Voltage Mode-to-Current Mode Transformation

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***Abstract*— This paper proposes a procedure for converting a class of Op Amp-, FTFN-, CC- and CFA-based voltage mode circuits to corresponding current mode circuits without requiring any additional circuit elements and finally from Op Amp-based voltage mode circuits to any of the FTFN, CC and CFA current mode circuits. The latter circuits perform better at high frequency than the former ones. The validity of the transformation has been checked on simulated circuits with PSPICE.**

Keywords— Voltage mode, Current mode, Transformation, Current feedback amplifier, Current conveyor, Four terminal floating nullor

I. Introduction

Current-mode (CM) filters are attractive because of their wider bandwidth, higher slew rate, wider dynamic range and lower power consumption compared to voltage-mode (VM) counterparts [1]. However, a large number of op-amp (OA)-based VM circuits with excellent performance and their elegant realization procedures were put forward in the past [2, 3]. It is, therefore, worthwhile to convert them into CM circuits. FTFN (Four terminal floating nullor) [4-10], CC (current conveyor) [11-14] and CFA (Current Feedback Amplifier) [15-22] based CM circuits have received considerable attention in many filtering and signal processing applications, particularly, the CFA-based circuits are attractive due to the high slew rate and bandwidth independent of closed loop gain. In this paper, FTFN- CC- and CFA-based CM circuits are obtained by transforming a class of OA-based VM circuits. Obviously, one type of circuit can then be converted into the other type through the proposed transformation. Similar attempts were made in the past to convert OTA-C (operational trans-conductance amplifier) circuits into CFA-based *RC* circuits [23] and from SAB (single amplifier biquad) circuit to current amplifier based biquad [24].

II. Proposed VM-To-CM Transformation Method

Let us examine the two circuits shown in Fig. 1 where N_a is the active network. Simpler circuits are taken for the sake of convenience of analysis and more general circuits will be taken up in the next section. Analysis of the circuits shown in Fig. 1(a) and (b), respectively, lead to the following relations.

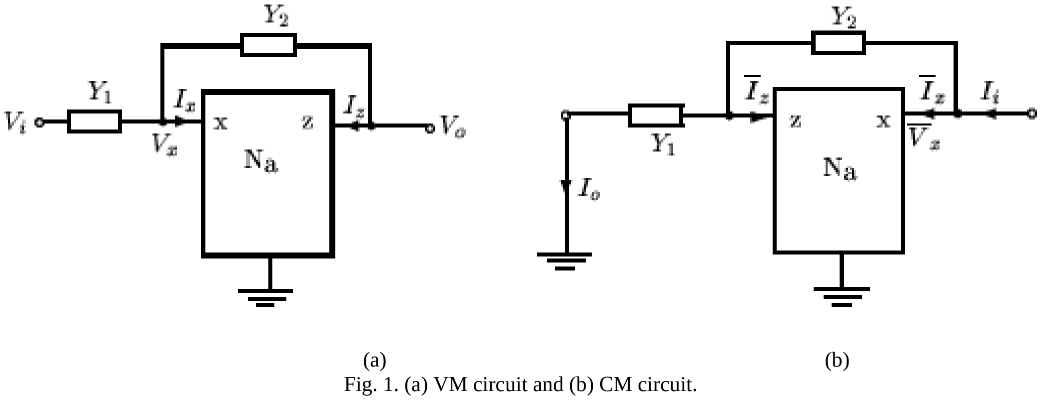


Fig. 1. (a) VM circuit and (b) CM circuit.

$$\frac{V_o}{V_i} = -\frac{Y_1}{Y_2} + \frac{V_x}{V_i}\left(1+\frac{Y_1}{Y_2}\right) + \frac{I_x}{V_i Y_2} \tag{1}$$

$$\frac{I_o}{I_i} = -\frac{Y_1}{Y_2} + \frac{\bar{V}_x Y_1}{I_i} + \frac{\bar{I}_x}{I_i Y_2} \tag{2}$$

where V_x [$\overline{V_x}$] and I_x [$\overline{I_x}$] are the voltage and current at terminal x in Fig. 1(a) [(b)]. Note that (1) and (2) are independent of I_z and $\overline{I_z}$, respectively. Thus, it is immaterial, whether there is a flow of I_z and [$\overline{I_z}$] in the z terminal of the active device or not. The two transfer functions will be the same, if

$$T(s) = \frac{V_o}{V_i} = \frac{I_o}{I_i} \tag{3}$$

which requires that

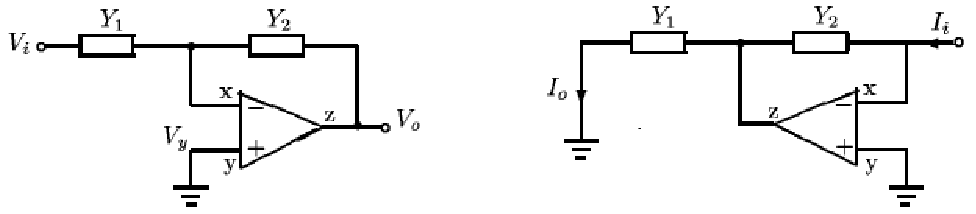
$$\frac{V_X}{V_i}\left(1+\frac{Y_1}{Y_2}\right)+\frac{I_X}{V_i Y_2} = \frac{\overline{V_X}Y_1}{I_i}+\frac{\overline{I_X}Y_1}{I_i Y_2}. \tag{4}$$

This can be satisfied under the following 3 cases.

Case A

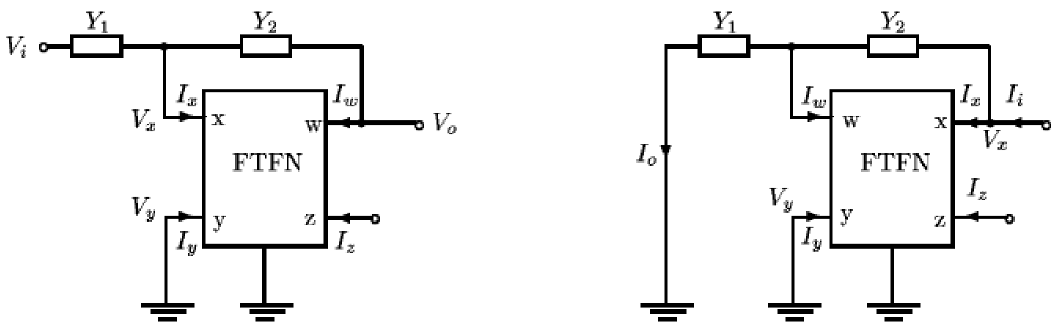
$$V_X = \overline{V_X} = 0,\ I_X = \overline{I_X} = 0. \tag{5}$$

