International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 6, Issue 6 (June 2017), PP.01-07

Realization of Electronically Tunable Current-Mode Square-Root-Domain Multifunction Filter

M. Serhat Keserlioglu[1],Ali Kircay[2]
[1]*Electrical AndElectronics Engineering Department, Pamukkale University,Denizli, Turkey*
[2]*Electrical AndElectronics Engineering Department, Harran University,Sanliurfa, Turkey*

Abstract:-In thisstudy, in a square- rootdomain, electronicallyadjustablecurrent-mode, second-ordermultifunctionfilter circuit isdesigned. High-pass, band-reject and band-pass output currentscanbeobtained as the output current of the multifunctionfilter circuit. In addition, the $f_0$cut-off frequency and Q quality factor of the filter circuit canbeadjustedelectronically by changing the values of the current I_0 dc in the circuit. PSPICE computer simulations wereperformed to verify the theoreticalresultobtained.
Keywords:-Compandingsystems, current-mode circuits, square-root-domainfilters

I. INTRODUCTION

It can be said that log domain and square-root domain filter circuits are the most common translinearcircuits to which the companding technique is applied. The advantages of companding technology, such as wide dynamic range, low supply voltage and electronically adjustable design, increase the interest in this technique. The classical translinear principle or the bipolar translinear principle (BTL) [1, 2] uses the exponential current-voltage relationship of BJT's or MOS transistors in the weak invertion region. The MOS translinear (MTL) principle developed by Seevinck using the BTL principle uses the quadrature current-voltage relationship of a MOS transistor operating in strong invertion or saturation region [3]. In the first phase of the square-root domain circuit design, the desired circuit function is transformed into state-space equations. At this stage, different sets of state-space equations representing the same circuit function can be generated. Each of these state-space equation sets corresponds to a different circuit having the same circuit function. In the second stage of the design, the current equations are obtained by using the quadratic current-voltage relation of the MOS transistor in the state-space equations. In the final stage, the resulting current equations are converted to square-root-domain circuits using analog processing blocks such as square-root and squarer/divider [5-10], current mirrors and dc current sources [4-20].

It can be seen that studies on first-order filter circuits [10-13], second-order filter circuits [7, 13-19] and third-order filter circuits [20] have been performed by various researchers when a literature survey on square-root domain circuits is carried out. There are also studies on trans-admittance and trans-impedance circuits [12,11,19]. In this study, a square-root domain second order current-modemultifunctional filter was implemented using state-spacesynthesis. High-pass, band-pass and band-reject output signals can be obtained from the output end of the implemented filter circuit. The f_0 cut-off frequency and the Q quality factor of the obtained output signals can be electronically adjusted by changing the current valueof the dc current sources.

II. SRD MULTIFUNCTION FILTER

To implement the square-root domain multifunction filter design, let's first consider the second order high-pass filter transfer function as given by general structure (1).

$$F(s) = \frac{P(s)}{Q(s)} = \frac{s^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \qquad (1)$$

The high-pass transfer function given in (1) above can be transformed into state-space equations given in (2), (3) and (4) below.

$$\dot{x}_1 = -\frac{\omega_0}{Q}x_1 - \omega_0 x_2 + \frac{\omega_0}{Q}u_1 \qquad (2)$$

$$\dot{x}_2 = \omega_0 x_1 + \omega_0 u_2 \qquad (3)$$

$$y = u_1 - x_1 \qquad (4)$$

Here, the terms x_1 and x_2 represent the state variables, the term y represents the output size of the filter circuit and u_1 and u_2 terms represent the input signals. I_1 and I_2, the drain currents of the MOS transistor in the saturation region which are represented by the state-variables x_1 and x_2 in the state-space equations can be defined as given in (5) and (6) [11, 21].

$$I_1 = \frac{\beta}{2}(V_1 - V_{th})^2 \quad (5)$$

$$I_2 = \frac{\beta}{2}(V_2 - V_{th})^2 \quad (6)$$

Here, the term $\beta = \mu_0 C_{ox}(W/L)$ is the conductivity value of MOS transistor, V_1 and V_2 voltages are the gate-to-source voltages and V_{th} is the threshold voltage. In the currents (5) and (6) given above, (7) and (8) are obtained after taking derivatives of both sides.

