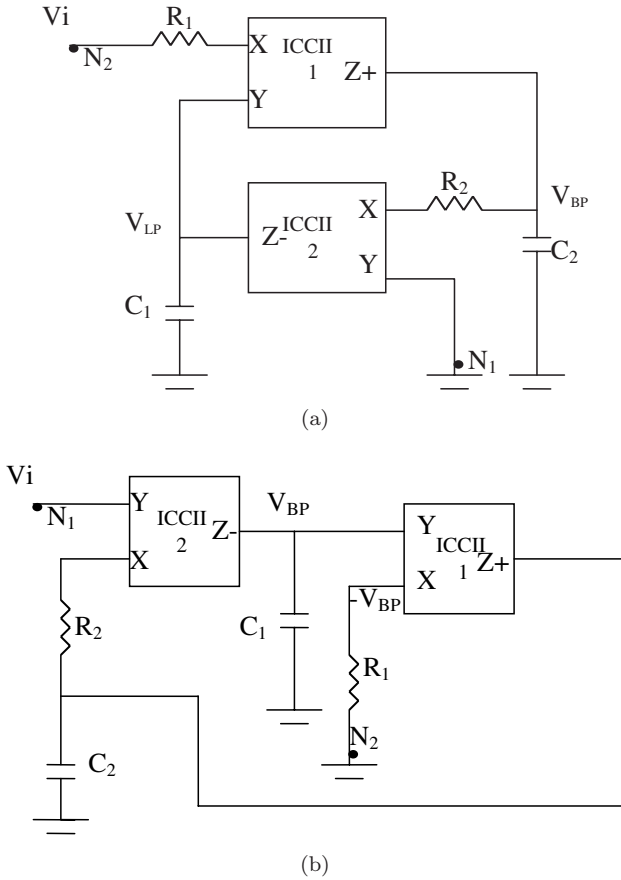


Fig. 7. (a) A new grounded C voltage-mode band-pass filter using two opposite polarity ICCII and obtained from the FDNR-C circuit in Fig. 3. (b) A grounded C voltage-mode band-pass filter using two opposite polarity ICCII obtained from (a).

For a specified ω_0 and Q the design equations (Equal RC design), are given by

$$C_2 = QC_1, \tag{11}$$

$$R_1 = \frac{1}{\omega_0 C_1}, \quad R_2 = \frac{1}{\omega_0 C_2}. \tag{12}$$

The circuit provides also two opposite polarity low-pass responses at both X and Y of the ICCII+ terminals.

This circuit has finite input impedance; however, it is of interest to see how it can be converted to a high input impedance band-pass filter. Applying the input V_i at node N_1 and grounding node N_2 results in the circuit shown in Fig. 7(b). This circuit provides noninverting and inverting band-pass responses as shown in Fig. 7(b). The voltage transfer function is given by

$$\frac{V_{BP}}{V_i} = \frac{sC_2R_1}{s^2C_1C_2R_1R_2 + sC_1R_1 + 1}. \tag{13}$$

The design equations are the same as given by Eqs. (11) and (12). It is worth noting that this circuit has the same topology as the CCII+ circuit in Fig. 5 except for the use of ICCII+ and ICCII- instead of the two CCII+ and the interchange of C_1 and C_2 . It should be noted that if the adjoint network theorem is applied to the circuit in Fig. 7(b), a new current-mode band-pass filter different from that of Fig. 6 is obtained, which employs a CCII+ and an ICCII+ as shown in Fig. 8. It is worth noting that the adjoint of the ICCII- is a CCII+ and the adjoint of the ICCII+ is also an ICCII+.² Of course the CCII+ in Fig. 8 can be replaced by a CCII- to have a noninverting band-pass response.