These terminal characteristics are satisfied when the active network N_a is an Op Amp, $V_x = V_y, I_x = I_y = 0$, an FFTN, $V_x = V_y, I_x = I_y = 0, I_z = \pm I_w$ or a CCII±, $V_x = V_y, I_y = 0, I_z = \pm I_x$ as shown in Figs. 2, 3 and 4, respectively, wherein terminal x (y) is maintained at virtual ground by making V_y (V_x) = 0. For these circuits



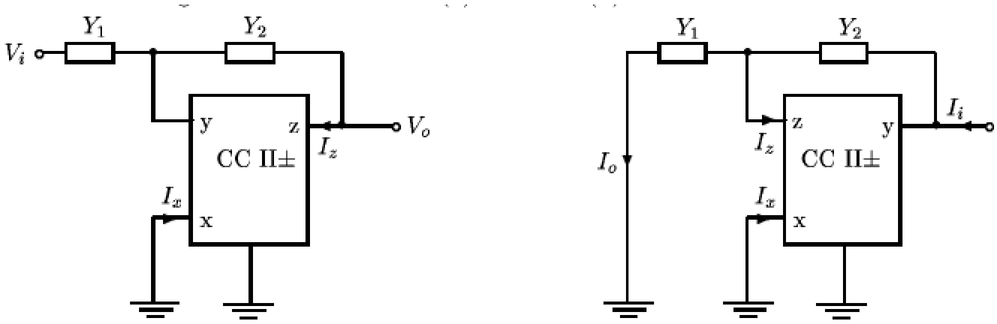
(a) (b)

Fig. 2. OA-based (a) VM circuit and (b) CM circuit.



(a) (b)

Fig. 3. FTFN-based (a) VM circuit and (b) CM circuit.



(a) (b)

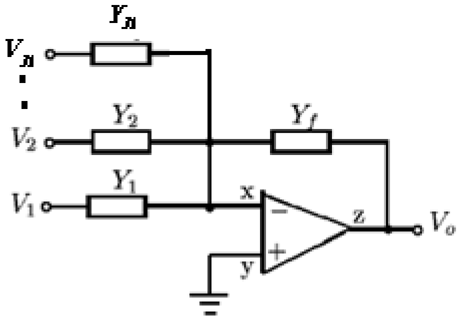
Fig. 4. CCII-based (a) VM circuit and (b) CM circuit.

$$T(s) = \frac{V_o}{V_i} = \frac{I_o}{I_i} = -\frac{Y_1}{Y_2}. \tag{6}$$

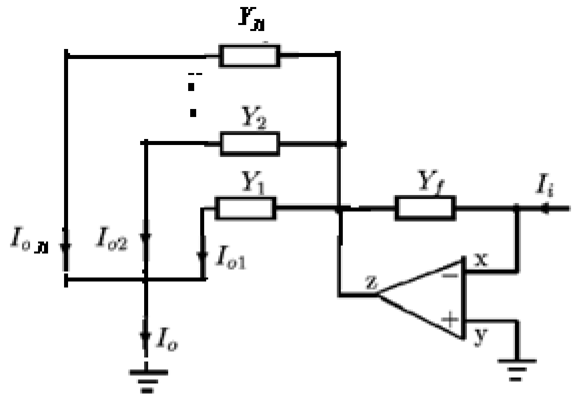
From these figures, we see that the VM circuit can be converted into the CM circuit by interchanging the terminals x and z in case of OA, the terminals x and w in case of FTFN, the terminals y and z in case of CCII, and replacing the input-output sources. Connections of passive elements remain unchanged.

Let us consider a multi-input ($V_1, V_2, \ldots, V_n$) VM circuit shown in Fig. 5(a) and its transformed multi-output $I_{o1}, I_{o2}, \ldots, I_{on}$ circuit shown in Fig. 5(b). The output of the VM circuit is given as

$$V_o = -\sum_{i=1}^{n} \frac{Y_i}{Y_f} V_i . \tag{7}$$



(a)



(b)

Fig. 5. OA-based (a) multi-input VM circuit and (b) multi-output CM circuit.

The n current outputs of the CM circuit are given as

$$I_{oi} = -\frac{Y_i}{Y_f} I_i , \quad i = 1, 2, \cdots, n. \tag{8}$$

These circuits can be used as the basic building blocks for realizing more complex functions.

Example 1: Consider the Lovering's circuit [25] shown in Fig. 6(a). Sub-networks A and B can be identified as the OA based multi-input blocks.

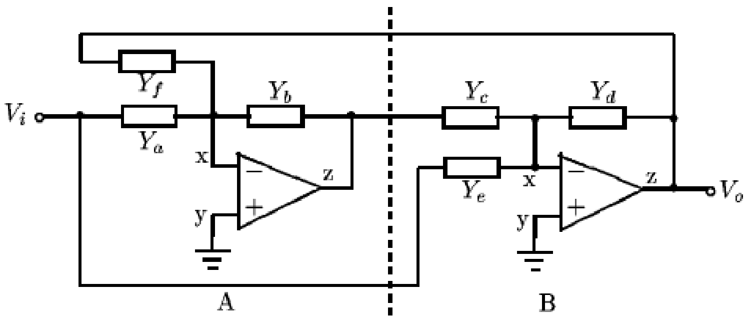
Equation (7) is used for each building block and then solved for $T(s) = \frac{V_o}{V_i}$ to yield

$$T(s) = \frac{V_o}{V_i} = \frac{I_o}{I_i} = \frac{Y_a Y_c - Y_b Y_e}{Y_b Y_d - Y_c Y_f}. \tag{9}$$

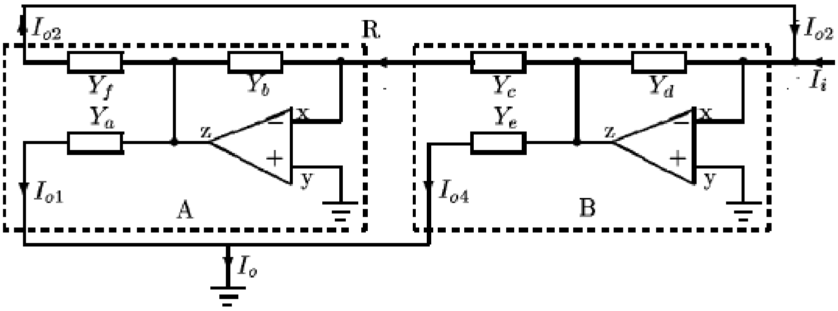
A corresponding circuit using the multi-output CM blocks is shown in Fig. 6(b). Equation (8) is used for each building block in Fig. 6(b) and solved for $T(s) = \frac{I_o}{I_i}$ where $I_o = I_{o1} + I_{o4}$.

