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SQUARE-ROOT-DOMAIN SECOND-ORDER TRANS-ADMITTANCE TYPE UNIVERSAL FILTER DESIGN

KAREKÖK ORTAMLI İKİNCİ DERECEDEN GEÇİŞ-İLETKENLİĞİ TÜRÜ EVRENSEL SÜZGEÇ TASARIMI

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Abstract

In this study, a square-root-domain (SRD) electronically-tunable second-order trans-admittance type filter is proposed. The proposed filter has one voltage input and two current outputs and can simultaneously realize low-pass (LP) and band-pass (BP) responses without any changes in the circuit topology. Additionally, trans-admittance type second-order universal filter that has low-pass, band-pass, high-pass (HP), all-pass (AP) and notch (N) outputs is realized by adding a circuitry. The transfer admittance parameter g_0, natural frequency f_0 and quality factor Q of the trans-admittance type filter can be electronically tuned by changing DC control current sources. Some time and frequency domain simulations are performed using PSPICE program for the proposed trans-admittance type filters.
Keywords: Square-root-domain filter, Universal filter, Trans-admittance type filter

Öz

Bu çalışmada, kare-kök-ortamlı, elektronik olarak ayarlanabilen, girişi gerilim çıkışı akım olan ikinci dereceden bir geçiş-iletkenliği türü süzgeç sunuldu. Önerilen süzgeç bir gerilim girişi ve iki akım çıkışına sahiptir ve devre üzerinde bir değişiklik yapılmaksızın alçak geçiren (AG) ve bant geçiren (BG) cevaplar elde edilebilir. İlave olarak, bir devre eklenerek, alçak geçiren, bant geçiren, yüksek geçiren (YG), tüm geçiren (TG) ve çentik (Ç) süzgeç çıkışlarına sahip geçiş-iletkenliği türü ikinci dereceden bir evrensel süzgeç gerçeklendi. Geçiş iletkenliği türü süzgecin geçiş-iletkenliği parametresi g_0, doğal frekansı f_0 ve kalite faktörü Q doğru akım kaynaklarının değerleri değiştirilerek elektronik olarak ayarlanabilir. Geçiş iletkenliği türü süzgecin zaman ve frekans ortamı benzetimleri PSPICE kullanılarak gerçekleştirilmiştir.
Anahtar kelimeler: Kare-kök-ortamlı süzgeç, Evrensel süzgeç, Geçiş iletkenliği türü süzgeç

1 Introduction

Log-domain filters and square-root-domain filters are important classes of companding filters, in which the signals are compressed at the input stages before being processed and then expanded at the output stages. A log-domain filter was previously proposed by Adams [1] and then the first implementation of a log-domain filter was achieved by Frey [2]. The classical translinear principle is based on the exponential I–V characteristics of BJTs and MOS transistors in weak inversion region [3],[4]. A simple example of the quadratic law of MOS is the linear transconductor that was proposed by Bult [5]. The MOS translinear (MTL) principle is derived by Seevinck [6] from the bipolar translinear (BTL) principle [7]. Afterward studies that were lead to SRD filters, the quadratic law of MOS in strong inversion region and saturation region and the voltage translinear principle were used [8]-[12].

Companding filters were studied by a number of researchers, because these filters have the advantages of high-frequency operation, electronic tunability and large dynamic range under low power supply voltages [11],[12].

A number of SRD circuits such as first-order filters [13]-[15], second-order voltage-mode (VM) [16], [17] and current-mode (CM) filters [11],[15],[18],[19] and trans-admittance circuits [12],[13],[20] were presented by the authors in the literature. Also, there are some papers in the literature about the square-root and the squarer/divider structures that were used to obtain trans-admittance type filter circuits [10],[18],[21]. However, not many works have been proposed in the area of

SRD trans-admittance type filter design by using steady-space equations [22]. A trans-admittance type filter that has voltage-input current-output can be described as an interface connecting a VM circuit to a CM circuit [22]-[24].