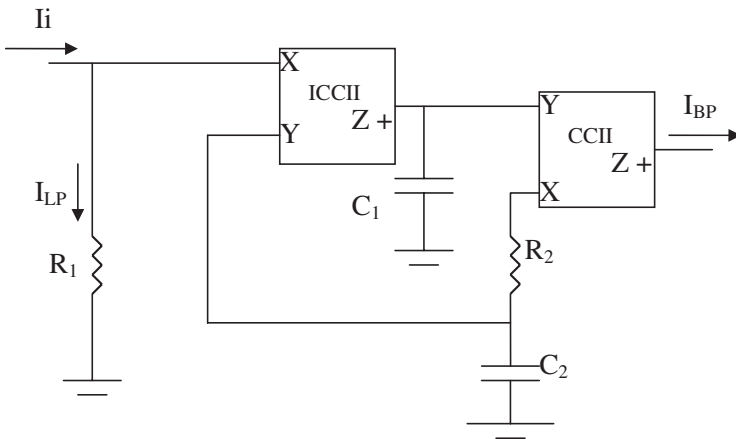


Fig. 8. New current-mode band-pass using ICCII+ and CCII+ and obtained from Fig. 7(b) using adjoint network theorem.

5. Current-Mode Band-Pass Filters with Grounded Passive Elements

All the circuits reported in previous sections employ the minimum number of passive components namely two resistors plus two capacitors, thus they cannot achieve independent control on the filter Q factor. In this section, a new grounded resistor and grounded capacitor current-mode band-pass filters are given. The first two circuits are shown in Figs. 9(a) and 9(b) and they represent the new current-mode noninverting band-pass and inverting band-pass, respectively. They are generated from Fig. 2(a) by replacing the grounded inductor by the gyrator circuit to the right of R and C_1 and port 2 of the gyrator is terminated by C_2 . The transfer function is given by

$$\frac{I_{BP}}{I_i} = \frac{sC_2R_2}{s^2C_1C_2R_1R_2 + \frac{sC_2R_1R_2}{R} + 1} \quad (14)$$

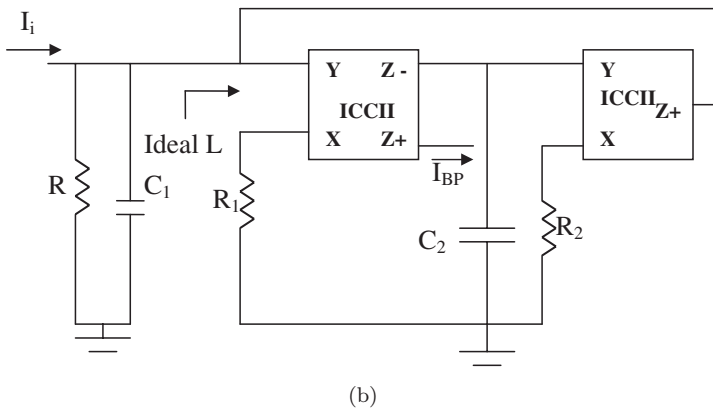
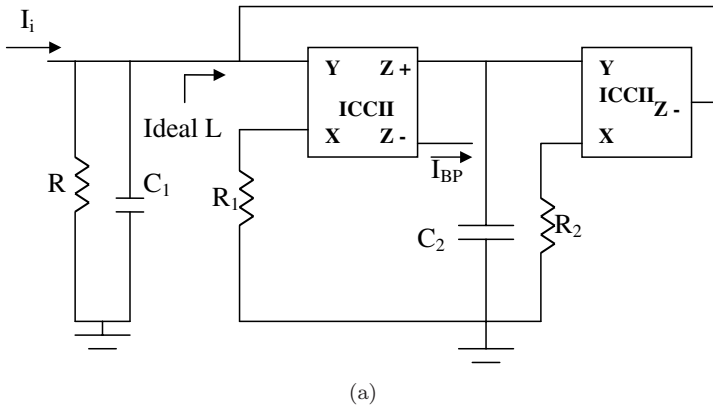


Fig. 9. (a) Current-mode noninverting band-pass filter with excitation at port Y. (b) Current-mode inverting band-pass filter with excitation at port Y.

For a specified ω_0 and Q the design equations are given by
 Taking; $C_1 = C_2 = C$

$$R_1 = R_2 = \frac{1}{\omega_0 C_1}, \quad R = QR_1. \tag{15}$$

It is seen that the resistor R controls Q of the filter without affecting ω_0 . The magnitude of the gain at the center frequency equals to Q .

Figure 9(b) represents the inverting band-pass filter with the same design equations as above. If the second ICCII is replaced by a two output ICCII then the second output can be used to deliver a low-pass output current.

It is worth noting that the current-mode band-pass filter reported in Ref. 12 uses the CCII to realize an ideal inductor¹³ based on a gyrator which uses the X terminals of the CCII as its two ports. Due to the nonzero R_x of the CCII it is preferable to use the Y terminals of the gyrator as its two ports as given in Ref. 1.