$$\dot{I}_1 = \dot{V}_1\sqrt{2\beta I_1} \quad (7)$$

$$\dot{I}_2 = \dot{V}_2\sqrt{2\beta I_2} \quad (8)$$

In the next step, equations (7) and (8) are written in the state-space equations given in (2), (3) and (4) and both sides of the equations are multiplied by the C constant. Then, necessary arrangements can be made to form (9) and (10) below.

$$C\dot{V}_1 = -\frac{C\,\omega_0 I_1}{Q\sqrt{2}\sqrt{\beta}\sqrt{I_1}} - \frac{C\,\omega_0 I_2}{\sqrt{2}\sqrt{\beta}\sqrt{I_1}} + \frac{C\,\omega_0 u_1}{Q\sqrt{2}\sqrt{\beta}\sqrt{I_1}} \quad (9)$$

$$C\dot{V}_2 = \frac{C\,\omega_0 I_1}{\sqrt{2}\sqrt{\beta}\sqrt{I_2}} - \frac{C\,\omega_0 u_2}{\sqrt{2}\sqrt{\beta}\sqrt{I_2}} \quad (10)$$

Here an I_0 current can be defined as given in (11) [7, 11]. (9) and (10) are converted to current equations (12) and (13) below using this I_0 current defined.

$$\sqrt{I_0} = \frac{C\,\omega_0}{\sqrt{\beta}} \quad (11)$$

$$C_1\dot{V}_1 = -\frac{1}{Q}\sqrt{\frac{I_0 I_1}{2}} + \sqrt{\frac{I_0 I_2^2}{2I_1}} + \frac{1}{Q}\sqrt{\frac{I_0 u_1^2}{2I_1}} \quad (12)$$

$$C_2\dot{V}_2 = \sqrt{\frac{I_0 I_1^2}{2I_2}} - \sqrt{\frac{I_0 u_2^2}{2I_2}} \quad (13)$$

Finally, an I_Q current as defined in (14) can be used in place of the $1/Q$ term in (12) and (13).

$$I_Q = \frac{1}{Q^2} I_0 \quad (14)$$

(14) can be used to set the value of quality factor Q. With the use of the defined I_Q current, the final state of the current equations becomes as given in (15) and (16).

$$C_1\dot{V}_1 = -\sqrt{\frac{I_Q I_1}{2}} + \sqrt{\frac{I_0 I_2^2}{2I_1}} + \sqrt{\frac{I_Q u_1^2}{2I_1}} \quad (15)$$

$$C_2\dot{V}_2 = \sqrt{\frac{I_0 I_1^2}{2I_2}} - \sqrt{\frac{I_0 u_2^2}{2I_2}} \quad (16)$$

Using the obtained current equations (15) and (16), the square-root domain second-order current-mode filter circuit can be implemented as shown in Fig.1.

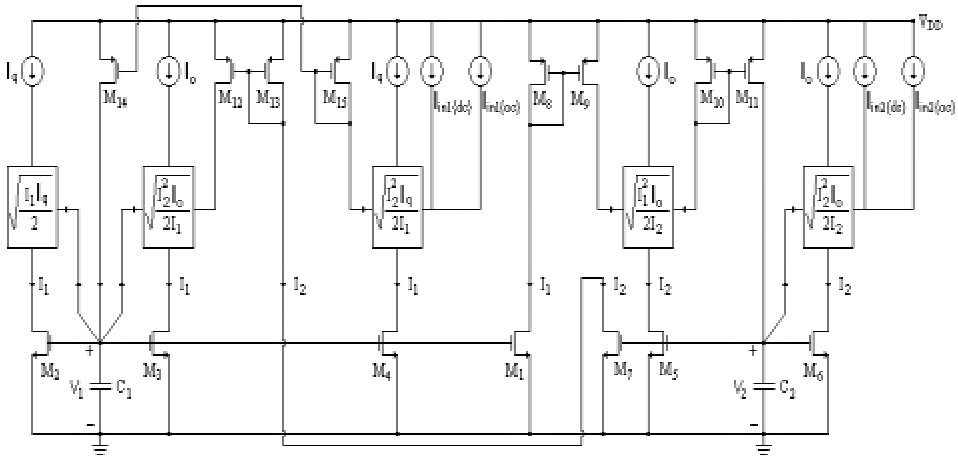

Figure 1.SRD multifunction filter.