The procedure can be extended for converting VM circuits with *n* OAs (each with the non-inverting terminal grounded) into OA based CM circuits by interchanging x and z terminals of each OA and replacing the input-output sources.

The above procedure can be carried forward to VM circuits with *n* FTFN (CCII) circuits in which all the FTFNs (CCIIs) have $V_y(V_x) = 0$.



(a)



(b)

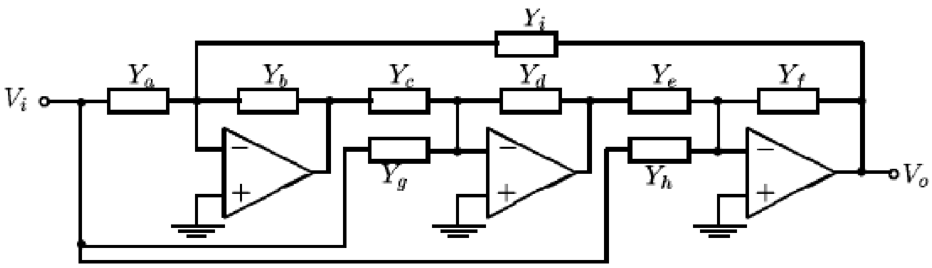
Fig. 6. (a) Lovering VM OA circuit and (b) CM OA circuit.

Example 2: Akerberg and Mossberg's 3-OA VM biquad [26] [27] and Thomas's 4-OA VM biquad [3] (pp. 345-347), [27] shown in Figs. 7(a) and 8(a), respectively are converted into CM circuits shown in Figs. 7(b) and 8(b), respectively. The transfer function of the circuits shown in Fig. 7 is

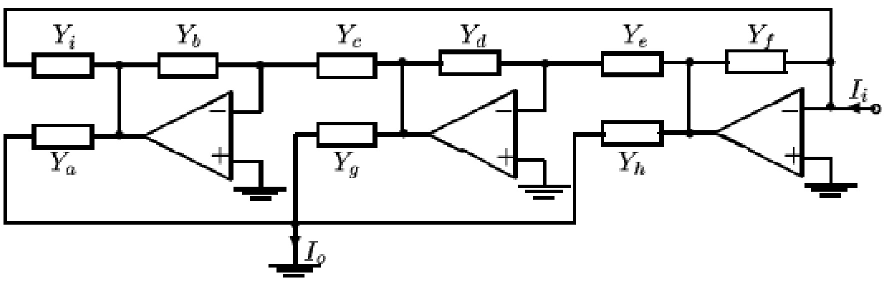
$$\frac{V_o}{V_i} = \frac{I_o}{I_i} = \frac{Y_b Y_e Y_g - Y_a Y_c Y_e - Y_b Y_d Y_h}{Y_b Y_d Y_f + Y_c Y_e Y_i} \tag{10}$$

and that for the circuit shown in Fig. 8 is

$$\frac{V_o}{V_i} = \frac{I_o}{I_i} = \frac{Y_a Y_c Y_e Y_h + Y_a Y_d Y_f Y_i - Y_b Y_d Y_f Y_j - Y_c Y_e Y_g Y_j}{Y_b Y_d Y_f Y_k + Y_c Y_e Y_g Y_k}. \tag{11}$$



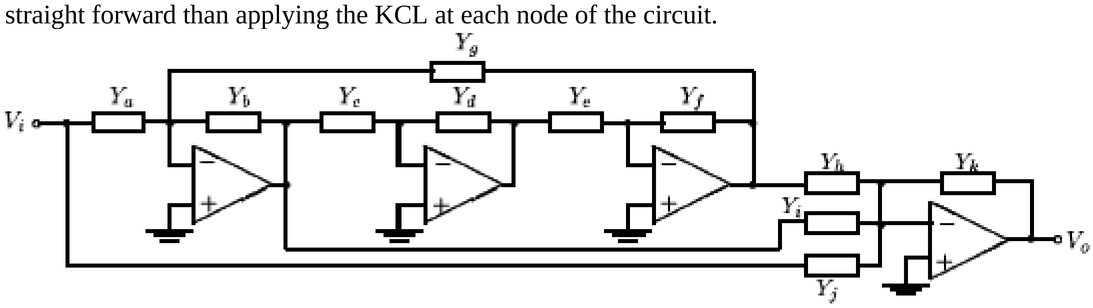
(a)



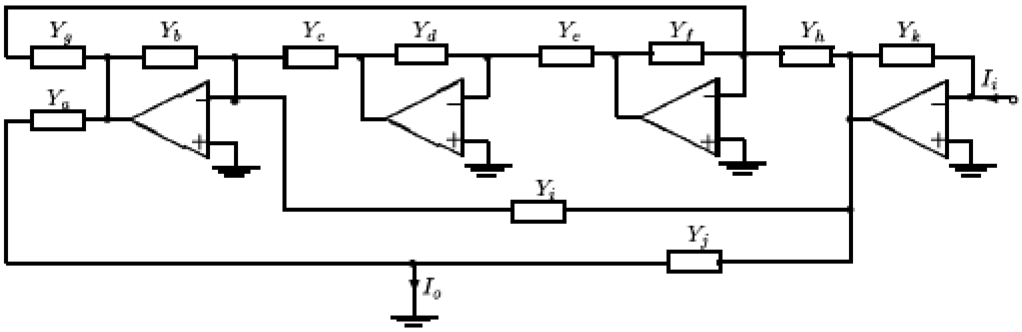
(b)

Fig. 7. (a) 3-OA VM biquad circuit, (b) 3-OA CM biquad circuit.

It may be mentioned that the method used for determining the current transfer function in the above example is more straight forward than applying the KCL at each node of the circuit.



(a)



(b)

Fig. 8. (a) 4-OA VM biquad circuit, (b) 4-OA CM biquad circuit.

