Current-Mode Second-Order Square-Root-Domain Bandpass Filter for Low Frequency Applications

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Abstract -In this study, square-root-domain current-mode second order bandpass filter circuit has been suggested for low frequency applications. The design of the circuit was carried out with two subcircuits which are square-root circuit and squarer/divider circuit and this is based on state-space-synthesis method. The circuit's all the input and output values are current. Only grounded capacitors and MOS transistors are needed in order to actualize the filter circuit. The central frequency of the filter can be adjusted by changing the values of the external current sources. Frequency and time response simulations of PSPICE was used in order to verify the filter theory and indicate its performance. To this end, the simulation of the filter was carried out by using the TSMC 0.25μm Level 3 CMOS process parameters.

Keywords: Square-root-domain filters, companding systems, current-mode circuits, allpass filters, quadrature oscillators, electronically tunable.

1. Introduction

In recent years, many researches are trying to develop companding filters containing the square-root-domain and log-domain filters. The reason why companding filters are studied by many researchers is that they can be adjusted electronically, have a wide dynamic range under low power/supply voltage and because they can operate at high frequency applications (Frey, 1993; Kircay and Cam, 2006; Kircay and Cam, 2008; Mulder, 1996; Mulder, 1998; Mulder et al., 2000; Seevinck, 1990; Tsividis, 1990). A significant class of dynamic translinear circuits and companding filters is square-root-domain filters (Mulder, 1996; Mulder, 1998; Mulder et al., 2000). Input signals are first compressed in companding filters after which they are processed in a suitable manner and finally they are expanded at the outlet. The operating principle of companding filters is based on the exponential I-V characteristic of BJT and the MOSFETs at the weak inversion region. The quadratic law of MOSFET was suggested in (Bult and Wallinga, 1987). MOS translinear (MTL) feature was derived by (Seevinck and Wiegerink, 1991) based on the bipolar translinear (BTL) principle of (Gilbert, 1975). The quadratic law of MOSFET at the linear and saturation region has been used in (Eskiyerli and Payne, 2000; Lopez-Martin and Carlosena, 2002; Mulder et al., 1996). MOS translinear approach has been used in many analog structure block applications such as square-root-domain integrators (Mulder et al., 1996; Psychalinos and Vlassis, 2002), oscillators (Mohammed and Soliman, 2005; Mulder et al., 1998) and filters (Menekay et al., 2007; Veerendra Kumar and Radhakrishna Rao, 2003; Yu et al., 2000; Yu et al., 2005).

The proposed square-root-domain current-mode second order band pass filter circuit can be defined as current-mode since the suggested circuit's all the input and output signals are current. Majority of the fundamental mathematical functions can be obtained from current signals rather than voltage. It is easier

to express the mathematical operations of addition, subtraction or multiplication signals via current instead of voltage. Hence, the actualization of current mode integrated systems is closer to the transistor level in comparison with the traditional voltage mode actualizations and as a result it is more suited to simple systems and the carrying out of circuit finalization (Kircay, 2014). Until now, several square-root-domain current-mode second order band pass filters have been suggested in literature (De La Cruz-Blaz et al., 2005; Kircay, 2014; Yu and Lin, 2010; Yu et al. 2005).

In this study, square-root-domain current-mode second order band pass filter circuit for low frequency applications has been presented. Low frequency offers low signal attenuation for long distance communications. In some areas, part of the low frequency spectrum is used for AM broadcasting as the long-wave band. In other areas, its main use is for navigation, information, and weather systems. A number of time signal broadcasts are also broadcast in this band.

The filter circuit suggested in this study has various advantages over the other band pass filters such as the fact that it is current-mode, that it is made up only of transistors and grounded capacitors, that it provides a wide dynamic range and low THD, that the central frequency can be adjusted electronically via external current sources and that it is suitable for low voltage/power applications.