Here, the input currents of the filter circuit are represented by I_{in1} and$I_{in2}$and the output currents are represented I_1andI_2.Also, by means of (17), the cut-off frequency of the filter circuit $\omega_0$can be determined depending on the valuesI_0, β and$C$.

$$\omega_0 = \frac{\sqrt{\beta I_0}}{C} \tag{17}$$

Since the input current source I_{in}has both dc and ac components, it can be formed by connecting the dc and ac current sources in parallel, as shown Fig.2 [10].

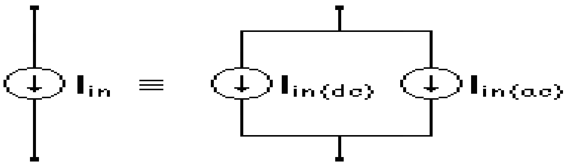

Figure 2. Input current sources.

Using the state-space equations (2) and (3),the output of the multifunction filter circuit the currents I_1 andI_2can be obtained as given in (18) and (19) below depending on $\omega_0$and$Q$.Here, $I_{in1} = I_{in2} = I_{in}$ is taken so that high-pass output can be obtained.

$$I_1 = \frac{\frac{\omega_0}{Q}s + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} I_{in} \tag{18}$$

$$I_2 = \frac{-\omega_0 s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} I_{in} \tag{19}$$

Here, the I_1current given in (18) is obtained as given by the high-pass filter current output (20) by being used in the definition of the multifunction filter output current given by (4).

$$I_{HP} = I_{in} - I_1 = \frac{s^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} I_{in} \tag{20}$$

To obtain the second-order current-mode band reject filter output current, we take $u_2 = 0$ in the state-space equation (2) and (3). The new equations obtained, in this case, will be as given in (21) and (22).

$$\dot{x}_1 = -\frac{\omega_0}{Q}x_1 - \omega_0 x_2 + \frac{\omega_0}{Q}u_1 \tag{21}$$

$$\dot{x}_2 = \omega_0 x_1 \qquad (22)$$

Here, current equations (23) and (24) can be obtained by using the MOS transistor saturation region currents I_1 and I_2 instead of the x_1 and x_2 state variables; and by making the necessary adjustments.

$$C_1\dot{V}_1 = -\sqrt{\frac{I_Q I_1}{2}} + \sqrt{\frac{I_0 I_2^2}{2I_1}} + \sqrt{\frac{I_Q u_1^2}{2I_1}} \qquad (23)$$

$$C_2\dot{V}_2 = \sqrt{\frac{I_0 I_1^2}{2I_2}} \qquad (24)$$

Equations (24) and (24) given above correspond to the case of $I_{in2(ac)} = 0$ in the circuit given in Fig.1. For this case I_1 and I_2 currents are obtained as given in (25) and (26) depending on ω_0 and Q. It can be said here that $I_{in1} = I_{in}$ and $I_{in2} = 0$ are taken in order to obtain the band-reject output.

$$I_1 = \frac{\frac{\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} I_{in} \qquad (25)$$

$$I_2 = \frac{\frac{\omega_0^2}{Q}}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} I_{in} \qquad (26)$$

In this case, the current I_1 given in (26) can be obtained as given in theband-reject filter output current (27), after it is used in the definition of the multifunction filter output current given in (4).

$$I_{BR} = I_{in} - I_1 = \frac{s^2 - \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} I_{in} \qquad (27)$$

Furthermore, the current I_1 itself corresponds to a band-pass output current as given in (28).

$$I_{BP} = I_1 = \frac{\frac{\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} I_{in} \qquad (28)$$

Thus, as the output current of the same circuit given in Fig.1, it is possible to obtain high-pass, band-reject and band-pass output currents as defined in Table.1.