Case B

$$V_X = \overline{V_X} = 0,\ I_X \neq 0,\ \overline{I_X} \neq 0. \tag{12}$$

Under these conditions (4) reduces to

$$\frac{I_x}{\overline{I_x}} = \frac{V_i Y_1}{I_i}. \tag{13}$$

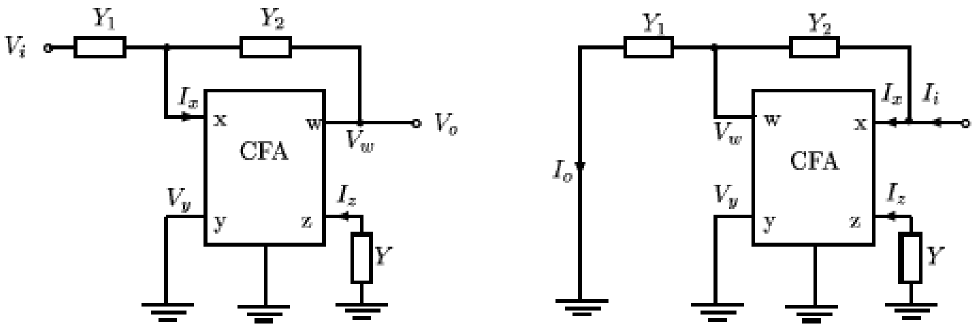
Using (3), we get

$$\frac{I_x}{\overline{I_x}} = \frac{V_o Y_1}{I_o} = \frac{V_z}{\overline{V_z}}. \tag{14}$$

This condition and those in (12) are satisfied when the active network N_a is a CFA where $I_Z = I_X, V_W = V_Z, V_X = V_y$ as shown in Fig. 9. For both the Figs. 9(a) and (b), we have

$$I_x = I_z = -V_w Y = -V_z Y \tag{15}$$

where $Y \neq \infty$. Thus, the current I_x, as desired for the transformation to hold, satisfies the condition in (14).



(a) (b)

Fig. 9. CFA-based (a) VM and (b) CM circuits.

Now, from (1)

$$T(s) = -\frac{Y_1}{Y_2} + \frac{I_x}{V_i Y_2} = -\frac{Y_1}{Y_2} - \frac{V_w Y}{V_i Y_2} = -\frac{Y_1}{Y_2} - \frac{V_o Y}{V_i Y_2} \tag{16}$$

which leads to

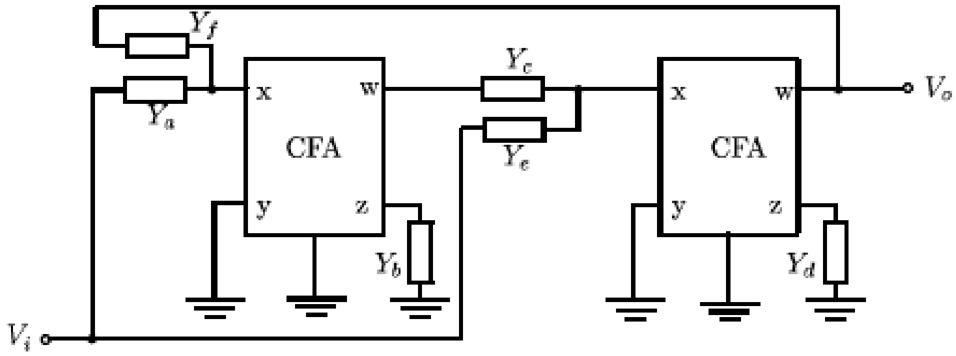
$$T(s) = -\frac{Y_1}{Y_2 + Y}. \tag{17}$$

From Fig. 9, we note that the CFA based VM circuit (with terminal y grounded and the output tapped from the terminal w) can be converted into CFA based CM circuit by interchanging the terminals x and w of the CFA and replacing input-output sources. Connections of passive elements remain unchanged. Thus, the procedure is the same as that for the OA based circuits under case A.

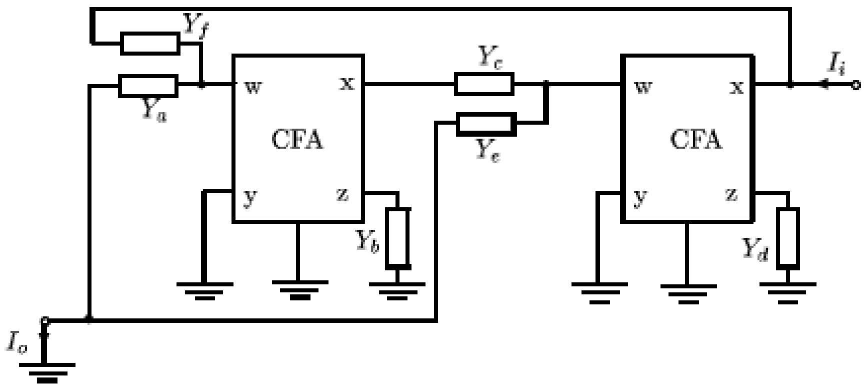
In a manner similar to the one used in case of OA based circuits, it can be shown that the procedure is applicable to CFA based VM circuits having more number of CFAs all with terminal y grounded.

Example 3: Consider the VM circuit shown in Fig. 10(a). Following the above procedure, the CM circuit obtained as shown in Fig. 10(b). The two circuits have the same transfer function as given by (10). In (10), if $Y_b = Y_c = 1\,\mathbf{S}$, the transfer function becomes

$$T(s) = \frac{Y_a - Y_e}{Y_d - Y_f}. \tag{18}$$



(a)



(b)

Fig. 10. (a) VM and (b) CM circuits with more number of CFAs.

Example 4: The realization of $T(s) = \dfrac{s^2 - s + 1}{s^2 + s + 1}$ is obtained using (18) and is shown in Fig. 11.

In both the cases A and B, it is required that all the active devices should have virtual ground.

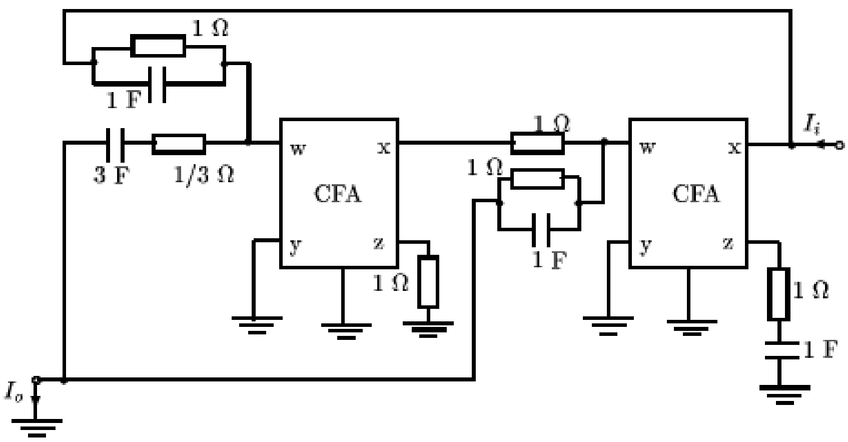


Fig. 11. CM all-pass filter.