In this study, SRD trans-admittance type universal filter is designed by using steady-space synthesis method. Proposed filter circuit consists of two type SRD analog process block: square-root and squarer/divider structures. Beside of these analog blocks, DC current sources, MOS current mirrors, DC power supply and two grounded capacitors are included by the proposed filter circuit. The natural frequency f_0 trans-admittance parameter g_0 and quality factor Q of the filter can be electronically tuned by changing values of DC control current sources. To obtain a variable quality factor, a negative feedback is applied to the filter circuit [19],[25].

2 The Realization of Trans-admittance Type Universal Filter

The trans-admittance type SRD multifunction filter that has second-order LP and BP outputs can be described by the state-space equations as follows:

$$\dot{x}_1 = -a_1\omega_0 x_1 + a_2\omega_0 x_2 \qquad (1a)$$

$$\dot{x}_2 = -a_3\omega_0 x_2 - k(x_1 - x_2)a_4\omega_0 + a_4\omega_0 g_0 u \qquad (1b)$$

Where ω_0 is the cut-off frequency of filter and, a_1, a_2, a_3 and a_4 are constants, u is the input, x_1 and x_2 are the state variables, g_0 is the trans-admittance parameter of filter and k is the feedback coefficient. The output variables y_1 and y_2 are defined by equations (2a) and (2b) as given below:

$$y_1 = x_1 \tag{2a}$$

$$y_2 = (2 - k)(x_1 - x_2) \tag{2b}$$

Where y_1 and y_2 are represented by LP and BP outputs, respectively. The Eq. (1a) and Eq. (1b) can be transformed into a set of nodal equations by using square mappings on the input and state variables. The following mappings can therefore be applied to quantities in equation (1a) and (1b) [10],[14],[21]:

$$x_1 = \frac{\beta}{2}(V_1 - V_{th})^2 \tag{3a}$$

$$x_2 = \frac{\beta}{2}(V_2 - V_{th})^2 \tag{3b}$$

$$I_U = \frac{\beta}{2}(u - V_{th})^2 \tag{3c}$$

Where, $\beta = \mu_0 C_{ox}(W/L)$, V_1 and V_{th} are the device trans conductance parameter, the gate-to-source voltage and the threshold voltage respectively. U and the derivatives of x_1 and x_1 are given by

$$\dot{x}_1 = \beta \dot{V}_1 (V_1 - V_{th}) = \dot{V}_1 \sqrt{2\beta x_1} \tag{4a}$$

$$\dot{x}_2 = \beta \dot{V}_2 (V_2 - V_{th}) = \dot{V}_2 \sqrt{2\beta x_2} \tag{4b}$$

$$u = V_{th} + \sqrt{2I_u/\beta} \tag{4c}$$

The above relationships are applied to Eq. (1a) and (1b) as follows:

$$C_1 \dot{V}_1 = -\frac{a_1 C_1 \omega_0 \sqrt{x_1}}{\sqrt{\beta}\sqrt{2}} + \frac{a_2 C_1 \omega_0 x_2}{\sqrt{\beta}\sqrt{2}\sqrt{x_1}} \tag{5a}$$

$$C_2 \dot{V}_2 = -\frac{a_3 C_2 \omega_0 \sqrt{x_2}}{\sqrt{\beta}\sqrt{2}} - k(x_1 - x_2)\frac{a_4 C_2 \omega_0}{\sqrt{\beta}\sqrt{2}\sqrt{x_2}} + \frac{a_4 C_2 \omega_0}{\sqrt{\beta}\sqrt{2}\sqrt{x_2}}\left[g_0 V_{th} + \frac{g_0}{\sqrt{\beta}}\sqrt{2I_u}\right] \tag{5b}$$

Then, I_{g0}, I_{T0} and I_k currents can be defined as given below [22]:

$$I_{T0} = g_0 V_{th} \tag{6a}$$

$$I_{g0} = g_0^2/\beta \tag{6b}$$

$$I_k = I_{T0} + 2\sqrt{\frac{I_u I_{g0}}{2}} \tag{6c}$$

These currents are used in Eq. (5a) and (5b) and they can be rearranged to form the following nodal equations:

$$C_1 \dot{V}_1 = -\sqrt{\frac{I_{01} x_1}{2}} + \sqrt{\frac{I_{02} x_2^2}{2x_1}} \tag{7a}$$

$$C_2 \dot{V}_2 = -\sqrt{\frac{I_{03} x_2}{2}} + \sqrt{\frac{I_{04}}{2x_2}}[I_k - k(x_1 - x_2)] \tag{7b}$$