The next two circuits given in Fig. 10 are based on the active circuit in Fig. 2(b), that is, the active circuit to the right of R_1 and C represents an ideal FDNR realized

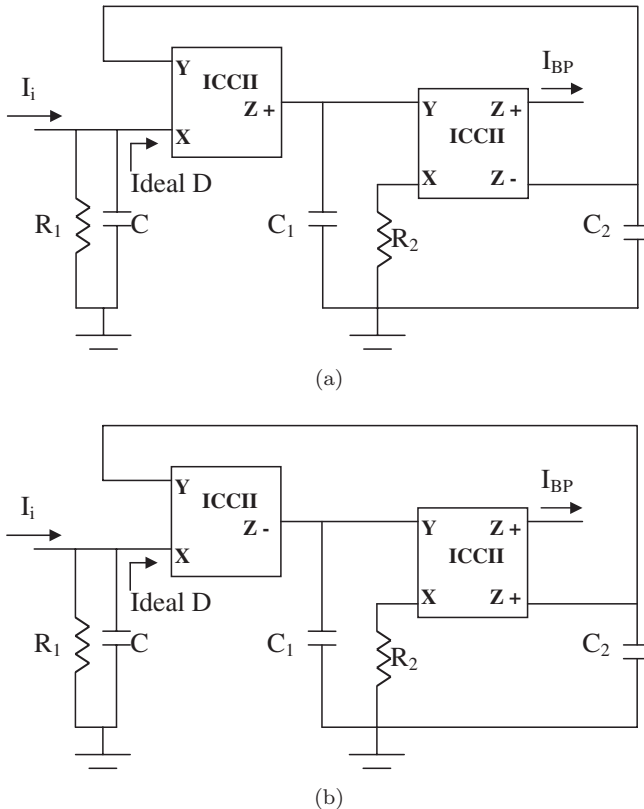


Fig. 10. (a) Current-mode noninverting band-pass filter with excitation at port X . (b) Current-mode inverting band-pass filter with excitation at port X .

using two ICCII. The current transfer function is given by

$$\frac{I_{BP}}{I_i} = \frac{sC_2R_1}{s^2C_1C_2R_1R_2 + sCR_1 + 1}. \tag{16}$$

For a specified ω_0 and Q the design equations are given by Taking; $C_1 = C_2$

$$R_1 = R_2 = \frac{1}{\omega_0 C_1}, \quad C = \frac{C_1}{Q}. \tag{17}$$

The magnitude of the gain at the center frequency equals to Q as in the circuits in Fig. 9. It should be noted that the circuits in Fig. 10 are noncanonic as they employ three capacitors. If the first ICCII is replaced by a two output ICCII then the second output can be used to deliver a high-pass output current. Of course the current in R_1 is of a lowpass nature, and to use this current a current follower will be necessary. In this case, the circuit will be a universal current-mode filter and notch and all-pass responses can be easily obtained by adding the proper currents.

6. Spice Simulation Results

Spice simulations with $0.35\mu\text{m}$ transistors model have been carried out for the circuit in Fig. 4(b) using the ICCII– shown in Fig. 1(b) and biased with $\pm 1.5\text{V}$.

The transistor aspect ratios are given in Table 1, and the ICCII– properties are given in Table 2.