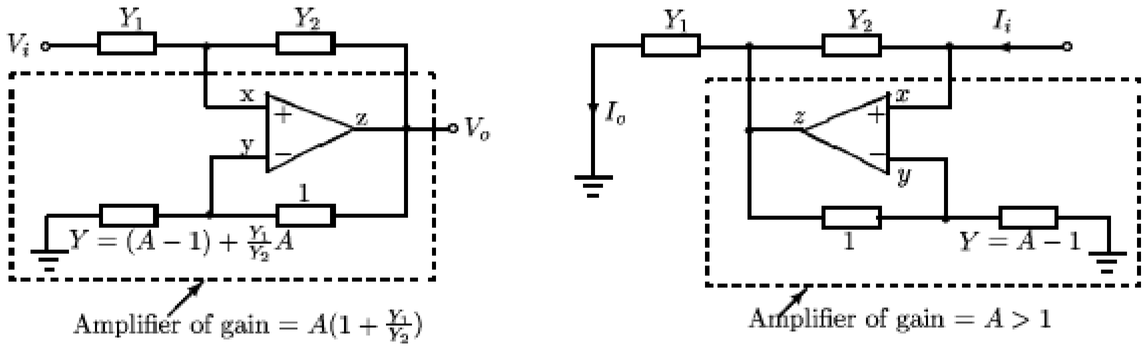
Case C

$$V_x \neq 0, \overline{V_x} \neq 0, I_x = 0, \overline{I_x} = 0. \tag{19}$$

Under these conditions, (4) results in

$$\frac{V_x}{\overline{V}_x}\left(1+\frac{Y_1}{Y_2}\right)=\frac{V_iY_1}{I_i}=\frac{V_z}{\overline{V}_z}. \tag{20}$$

The conditions given in (19) and (20) are satisfied when N_a is an amplifier of gain $A\left(1+\frac{Y_1}{Y_2}\right)$ in voltage mode and gain A in current mode as shown in Fig. 12.



(a) (b)

Fig. 12. (a) VM circuit and (b) CM circuit with active device having no input terminal at virtual ground.

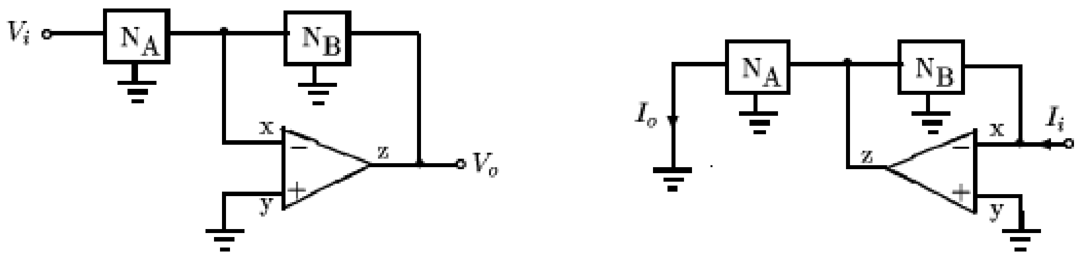
In the VM circuit, the amplifier gain is complex (a function of Y_1 and Y_2) whereas it is positive real in the CM circuit. Hence, the VM circuit will require a larger number of passive elements than the CM circuit. Moreover, both these circuits are more complex than those shown in Figs. 2, 3, 4, and 9. For these circuits

$$T(s)=\frac{V_o}{V_i}=\frac{I_o}{I_i}=-\left(\frac{A}{A-1}\right)\frac{Y_1}{Y_2}. \tag{21}$$

This relation does not offer any special advantage of these circuits over those of Figs. 2, 3, 4, and 9. Hence, this case will not be dealt with any more.

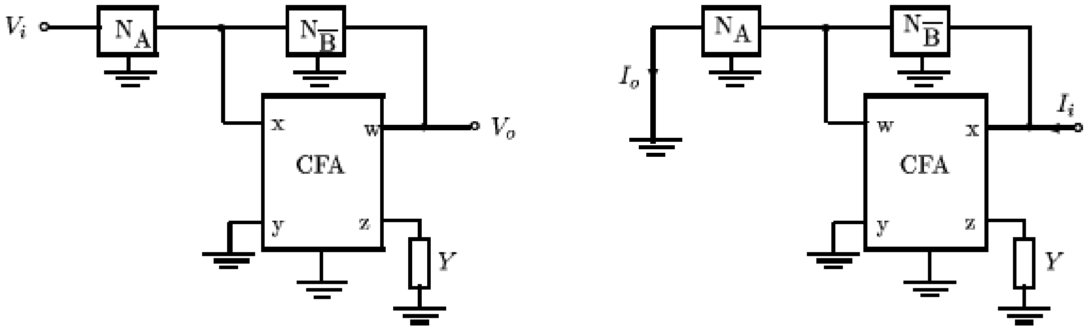
III. Applications Of Transformation Method To General Circuits

More general circuits in voltage mode and their transformed circuits in current mode corresponding to the cases A and B are obtained from Figs. 2 and 9, by replacing 2-terminal passive elements by 3-terminal passive networks N_A and N_B or $N_{\overline{B}}$ and these circuits are shown in Figs. 13 and 14, respectively. Analysis of these two circuits gives



(a) (b)

Fig. 13. Generalized OA based (a) VM and (b) CM circuits with 3 terminal passive network.



(a) (b)

Fig. 14. Generalized CFA based (a) VM and (b) CM circuits.

and

$$T(s) = \frac{V_o}{V_i} = \frac{I_o}{I_i} = -\frac{Y_{21A}}{Y_{21B}}. \quad (22)$$

and

$$T(s) = \frac{V_o}{V_i} = \frac{I_o}{I_i} = -\frac{-Y_{21A}}{\left(-Y_{21\overline{B}} + Y\right)} = -\frac{-Y_{21A}}{-Y_{21B}}, \quad (23)$$

Respectively, where Y_{21A}, Y_{21B} and $Y_{21\overline{B}}$ are the transfer admittances of networks N_A, N_B and $N_{\overline{B}}$, respectively and $Y_{21B} = Y_{21\overline{B}} - Y$.

Special features

1. A close examination of (22) and (23) shows that the following procedure can be used for converting OA based VM/CM circuit of Fig. 13 into CFA based circuit shown in Fig. 14 without increasing the number of passive components. Take out a suitable driving point admittance *Y* from Y_{21B} of the OA based circuit and realize the remaining admittance $Y_{21\overline{B}}$ as transfer admittance by the network $N_{\overline{B}}$.

   Example 5: For example, the OA based VM low-pass filter shown in Fig. 15(a) is converted into four CFA based CM low-pass filters shown in Fig. 15(b). One can now easily visualize that CFA based CM circuit of Fig. 10(b) is derivable from the OA based VM circuit of Fig. 6(a).

2. All the linear operations performed by single-input OA circuits can also be performed by CFA circuits in both voltage and current modes.

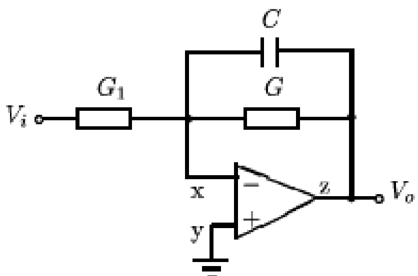
   Example 6: A CM phase shift oscillator shown in Fig. 16 is derived from the OA based one.

