Simulating Elliptic Low-pass Filter based on MOCCCII

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Abstract. Multiple output current-control current conveyer (MOCCCII) based Elliptic low-pass filter by using a simulating of RLC ladder prototype is presented in this work. The good performances of RLC ladder as well as low-sensitivity are inherited. Signal flow graph (SFG) method is applied to convert the RLC Elliptic ladder low-pass filter prototype to be the different function blocks. These function blocks can be realized by integrator and differentiator. Lossy integrator, lossless integrator and lossless differentiator realized from MOCCCII are straightforward replaced in SFG. Due to the tuning ability of MOCCCII, the proposed Elliptic low-pass filter can be tuned by adjusting the bias current ($I_B$). In addition, the frequency responses can be varied from 50kHz to 1MHz by tuning $I_B$ from 1µA to 100 µA to prove the electronic tuning performance of the proposed filter. The simulation results are carried out by PSpice that the performances are totally agreed with the theory.

Keywords-MOCCCII, Elliptic, Low-pass, Electronic tuning

1. Introduction
Continuous time signal processing is very important process in telecommunication works. High performance filter plays important role for selecting the desired signal and removing unwanted signal. Many types of filter are developed for specific applications as well as noise reduction in electronic circuit and digital to analog conversion. However, the characteristic of the filters should be selected which suitable for using in applications. Some usage required only simple and low-performance filter such as first-order passive filter [1-2] to complete the requirement. When the requirements are more complex, higher performance filters are required to achieve the requirement. Second-order filters were introduced with many active building blocks, such as OPAMP, OTA or CCII [3-5] with limitations, for example, required addition resistance and consist of floating capacitor. These limitations lead to large die area, complex structure and high sensitivity.

In high performance applications, low-order of filters and the mentioned first and second-order filters provided insufficient performances. High-order passive ladder filters were considered due to their performance and additional reliability as well as low sensitivity [6-8]. Chebyshev and Elliptic approximation functions are interested in high-order ladder filters realization. The RLC ladder Chebyshev type is preferred approximation type and it also called all poles filter because the transfer function has only poles without zeros. The Elliptic approximation type has both of poles and zeros in
the transfer function. The cutoff frequency of RLC Elliptic ladder filter type is sharper than Chebyshev counterpart. Unfortunately, the passive RLC circuit has no electronic tuning and integration abilities. Few years ago, the filter circuits using active building blocks [9-11] were reported by using passive ladder filter prototype. These circuits were suffered from the complex structures and used of large number of passive elements. Recently, Chebyshev [12] and Elliptic [13] ladder filters were proposed with electronic tuning feature. The performances were good for the Chebyshev, but the Elliptic structure was rather complex. Due to the previous Elliptic ladder filter required the extremely low current gain which the current gain was very difficult to design and optimize. The poor performance of current gain was inevitable that meant the realized Elliptic filter had limitation for integration.

This paper focuses on a new synthesis of Elliptic ladder filter that has a simple structure by using lossless differentiator directly replace in SFG. Due to the simple SFG, its able to realized higher order filter. The proposed circuit uses only grounded capacitors which suits to further integrated circuit fabrication. The selected active building block is a MOCCCII which are versatile devices with electronic tuning ability that leads to the frequency tunable feature in the proposed Elliptic filter.

2. Principle and Theory

2.1. MOCCCII

MOCCCII [14] is versatile active building block which is developed from CCCI [15], its electronic symbol and structure are shown in Figure 1. and Figure 2., respectively. Current and voltage relationship can be written as

\[
\begin{bmatrix}
    i_y \\
    v_x \\
    i_z
\end{bmatrix} = \begin{bmatrix}
    0 & 0 & 0 \\
    1 & R_x & 0 \\
    0 & \pm 1 & 0
\end{bmatrix} \begin{bmatrix}
    v_y \\
    i_x \\
    v_z
\end{bmatrix}
\]

(1)

From (1) positive and negative signs at port \( Z \) illustrate the positive and negative signal. \( R_x \) is intrinsic resistance at port \( X \) which can be described by the transconductance \( (g_{mi}) \) of \( M_{12} \) and \( M_{14} \) in (2)

\[
R_x \approx \frac{1}{g_{m12} + g_{m14}}
\]

(2)

\( g_{mi} \) is a transconductance of MOS number \( i \). Assume that transistors \( M_{12} \) and \( M_{14} \) are matched, then \( g_{m12} = g_{m14} \) the equation can be rewritten to
\begin{equation}
R_x \approx \frac{1}{2g_m} = \frac{1}{2\sqrt{8\mu C_{ox} (W/L)I_B}}
\end{equation}

Where $\mu$, $C_{ox}$, $W$ and $L$ are surface mobility, oxide capacitance, channel width and length of MOS transistor, respectively. It can be seen that $R_x$ can be electronically tuned by bias current ($I_B$).