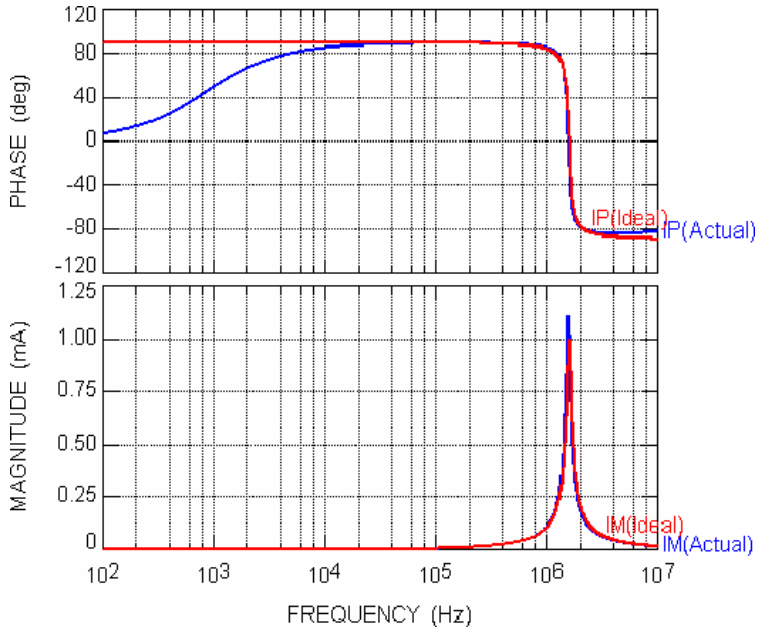
First, the band-pass filter in Fig. 4(b) is designed for $\omega_0 = 10\text{Mrad/s}$ and $Q = 10$, by taking equal C design with $C_1 = C_2 = 20\text{pF}$, $R_1 = 0.5\text{k}\Omega$ and $R_2 = 50\text{k}\Omega$, and using input current source of 1mA . Figure 11(a) represents the

Table 1. Transistor aspect ratios of the ICCII– shown in Fig. 1(b).

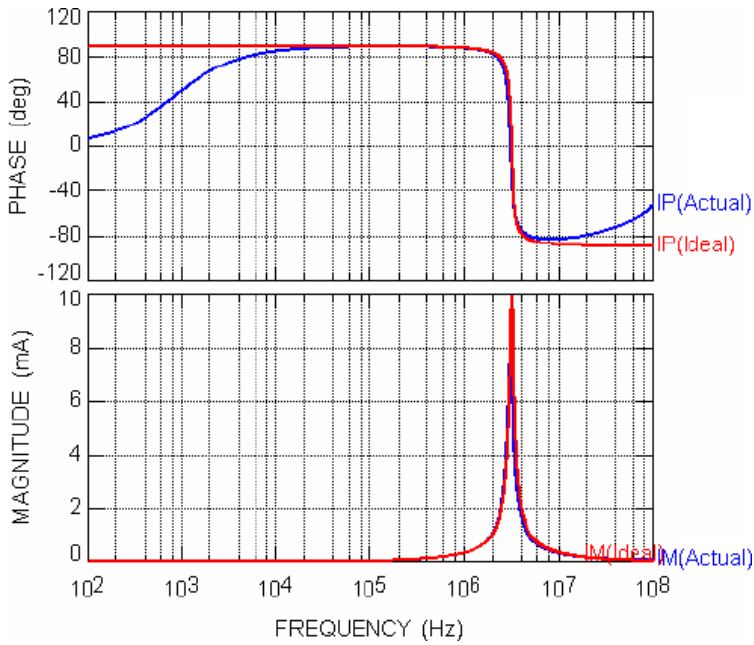
| Transistor | $W (\mu\text{m})/L (\mu\text{m})$ |
|--------------------------------|-----------------------------------|
| M1, M2, M3, M4, M5, M6, M7, M8 | 35/1.05 |
| M9, M10 | 8.75/1.05 |
| M11, M12 | 26.25/1.05 |
| M13, M14 | 17.5/0.35 |
| M15, M16 | 35/0.35 |
| M17 | 57.75/1.05 |
| M18 | 27.65/1.05 |

Table 2. Circuit parameters of the ICCII– shown in Fig. 1(b).

| Parameters | Units | ICCII– |
|--|---------------|---------------|
| Input voltage range | V | – 0.8 to 0.56 |
| Voltage offset | mV | 0.907 |
| 3 dB bandwidth of open circuit voltage transfer gain | MHz | 116 |
| Input current range | μA | – 300 to 300 |
| Current offset | μA | 0.3 |
| 3 dB bandwidth of current transfer gain | MHz | 860 |
| R_x | Ω | 7.6 |
| Power consumption | m-W | 1 |



(a)



(b)

Fig. 11. Spice simulation results of the current-mode band-pass filter Fig. 4(b) using (a) equal C design and (b) equal RC design.

magnitude and phase responses. It should be noted that the gain at the center frequency is slightly higher than the ideal value of unity due to the stray capacitances added to C_1 and C_2 . The center frequency, however, is very close to its theoretical value.