3. It may be noted from (22) that *T*(*s*) being a ratio of two transfer admittances, any stable voltage or current transfer function with zeros off the positive real axis can be realized using just one OA [2] and hence by one CFA.

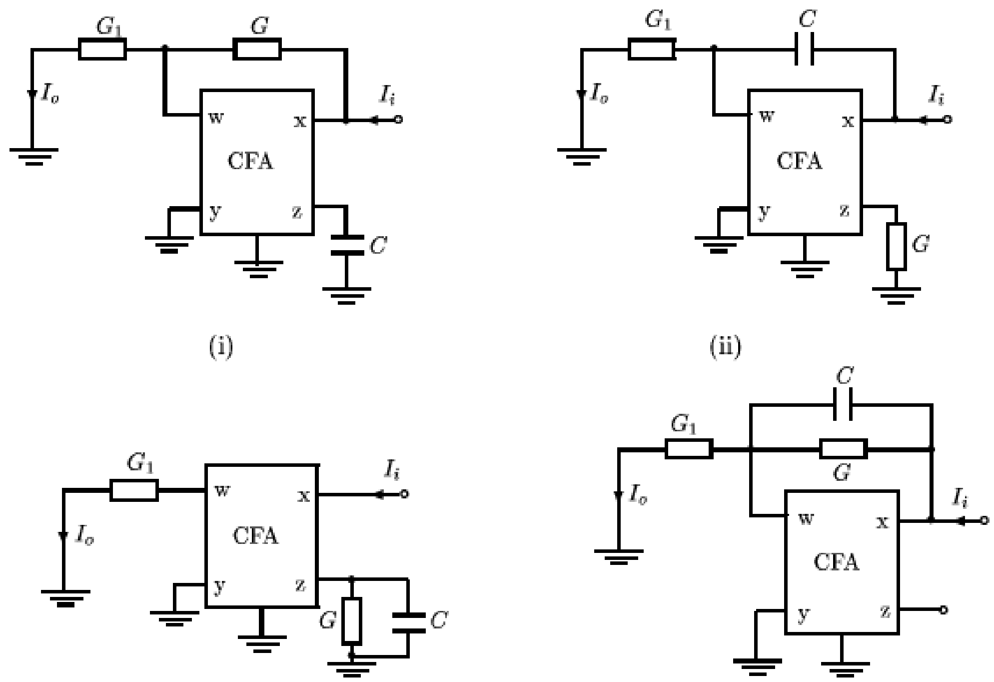
   Example 7: For the notch function

$$T(s) = -\frac{s^2 + 2}{s^2 + 0.2s + 2},$$

   following the procedure in [2] (p. 474) (after making corrections), is given in Fig. 17.



(a)



(b)
Fig. 15. (a) OA based VM low-pass filter and (b) four CFA based CM low-pass filters.

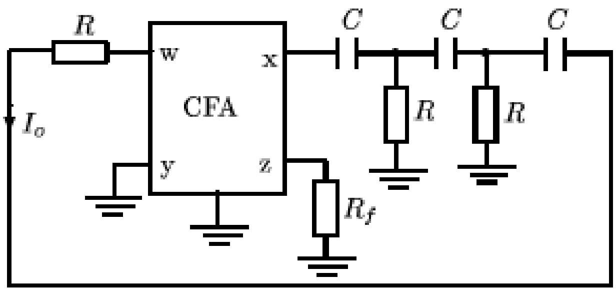


Fig. 16. CM phase shift oscillator.

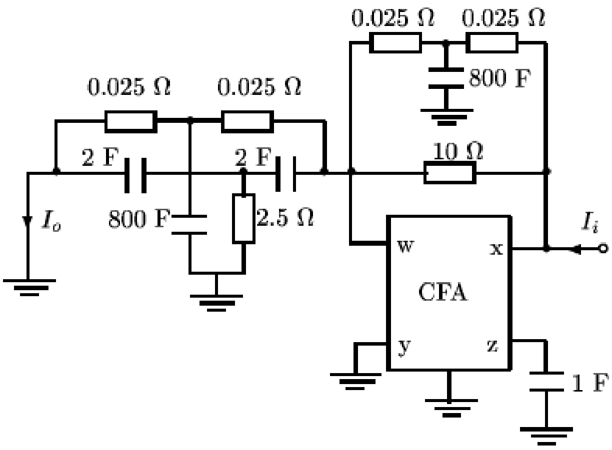


Fig. 17. CM notch filter.

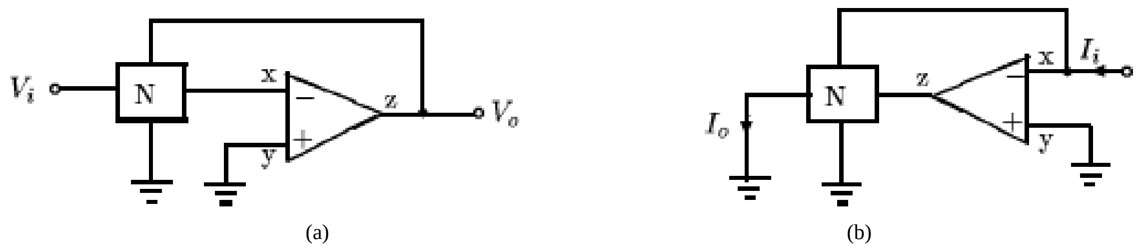


Fig. 18. Generalized OA based (a) VM and (b) CM circuits with 4 terminal passive network.

The procedure outlined is also applicable to more generalized OA based VM and CM circuits shown in Fig. 18 where N is a 4-terminal passive network.

Example 8: The OA based circuit of the VM band-pass filter [3] is transformed into four CM circuits shown in Fig. 19. The proposed technique leads to the transformation without any additional elements.