Where I_{01}, I_{02}, I_{03}, I_{04} can be defined as $I_{0i} = a_i^2 I_0$, $i = 1,2,3,4$ [19], and I_0 can be written as $I_0 = \omega_0^2 C^2/\beta$ [11],[16]-[19],[22]. It should be noted that ω_0 can electronically be tuned by changing I_0 as shown in Eq. (8) [11],[17],[22].

$$\omega_0 = \sqrt{\beta}\sqrt{I_0}/C \tag{8}$$

The proposed second order SRD trans-admittance type filter circuit with LP and BP outputs can be achieved via Eq. (7a), (7b) and (6c) as shown in Figure 1.

The feedback circuit that is consists of MOS current mirrors and an analog process block [11],[13],[18] that was built by connecting the output terminal of squarer/divider circuit to input terminal of square-root circuit is marked by dashed line in Figure 1. The current gain of feedback circuit is represented by the coefficient of k and it can be tuned by changing values of DC current sources I_{o5} and I_{o6} as given in equation (9):

$$k = \sqrt{I_{05}/2I_{06}} \tag{9}$$

The output variables y_1 and y_2 of the trans-admittance type filter can be derived from Eq. (2a) and (2b) via Eq. (1a) and (1b) given as written in Eq. (10a) and (10b).

$$y_1 = \frac{a_2 a_4 \omega_0^2 g_0}{s^2 + s(a_1 + a_3 - ka_4)\omega_0 + [a_1 a_3 - ka_4(a_1 - a_2)]\omega_0^2}u \tag{10a}$$

$$y_2 = \frac{(2-k)[-s + \omega_0(a_2 - a_1)]a_2 g_0 \omega_0}{s^2 + s(a_1 + a_3 - ka_4)\omega_0 + [a_1 a_3 - ka_4(a_1 - a_2)]\omega_0^2}u \tag{10b}$$

If the constants are chosen as $a_1 = a_2 = a_3 = a_4 = 1$ the output variables in Eq. (10a) and (10b) are reduced to

$$y_1 = \frac{g_0 \omega_0^2}{s^2 + (2-k)\omega_0 s + \omega_0^2}u \tag{11a}$$

$$y_2 = \frac{-g_0(2-k)\omega_0 s}{s^2 + (2-k)\omega_0 s + \omega_0^2}u \tag{11b}$$

A relationship can be derived from denominator polynomials of Eq. (11a) and (11b) for quality factor as given in Eq. (12):

$$Q = 1/(2-k) \tag{12}$$

N, HP and AP output currents are obtained by using y_1, y_2 and I_k in suitable algebraic equations as given follows:

$$y_N = y_2 + I_k = \frac{g_0(s^2 + \omega_0^2)}{s^2 + (2-k)\omega_0 s + \omega_0^2}u \tag{13a}$$

$$y_{HP} = y_1 - y_N = \frac{-g_0 s^2}{s^2 + (2-k)\omega_0 s + \omega_0^2}u \tag{13b}$$

$$y_{AP} = y_2 + y_N = \frac{g_0[s^2 - (2-k)\omega_0 s + \omega_0^2]}{s^2 + (2-k)\omega_0 s + \omega_0^2}u \tag{13c}$$