2.2. Lossless and Lossy Integrators

MOCCCII based lossless integrator can be easily realized by connecting a grounded capacitor to port $Y$, and connecting port $X$ to ground as shown in Figure 3. The current transfer function can be expressed as

\begin{equation}
\frac{I_{O1}}{I_{IN}} = \frac{1}{sCR_s}, \quad \frac{I_{O2}}{I_{IN}} = \frac{-1}{sCR_s}
\end{equation}

MOCCCII based lossy integrator can also be easily realized by connecting grounded capacitor to port $X$, and connecting port $Y$ to ground as shown in Figure 4. The current transfer function can be expressed as

\begin{equation}
\frac{I_{O1}}{I_{IN}} = \frac{1}{sCR_s + 1}, \quad \frac{I_{O2}}{I_{IN}} = \frac{-1}{sCR_s + 1}
\end{equation}

![Figure 3. MOCCCII based lossless integrator](image1)

![Figure 4. MOCCCII based lossy integrator](image2)

2.3. Lossless Differentiator

To realized lossless differentiator, we use lossy differentiator or high-pass filter [16] with positive feedback to the input as shown in Figure 5.

By using concept in Figure 5., we can realize MOCCCII based lossless differentiator as shown in Figure 6. and its current transfer function can be expressed as

\begin{equation}
\frac{I_{O1}}{I_{IN}} = sCR_s, \quad \frac{I_{O2}}{I_{IN}} = -sCR_s
\end{equation}

![Figure 5. Realization of lossless differentiator from lossy differentiator](image3)

![Figure 6. MOCCCII based lossless differentiator](image4)
3. MOCCCI based Elliptic Ladder Low-pass Filter

Using the RLC Elliptic prototype [17], applying Kirchhoff’s Current Law (KCL) to the RLC Elliptic ladder low-pass filter prototype in Figure 7, the current and voltage relationships can be written as

\[ I_1 = I_{IN} - V_1/R_S - I_2 - I_3 \]  
(7)
\[ I_2 = \frac{(V_1 - V_2)}{sL_2} \]  
(8)
\[ I_3 = (V_1 - V_2)sC_3 \]  
(9)
\[ V_1 = \frac{I_1}{sC_1} \]  
(10)
\[ V_2 = \frac{I_4}{sC_4} \]  
(11)
\[ I_4 = I_2 + I_3 - I_O \]  
(12)
\[ I_O = \frac{V_2}{R_L} \]  
(13)

From equations (7) to (13), the SFG can be written as Figure 8.

From Figure 8, it consists of various variables especially in the junctions of voltage and current variables. In the realization all junctions should be transformed into the same type. Transforming all junctions of SFG in Figure 8 into current variables by using resistance \( R_x \). Considering at the beginning and the end paths of SFG, the feedback paths \(-1/R_S\) and \(-1/R_L\) if we set \( R_S = R_L = R_x \) the functions perform as lossy integrators. Then we can simplify the SFG to Figure 9.
Considering SFG in Figure 9., the different junctions are incorporated as the transfer functions of lossy integrator, lossless integrator and lossless differentiator. Replacing the MOCCCII based integrators and differentiator into SFG, the proposed Elliptic ladder low-pass filter can be written as Figure 10. Compare the proposed circuit to previous work [13], due to previous work use converted current gains the achieve low-pass function, but the proposed structure directly replace SFG functions by integrator or differentiator, which means the proposed structure has less complexity and deploy less components. The capacitors can be set to achieve condition of low-pass filter instead of previous work current gains.

**Figure 10.** Proposed Elliptic ladder low-pass filter

### 4. Simulation Results

The simulation results are carried out by PSpice to confirm the theory. Supposed that, the RLC Elliptic ladder low-pass filter prototype operation frequency is set to 1 MHz ripple 0.1dB, the various passive elements are given by $R_s=R_L=1\Omega$, $C_1=C_4=158\text{nF}$, $L_2=172\text{nH}$, $C_3=9\text{nF}$. Using scaling technique ($k_f=1k$) to the proposed circuit by given the following parameters as $C_1=C_4=158\text{pF}$, $C_2=172\text{pF}$, $C_3=9\text{pF}$ and $I_{f}=120\mu\text{A}$.

The selected CMOS model in MOCCCII is MOSIS level 3 TSMC 0.25µm technology. The aspect ratio of NMOS and PMOS parameters are given in Table 1.

| Transistor | W(μm) | L(μm) |
|------------|-------|-------|
| NMOS       | 5     | 0.5   |
| PMOS       | 15    | 0.5   |
The frequency responses of proposed Elliptic low-pass filter compared with prototype are shown in Figure 11. It can be seen that the passband gain of the proposed filter is mitigated from the passband of RLC prototype.