Table.1 Different output currents of multi-function filter

Input		**Output**	**Type of filter**
$I_{in1(ac)}$	$I_{in2(ac)}$	$y = u - x_1$	
I_{in}	I_{in}	$I_{out} = I_{in} - I_1$	HP
I_{in}	0	$I_{out} = I_{in} - I$	BR
I_{in}	0	$I_{out} = I_1$	BP

III. SIMULATION RESULTS

The PSPICE simulation of the proposed square-root domain second order current-mode multi-function filter circuit were performed using TSMC 0.35μm Level3 CMOS transistor parameters [22]. The sizes of the transistor used in the circuit were chosen as $W/L = 10\mu m/10\mu m$ for $M_1 \sim M_7$ transistors and $W/L = 220\mu m/2\mu m$ for $M_8 \sim M_{15}$ transistors. $V_{DD} = 3V$ and $C = 300pF$ were taken for the supply voltage and capacitors values used in the circuit. Gain responses were obtained for different cut-off frequency values of the multifunctional filter circuit. For this purpose, it was observed that when the value of I_0 dc current sources is changed between $2.8\mu A \sim 140.2\mu A$, the cut-off frequency of the filter circuit changes between $5.5kHz \sim 45kHz$. The gain response curves for the different cut-off frequency values of the multifunction filter are shown in Fig.3.

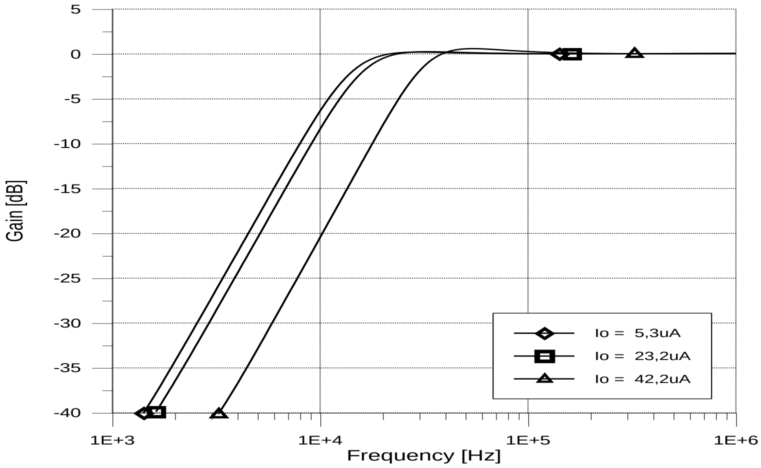

Figure 3. Gain responses of high-pass filter at different values of I_0.

The gain response curves for the band-reject and band-pass outputs of the different cut-off frequency values of the multifunctional filter circuit are shown in Fig.4 and Fig.5, respectively.

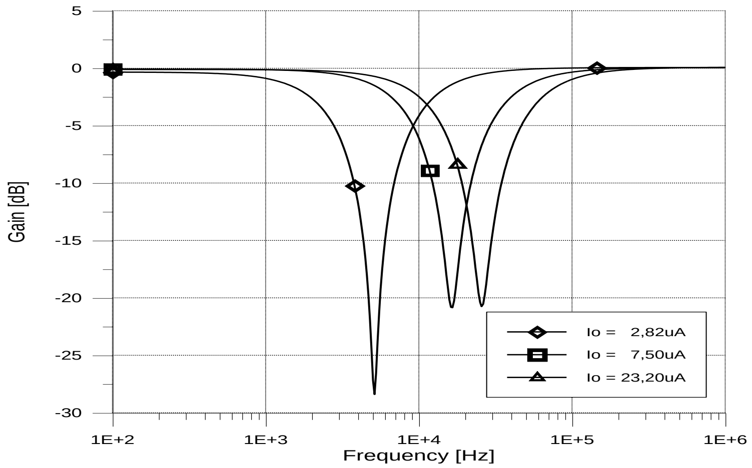

Figure 4. Gain responses of band-reject filter at different values of I_0.