The band-pass filter in Fig. 4(b) is also designed for $\omega_0 = 20$ Mrad/s and $Q = 10$, using the equal RC design and taking $R_1 = 2.5$ k Ω and $R_2 = 25$ k Ω , $C_1 = 20$ pF and $C_2 = 2$ pF, and using input current source of 1 mA. Figure 11(b) represents the magnitude and phase responses. The results are very close to the theoretical expected results, except that the gain at the center frequency is slightly lower than the ideal value of 10 (equals to Q).

7. Conclusions

In this paper, a new FDNR-C circuit using the ICCII+ is introduced. The circuit is canonic and it uses two grounded capacitors. This circuit is used to realize a new current-mode band-pass filter as shown in Fig. 4(a). A second ICCII- is added to the circuit resulting in an attractive current-mode band-pass filter as given in Fig. 4(b). That is the current-mode band-pass filter in Fig. 4(b) is generated from the passive RLC filter shown in Fig. 2(a). It is observed that a voltage-mode band-pass filter¹¹ using two CCII+ has similar transfer function to that of the current-mode filter. The adjoint network theorem is used to show the transformation between the two circuits. Therefore, this paper also serves as a method of generating the well-known voltage-mode band-pass circuit in Fig. 5¹¹ from the passive LRC filter shown in Fig. 2(a). Thus a generation method for the CCII+ band-pass circuit given in Ref. 11 from passive LRC filter through successive generation steps is given. Spice simulation results are included for equal C and for equal RC designs to demonstrate the practicality of the proposed current-mode band-pass filter. It is recommended to use equal RC design which results in a resistor spread equal to Q . The simulation results are in good agreement with the theoretical expected results.

Two additional grounded R and grounded C current-mode band-pass filters generated from the passive LRC circuit in Fig. 2(a) and the active RCD circuit in Fig. 2(b) are also given. These circuits have the advantage of independent control on the filter Q . These circuits, however, require a single output ICCII and a two output ICCII to deliver the band-pass current. For perfect operation of these circuits it is recommended to use an additional current follower as an input stage to achieve the very low input impedance as is desirable from a current-mode filter.

Acknowledgment

The author thanks the reviewers for the useful comments.

References

1. A. S. Sedra and K. C. Smith, A second-generation current conveyor and its applications, *IEEE Trans. Circuit Theor.* **132** (1970) 132–134.

2. I. A. Awad and A. M. Soliman, Inverting second-generation current conveyors: The missing building blocks, CMOS realizations and applications, *Int. J. Electron.* **86** (1999) 413–432.
3. H. O. Elwan and A. M. Soliman, A novel CMOS differential voltage current conveyor and its applications, *IEE Proc. Circuits Dev. Syst.* **144** (1997) 195–200.
4. A. Carlosena and G. S. Moschytz, Nullators and norators in voltage to current mode transformations, *Int. J. Circuit Theor. Appl.* **21** (1993) 421–424.
5. G. W. Roberts and A. S. Sedra, All current-mode selective circuits, *Electron. Lett.* **25** (1989) 759–761.
6. L. T. Bruton, Network transfer functions using the concept of frequency dependent negative resistance, *IEEE Trans. Circuit Theor.* **14** (1969) 406–408.
7. R. L. Ford and F. E. J. Girling, Active filters and oscillators using simulated inductance, *Electron. Lett.* **2** (1966) 52.
8. A. M. Soliman, Ford–Girling equivalent circuit using CCII, *Electron. Lett.* **14** (1978) 721–722.
9. A. M. Soliman, Generation of current conveyor based low-pass filters from passive RLC filter, *J. Franklin Inst.* **335** (1998) 1283–1297.
10. A. M. Soliman, Generation of CCII and CFOA filters from passive RLC filters, *Int. J. Electron.* **85** (1998) 293–312.
11. A. Fabre, F. Dayoub, I. Duruisseau and M. Kamoun, High input impedance insensitive second order filters implemented from current conveyors, *IEEE Trans. Circuits Syst.* **41** (1994) 918–921.
12. H. O. Elwan and A. M. Soliman, A novel CMOS current conveyor realization with an electronically tunable current mode filter suitable for VLSI, *IEEE Trans. Circuits Syst.* **43** (1996) 663–670.
13. P. V. A. Mohan, Grounded capacitor based grounded and floating inductance simulation using current conveyors, *Electron. Lett.* **34** (1998) 1037–1038.