Finally, the sub-circuit that is shown in Figure 2 is connected to main filter circuit via A, B and C terminals to obtain N, HP and AP responses.
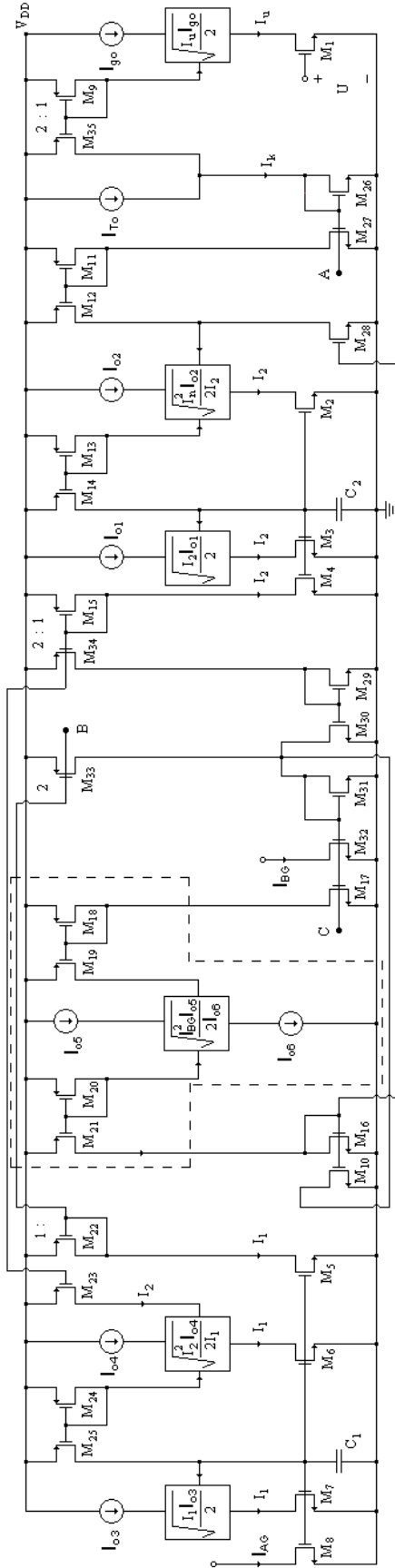
Figure 1: SRD trans-admittance type filter with LP and BP outputs.

3 Simulation Results

The proposed SRD trans-admittance type universal filter was simulated by *TSMC 0.35 µm Level 3 CMOS* process parameters [26]. The circuit parameters are chosen as, $V_{DD} = 3V$ and $C_1 = C_2 = 280pF$. The transistor dimensions are chosen as $W/L = 10\mu m/10\mu m$ for $M_1 \sim M_8$, $W/L = 220\mu m/2\mu m$ for $M_9 \sim M_{32}$ and $W/L = 440\mu m/2\mu m$ for $M_{33} \sim M_{35}$. Also, $W/L = 220\mu m/2\mu m$ all transistors in sub-circuit.
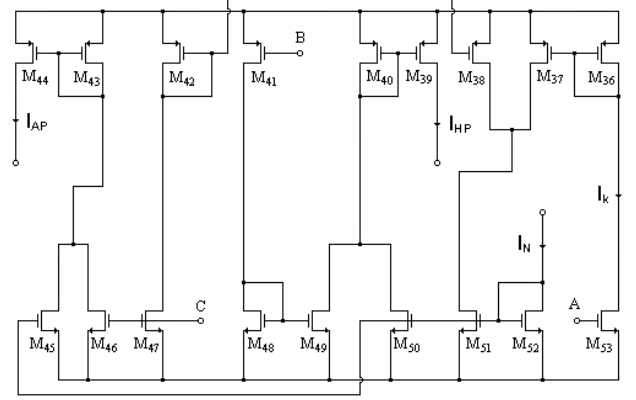

Figure 2: Sub-circuit for HP, N and AP outputs.

The natural frequency of universal filter is $f_0 = 10kHz$ for $I_{01} = I_{02} = I_{03} = I_{04} = 2.1\mu A$, the quality factor is $Q = 1$ for $I_{05} = 60\mu A$ and $I_{06} = 30\mu A$ and the trans-admittance parameter $g_0 = 30\mu S$ for $I_{go} = 6\mu A$ and $I_{To} = 10\mu A$. For this situation gain responses of LP, HP, BP, N and AP outputs are shown in Figure 3.