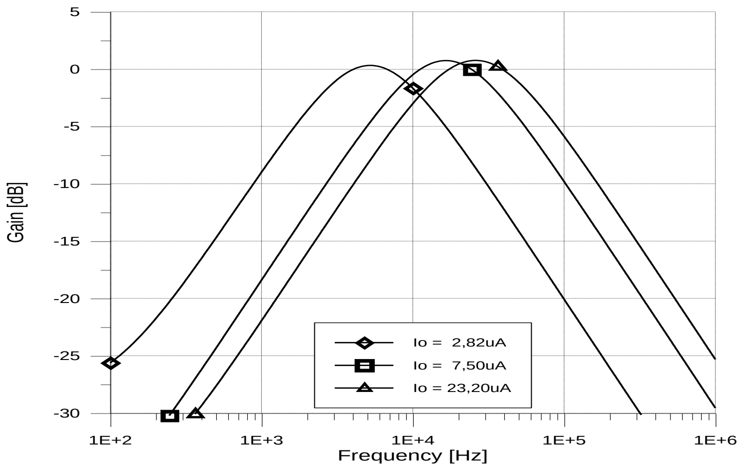

Figure 5. Gain responses of band-pass filter at different values of I_0.

When an input signal with a frequency of $25kHz$ and a peak amplitude of $20\mu A$ is applied to the input of the multifunction filter circuit, the time-dependent changes of the input current and the output current obtained from the band-pass output for $I_0 = 23.2\mu A$ are obtained as shown in Fig.6.

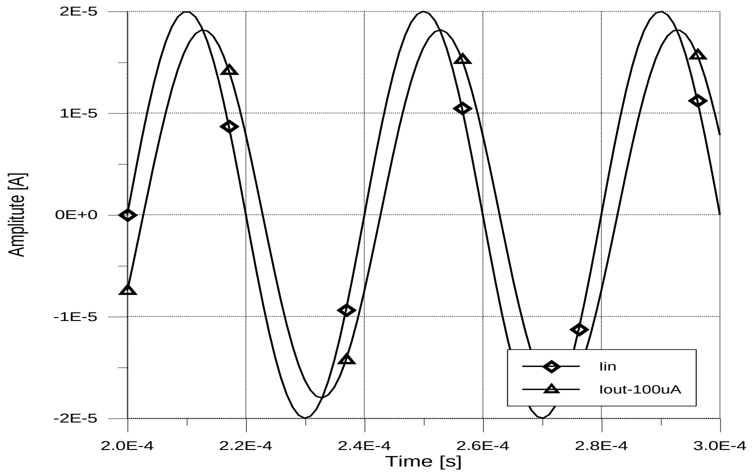

Figure 6. Time domain responses of band-pass filter.

When the amplitude peak value of the signal with frequency value of $25kHz$ applied to the input of the multifunction filter circuit is changed within the range of $15\mu A \sim 100\mu A$, the total harmonic distortion (THD) occurring in the band-pass output current is less than 2%. The power consumption of the multifunctional filter circuit is on the level of $25mW$.

IV. CONCLUSION

In this study, a square-root domain second order current-mode multifunction filter circuit was implemented using a state-space synthesis method. High-pass, band-reject and band-pass current outputs can be obtained from this multifunction filter circuit. In the filter circuit, square-root and squarer/divider analogue processing blocks with square-root domains as well as current mirrors and dc current sources were used. Apart from these, two grounded capacitors and one dc voltage source were used. The cut-off frequency f_0 and the Q quality factor of the filter circuit can be adjusted electronically by changing the values of the I_0 dc current sources. By changing the current values of the dc current sources I_0, gain responses with different cut-off frequency values were obtained. The theoretical results obtained were verified by PSPICE simulations.