IV. SENSITIVITY TO NONIDEALITIES

Considering the non-idealities arising from the physical implementation of the CFA, its terminal relationship can be given as

$$\begin{bmatrix} V_x \\ I_y \\ I_z \\ V_w \end{bmatrix} = \begin{bmatrix} 0 & \gamma & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 \\ 0 & 0 & \beta & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ V_z \\ I_w \end{bmatrix} \tag{24}$$

where α is the current gain and β and γ are the voltage gains which can be expressed as $\alpha = 1 - \varepsilon_1$, $\beta = 1 - \varepsilon_2$, and $\gamma = 1 - \varepsilon_3$. Here, ε_1 (ε_1 << 1) denotes the current tracking error of the CFA and ε_2 (ε_2 << 1), ε_3 (ε_3 << 1) are the voltage tracking errors. There is no effect of the voltage tracking error ε_3 as the y terminal of the CFA is grounded. The transfer function I_o/I_i of the low-pass filter shown in Fig. 15(b) can be written as

$$\frac{I_o}{I_i} = \frac{-\frac{\alpha\beta G_1}{C}}{s + \frac{\alpha\beta G}{C}}. \tag{25}$$

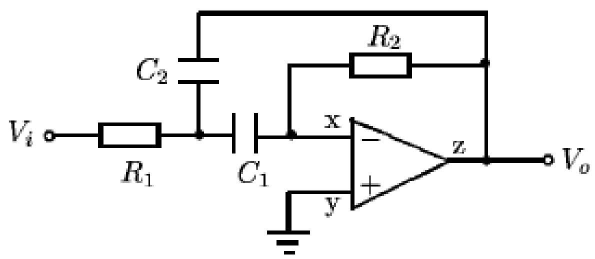
As the y terminal of CFA is grounded, the voltage gain γ does not appear in the transfer function. Applying the usual definition of sensitivity

$$S_y^x = \frac{y\delta x}{x\delta y} \tag{26}$$

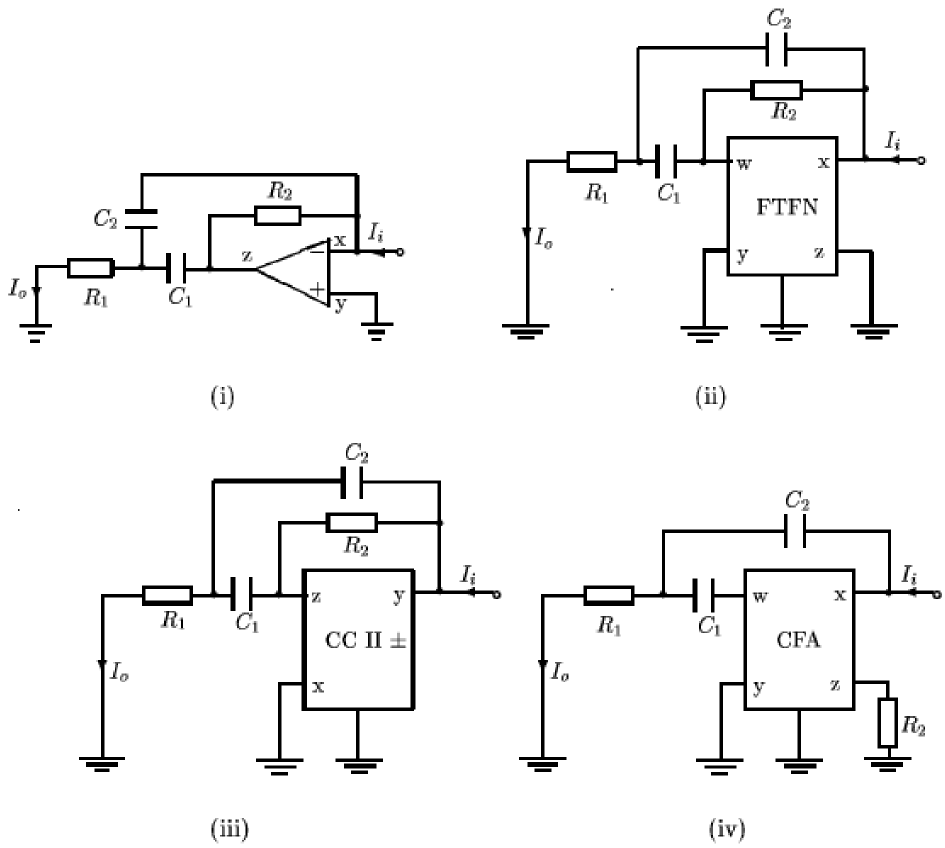
it is found that the passive and active sensitivities of these low-pass filters are

$$S_G^{\omega_0} = -S_C^{\omega_0} = 1, S_{G_1}^{\omega_0} = 0, S_\alpha^{\omega_0} = S_\beta^{\omega_0} = 1. \tag{27}$$

Thus the passive and active sensitivities for the presented filters are low, no more than unity in magnitude.



(a)



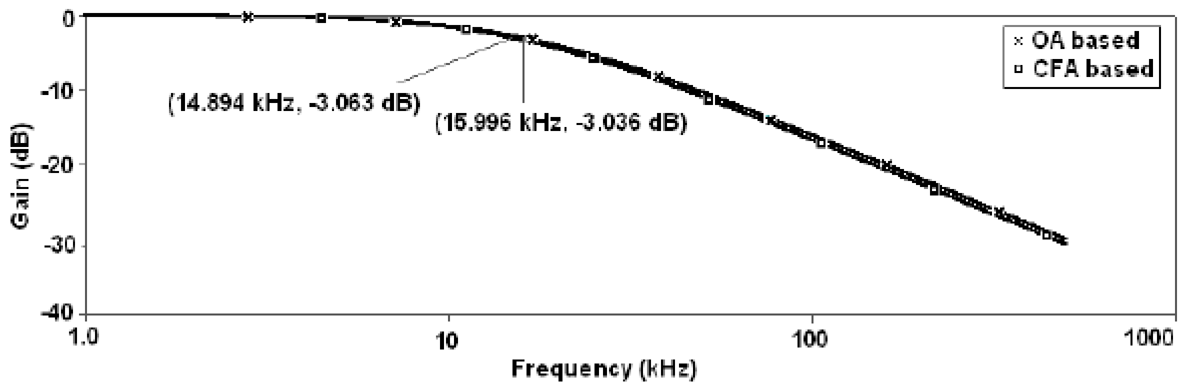
(b)
Fig. 19. (a) OA based VM band-pass filter and (b) four CM band-pass filters.