The natural frequency of the filter changes from about $10kHz$ to $110kHz$, when I_{01}, I_{02}, I_{03} and I_{04} DC control currents are changed from $2.1\mu A$ to $330\mu A$. Thus the natural frequency of the filters can be adjusted in a frequency range of about $100kHz$. The natural frequency tuning range for gain responses of the LP, HP, BP, N and AP filters for $Q = 1$ are shown in Figure 4.

The trans-admittance parameter of the universal filter changes from about $30\mu S$ to $60\mu S$ when I_{go} dc biasing current is changed from $6\mu A$ to $36\mu A$. The trans-admittance parameter tuning range for gain responses of the universal filter is shown in Figure 5 for LP and HP responses.

The gain responses of trans-admittance type universal filter for different quality factor are given in Figure 6 for LP and HP responses. The different quality factor could be obtained by chancing I_{05} and I_{06}. The values of DC current sources are chosen as $I_{05} = 26\mu A$ and $I_{06} = 87\mu A$ for $Q = 1/\sqrt{2}$, $I_{05} = 60\mu A$ and $I_{06} = 30\mu A$ for $Q = 1$ and $I_{05} = 80\mu A$ and $I_{06} = 12\mu A$ for $Q = \sqrt{2}$.

When peak values of sinusoidal input voltages at $10kHz$ frequency are changed from $50mV$ to $400mV$, THD (Total Harmonic Distortion) of output currents remains less than 3% for $g_0 = 30\mu S$.

Time domain responses of BP and LP outputs for input signal that has $400mV$ peak value at $10kHz$ frequency are shown in Figure 7.
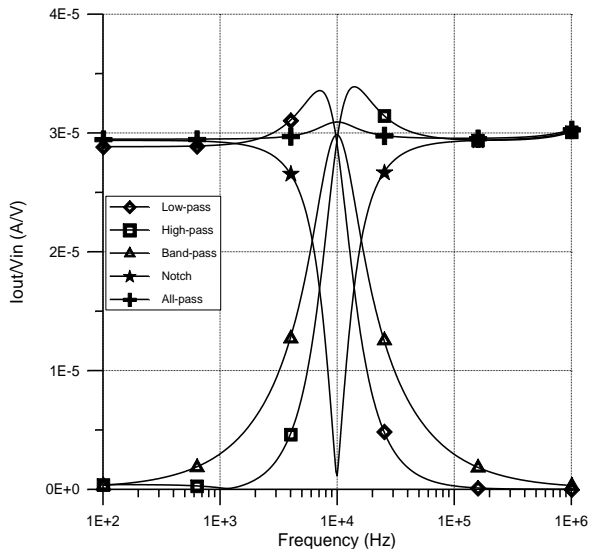
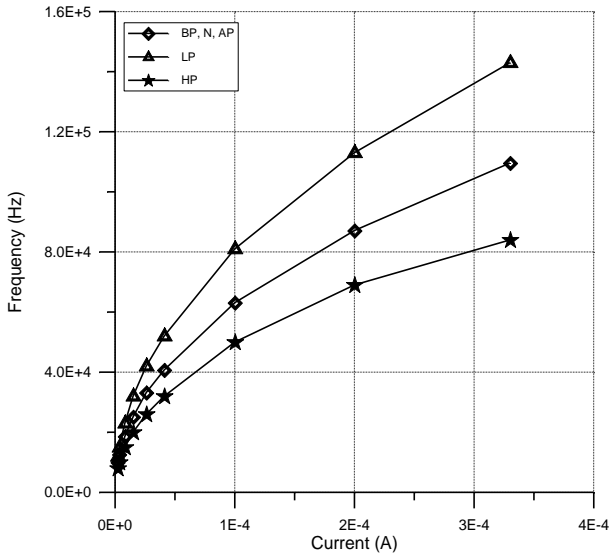Figure 3: Gain responses of the universal filter.
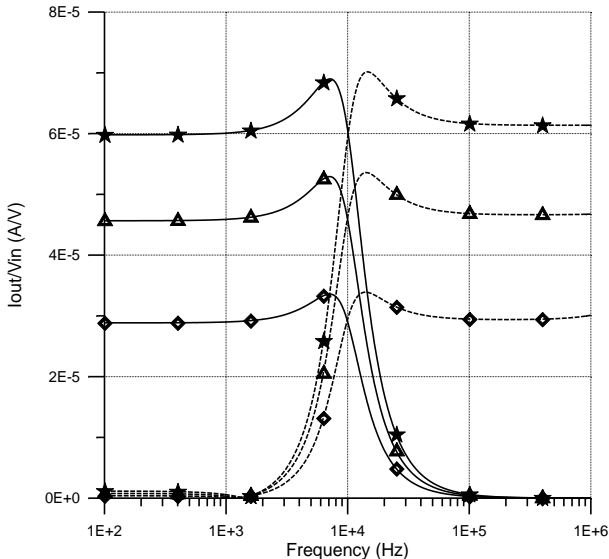