REFERENCES

[1]. B. Gilbert, Translinear circuits: A proposed classification, Electron. Lett., 11(1),, 1974, 14-16.
[2]. J. Ngarmnil and C. Toumazou, Micropower log-domain active inductor, Electron. Lett., 32(11), 1996, 953-955.
[3]. E. Seevinck and R. J. Wiegerink, Generalized translinear circuit principle, IEEE J. Solid-State Circuits, 26(8), 1991, 1098-1102.
[4]. J. Mulder, Static and dynamic translinear circuits, (Netherlands, Delft University Press, 1998).
[5]. A. Payne and C. Toumazou, Linear transfer function synthesis using non-linear IC components, Proc. ISCAS'96, Atlanta, USA, 1996, 53-56.
[6]. M. H. Eskiyerli, A. J. Payne and C. Toumazou, State-space synthesis of integrators based on the MOSFET square law,Electronics Letters, 32(6), 1996, 505-506.
[7]. M. H. Eskiyerli and A. J. Payne, Square root domain filter design and performance, Analog Integrated Circuits Signal Process, 22( ), 2000, 231-243.
[8]. A. J. Lopez-Martin and A. Carlosena, Systematic design of companding system by component substitution, Analog Integrated Circuits Signal Process, 28(1), 2001, 91-106.
[9]. S. Menekay, R. C. Tarcan and H. Kuntman, Novel high-precision current-mode circuits based on the MOS-translinear principle, Int. J. Electron Commun. (AEU), 63, 2009, 992-997.
[10]. M. S. Keserlioglu and A. Kircay, The design of current-mode electronically tunable first-order square-root domain filters using state-space synthesis method, Int.Review on Modelling and Simulation, 2(2), 2009, 124-128.

[11]. A. J. Lopez-Martin and A. Carlosena, 1.5V CMOS companding filter, Electronics Lett., 38(22), 2002, 1346-1348.
[12]. A. J. Lopez-Martin and A. Carlosena, Very low voltage CMOS companding filters based on the MOS translinear principle, Mixed-Signal Design SSMSD Southwest Symposium on, Austin, Texas, 2001, 105-109.
[13]. J. V. Kumar and K. R. Rao, A low-voltage low power CMOS companding filter, Proceedings of the 16th International Conf. on VLSI design (VLSI'03),2003.
[14]. G. J. Yu, B. D. Liu, Y. C. Hsu and C. Y. Huang, Design of square-root domain filters, Analog Integrated Circuits and Signal Processing, 43(1), 2005, 49-59.
[15]. S. Menekay R. C. Tarcan and H. Kuntman, The second-order low-pass filter design with a novel higher precision square-root circuit, Istanbul Univ. J. Electr. Electron., 7(1), 2007, 323-329.
[16]. M. H. Eskiyerli, A. J. Payne and C. Toumazou, State-space synthesis of biquads based on the MOSFET square law, Circuits and Systems ISCAS'96, Atlanta, GA, 1996, 321-324.
[17]. A. Kircay and M. S. Keserlioglu, Novel current-mode second order square-root-domain highpass and allpass filter, 6th Int. Conf. on Electrical and Electronics Eng., Bursa, Turkey, 2009.
[18]. A. Kircay, M. S. Keserlioglu and U. Cam, A new current-mode square-root-domain general notch filter, Journal of Circuits, Systems and Computers, 22(1), 2013, 1-10.
[19]. C. Laoudias, C. Psychalions and E. Stoumpou, 1.5V square-root domain universal biquad filters, Int. J. Circuit Theory Appl., (41), 2013, 307-318.
[20]. A. Kircay, M. S. Keserlioglu and F. Z. Sagi, Design of third order square-root-domain filters using state-space synthesis method, 9th Int. Conf. on Electrical and Electronics Eng., Bursa, Turkey, 2015.
[21]. J. Mulder, W. A. Serdjn, A. C. Van Der Woerd and A. H. M. Van Roermund, A 3.3 volt current-controlled √-domain oscillator, Analog Integrated Circuits and Signal Processing, 16(1), 1998, 17-28.
[22]. S. Minaei, Dual-input current-mode integrator and differentiator using single DVCC and grounded passive elements, IEEE MELECON 2004, Dubrovnik, Croatia, 2004.