V. Simulation Results

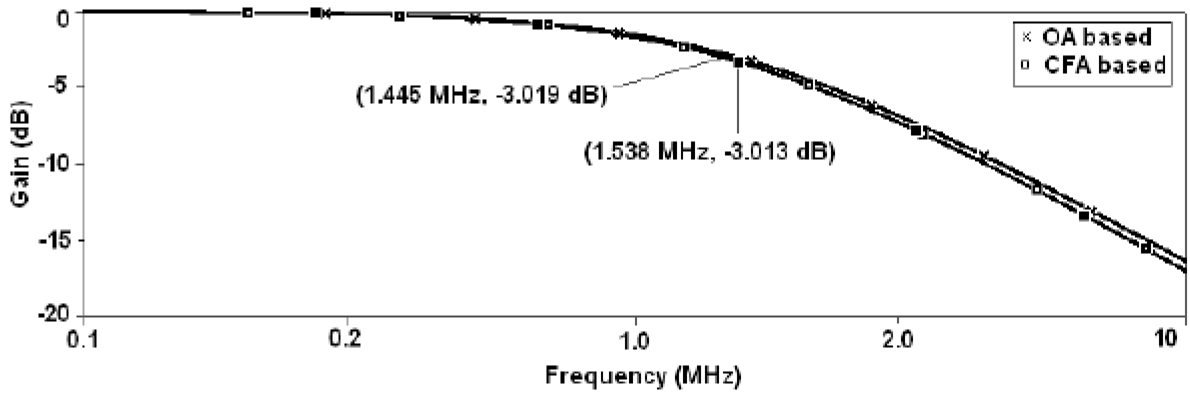
All the low-pass filters shown in Fig. 15 were simulated for 3-dB cut-off frequency of 15.9 kHz, using CFA AD844 and high frequency OA AD817 with supply voltages of ±15 V, and employing PSPICE software [28]. The circuit components were $R=R_1=1$ kΩ, $C=10$ nF. All the filters gave nearly the same magnitude response as shown in Fig. 20(a). The low-pass filters were also simulated for cut-off frequency as high as 1.59 MHz. The circuit components used for this purpose were $R=R_1=1$ kΩ, C = 100 pF. The corresponding magnitude responses are shown in Fig. 20(b). The phase shift oscillator of Fig. 16 was also simulated and the output waveform, as shown in Fig. 21, has peak-to-peak amplitude of 10 mA. It may be noted that, the oscillator circuit does not have a separate amplitude stabilizer and the oscillation levels are limited by the supply voltages. For supply voltages of ±6 V, the simulation resulted in peak-to-peak amplitude of 2 mA.

VI. Practical Results

To validate the transformation at high cut-off frequencies of the filters, the circuit for low-pass filter shown in Fig. 15(a) was assembled using a high frequency OA AD817 and that for low-pass filter shown in Fig. 15(b)(i) was assembled using CFA AD844. In case of CFA, to generate the input current, 1 kΩ resistor was connected in series with the input voltage source. The other circuit elements chosen for the cut-off frequency of 1.59 MHz are $R = R_1=1$ kΩ and C= 100 pF. Both the low-pass filters performed almost identically for the cut-off frequency as high as 1.59 MHz as shown in Fig. 22.



(a)



(b)

Fig. 20. Simulation results: Frequency responses of the low-pass filters for f_0 = 15.9 kHz and (b) for f_0 = 1.59 MHz.

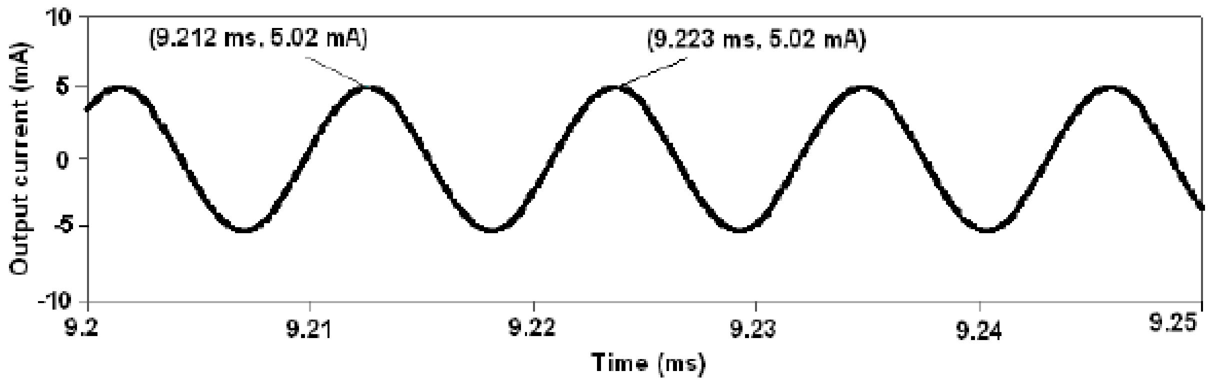


Fig. 21. I_o waveform of the phase shift oscillator with R = 649.74 Ω, C = 1 nF, R_f = 25 kΩ.

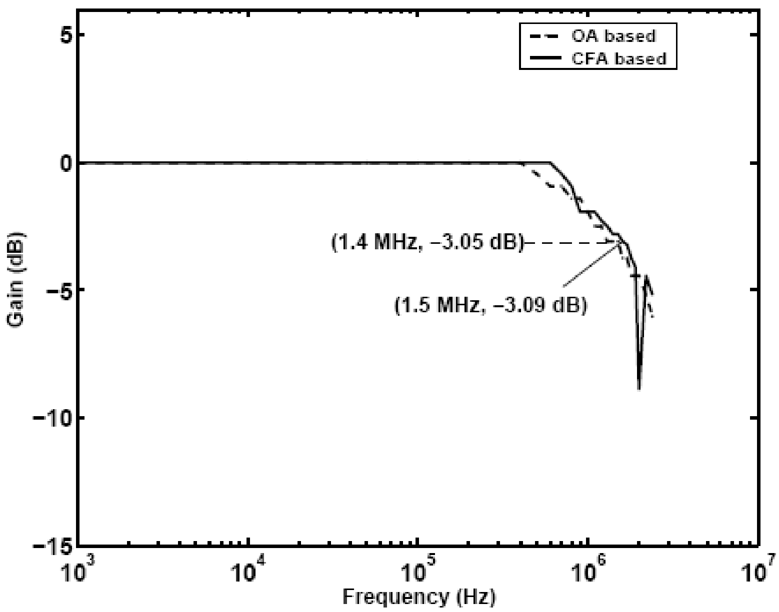


Fig. 22. Experimental results – Frequency responses of low-pass filters shown in Fig. 15 with $R = R_1$=1 kΩ, C = 100 pF for f_0 = 1.59 MHz.

VII. Concluding Remarks

A procedure for converting a class of VM circuits, which have all the active devices with virtual ground, into CM circuits without altering the transfer function and without requiring any additional components has been developed. It covers the circuits having active devices like OA, FTFN, CC, and CFA. Since voltage and current transfer functions (assuming the same active devices) are the same, the characteristics such as stability, tunability, sensitivity etc. remain unaltered. The procedure has been demonstrated by examples. Thus, a single circuit can be used in either mode. The validity of the proposed transformation procedure has been tested by simulating the transformation of the low-pass filter and phase shift oscillator with the help of PSPICE. The experimental results show that the frequency responses of both the VM and CM low-pass filters are identical. The active and passive sensitivities for the presented filters are very low. It has been shown that a single FTFN, CCII, and CFA based circuits can realize both stable voltage and current transfer functions with zeros off the positive real axis.

VIII. References

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