![Figure 11. Frequency responses of proposed filter compared with RLC prototype](image1)

Group delay of proposed filter compared with RLC prototype is shown in Figure 12. It is obviously found that the group delay of proposed filter and RLC prototype are closely which are around 200ns along passband and suddenly changed at 4MHz. MOCCCI frequency responses can be tuned by using $I_B$ which relate to $R_x$ and can be explain in equations (5) and (3), the proposed circuit can be also tuned. Figure 13. shows the electronic tuning ability of the proposed circuit by varying $I_B=1\mu A, 3\mu A, 10\mu A, 30\mu A$ and $100\mu A$, the operation frequencies can be tuned between 80kHz and 1.2MHz.
Multi-tone test can be verified the performance of filter how good to remove unwanted frequency. The multi-tone result is shown in Figure 14. by adding various frequency sinusoidal signals 100kHz, 300kHz, 1MHz, 3MHz and 10MHz as inputs with bias current $I_B=100\mu A$. The outputs show only signals in passband that agreed well with the theory.

Filter performance can be verified by applying 3 input frequencies (1MHz, 3MHz and 5MHz) to the proposed LPF while bias current $I_B=100\mu A$. It is clear that, only 1MHz sinusoidal signal appear at the output, other higher frequencies are removed as shown in Figure 15.
5. Conclusion
A new MOCCCII based Elliptic ladder low-pass filter is presented in this paper. Simple structure is designed based on RLC Elliptic ladder prototype. The SFG is used to synthesis the active signal processing building blocks. The proposed circuit consists of 2 lossy integrators, 1 lossless integrator, 1 lossless differentiator and 4 grounded capacitors. The proposed circuit has low complex structure suit to further integration. The operation frequencies can be electronically tuned between 50kHz and 1MHz by varying $I_B$ from 1µA to 100µA.

References
[1] I. A. Khan, P. Beg, T. Muslim Ahmed, “First Order Current Mode Filters and Multiphase Sinusoidal Oscillators Using MOCCIIs,” Microelectronics, pp. 146-149, 2006.
[2] S. Ozoguz, A. Toker, O. Cicekoglu, “First-order allpass sections-based current-mode universal filter using ICCIIs,” IET Electronics letters, Vol.36, No.17, pp. 1443-1444, 2000.
[3] G.W. Roberts and A.S. Sedra, “All current-mode frequency selective circuits,” Electronics Lett, vol. 25, pp.759-761, 1989.
[4] C.M. Chang, “Novel universal current-mode filter with single input and three outputs using only five current conveyors,” Electronics Lett, vol.29, pp. 2005-2007, 1993.
[5] S. Minaei and S. Turkoz “New current-mode current-controlled universal filter with single Input and three outputs,” Int’l J. Electronics, vol. 88, pp.333-337, 2001.
[6] J. Wu, E. El-Masry, Current-mode ladder filters using multiple output current conveyers. IEE Proceedings: Circuits, Devices and Systems, Vol.143, No.4, pp.218-222, 1996.
[7] J. Glisnianowicz, J. Jakusz, S. Szczepanski and Y. Sun, “High-frequency two-input CMOS OTA for continuous-time filter applications IEE Proceedings: Circuits, Devices and Systems, Vol.147. No. 1. Feb. 2000.
[8] J. A. De Lima and C. Dualibe, “A Linearly Tunable Low-Voltage CMOS Transconductor With Improved Common-Mode Stability and Its Application to gm–C Filters,” IEEE Trans. Circuits Syst. II, Vol. 48, No. 7, July 2001.
[9] G. Jacobs, D. Allstot, R. Brodersen, P. Gray, Design techniques for MOS switched capacitor ladder filters. IEEE Transactions on circuits and systems, Vol.25, No12, pp.1014-1021, 1978.
[10] F. Montecchi, Time-shared switched-capacitor ladder filters insensitive to parasitic effects. IEEE Transactions on circuits and systems, Vol.31, No.4, pp.349-353, 1984.
[11] A. Uygur, H. Kurtman, “Seventh-order elliptic video filter with 0.1 dB pass band ripple employing CMOS CDTAs,” Int. J. Electron. Commun. (AEÜ) Vol.61, pp.320–328, 2007.
[12] P. Prommee, P. Thongdit, K. Angkeaw, "Log-domain high-order low-pass and band-pass filters," AEU - International Journal of Electronics and Communications, Vol. 79, pp.234-242, 2017.

[13] P. Prommee, T. Kunto, M. Somdunyakanok and T. Prommee, "CMOS-based current-mode tunable ladder Elliptic low-pass filter," Proc. of 38th International Conference on Telecommunications and Signal Processing, pp.142-145, 2015.

[14] A. Fabre, O. Saaid, F. Wiest and C. Boucheron, “High frequency applications base on a new current controlled conveyor,” IEE Tran. Circuits and Syst. I, vol. CAS-43, pp. 82-91, Feb. 1996.

[15] P. Limpaibool, T. Kunto and P. Prommee, “Design of High-order Current-mode Ladder Low-pass Filters Using MOCCIIIs” International Symposium on Multimedia and Communication Technology, pp.34-37, 2015.

[16] P. Prommee, M. Somdunyakanok and K. Angkeaw, “CCCII-based Multiphase Sinusoidal Oscillator Employing High-pass Sections”, ECTI-CON 2009, Vol.1, pp.530-533, 2009.

[17] T. Deliyannis, Y. Sun and J. K. Fidler, “Continuous-Time Active Filter Design,” London: CRC Press, 1999.