Figure 4: Natural frequency tuning range.

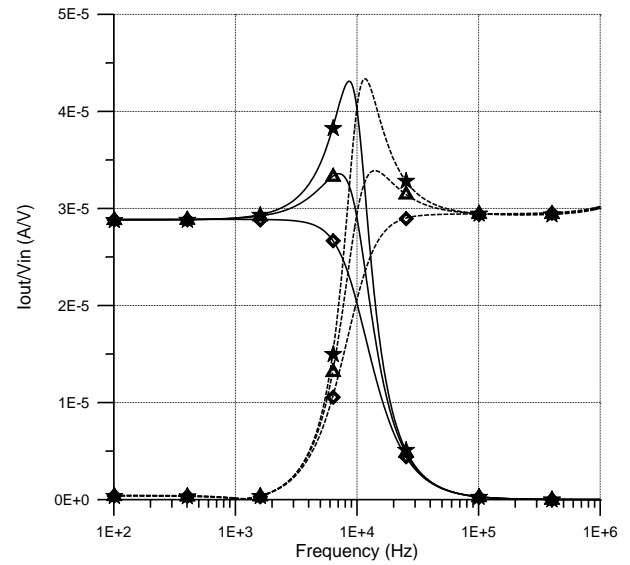Figure 5: LP and HP responses for different trans-admittance values.

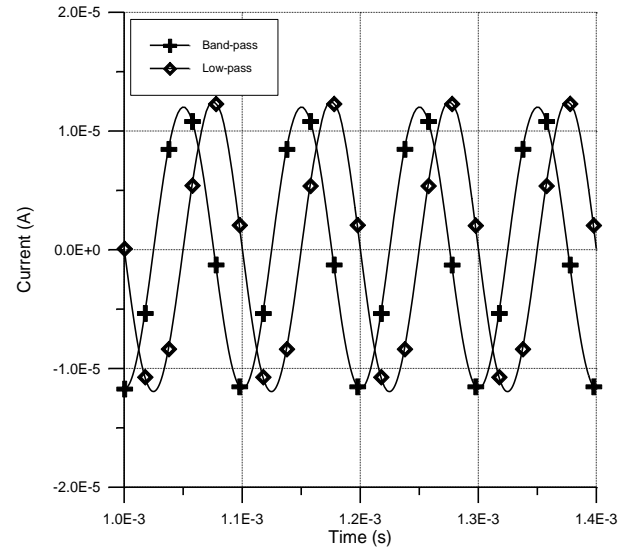Figure 6: LP and HP responses for different quality factors.

Figure 7: Time domain responses of BP and LP filters.

The calculated dynamic range at $10kHz$ is approximately equal to $38dB$ and the total power dissipation is $9.98mW$.

4 Conclusions

A SRD trans-admittance type universal filter is proposed in this work. Square-root and square/divider building blocks and current mirrors are used in the filter circuit and a feedback is applied to the filter in order to increase quality factor. PSPICE simulations confirm the theoretical analysis. The novelty of this paper is an application of steady-space synthesis method. The natural frequency, trans-admittance parameter and quality factor of filter can be tuned by changing values of DC control current sources.

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