2. Square-Root-Domain Current-Mode Second Order Band Pass Filter

Square-root-domain current-mode second order band pass filter has been designed using state-space-synthesis method in this study. Square-root-domain current-mode second order band pass filter's transfer function can be expressed as below:

$$H(s) = \frac{\frac{\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{1}$$

Here, ω_0 denotes central frequency and Q stands for the quality factor. The state-space-equations for square-root-domain current-mode second order band pass filter can be expressed as below:

$$\dot{x}_1 = -\frac{\omega_0}{Q}x_2 + \frac{\omega_0}{Q}u \tag{2}$$

$$\dot{x}_2 = Q\omega_0 x_1 - \frac{\omega_0}{Q}x_2 + \frac{\omega_0}{Q}u \tag{3}$$

The output equation is:

$$y = x_1 \tag{4}$$

Here, u denotes the input, y the output whereas x_1 and x_2 represent the state variables. Eqs. (2) and (3) can be transformed into nodal equations set using the square mappings of the input and state variables. Hence, the following transformations can be applied to the quantities in the equation:

$$x_1 = \frac{\beta}{2}(V_1 - V_{th})^2 \tag{5a}$$

$$x_2 = \frac{\beta}{2}(V_2 - V_{th})^2 \tag{5b}$$

In the equations, $\beta = \frac{\mu_0 C_{ox} \omega}{L}$ stands for transconductance, V_1 and V_2 represents gate-source voltages and V_{th} represents the threshold voltage. If we take the derivative of the saturation equation, we get:

$$\dot{x}_1 = \beta \dot{V}_1 (V_1 - V_{th}) \tag{6a}$$

$$\dot{x}_2 = \beta \dot{V}_2 (V_2 - V_{th}) \tag{6b}$$

The relation given above can be organized to yield the nodal equations below after they are applied to Eqs. (2) and (3):

$$C\dot{V}_1 = -\frac{\omega_0 C}{\sqrt{\beta}} \sqrt{\frac{x_2^2}{2x_1}} \frac{1}{Q} + \frac{\omega_0 C}{\sqrt{\beta}} \sqrt{\frac{u^2}{2x_1}} \frac{1}{Q} \tag{7}$$

$$C\dot{V}_2 = \frac{\omega_0 C}{\sqrt{\beta}} Q \sqrt{\frac{x_1^2}{2x_2}} - \frac{\omega_0 C}{\sqrt{\beta}} \sqrt{\frac{x_2^2}{2x_2}} \frac{1}{Q} + \frac{\omega_0 C}{\sqrt{\beta}} \sqrt{\frac{u^2}{2x_2}} \frac{1}{Q} \tag{8}$$

In these equations, C is a capacitor value resembling a multifunction factor. $C\dot{V}_1$ and $C\dot{V}_2$ in Eqs. (7) and (8) can be accepted as time dependent currents that are grounded via two capacitors.

I_0 is a positive constant as given below:

$$I_0 = \frac{\omega_0^2 C^2}{\beta} \tag{9}$$

Eqs. (7) and (8) can be arranged as follows:

$$C\dot{V}_1 = -\sqrt{\frac{x_2^2 I_0}{2x_1}} \frac{1}{Q} + \sqrt{\frac{u^2 I_0}{2x_1}} \frac{1}{Q} \tag{10}$$

$$C\dot{V}_2 = \sqrt{\frac{x_1^2 I_0}{2x_2}} Q - \sqrt{\frac{x_2 I_0}{2}} \frac{1}{Q} + \sqrt{\frac{u^2 I_0}{2x_2}} \frac{1}{Q} \tag{11}$$

If we accept the quality factor as $Q=1$, the state equations in Eqs. (10) and (11) can be written as below:

$$CV_1 = -\sqrt{\frac{x_2{}^2 I_0}{2x_1}} + \sqrt{\frac{u^2 I_0}{2x_1}} \qquad (12)$$

$$CV_2 = \sqrt{\frac{x_1{}^2 I_0}{2x_2}} - \sqrt{\frac{x_2 I_0}{2}} + \sqrt{\frac{u^2 I_0}{2x_2}} \qquad (13)$$

The output equation is:

$$y = x_1 = \frac{\beta}{2}(V_1 - V_{th})^2 \qquad (14)$$

Two subcircuits are used to obtain the suggested filter circuit. The first subcircuit includes the square-root circuit structure, whereas the second subcircuit includes the square-root circuit and squarer/divider structures (Eskiyerli and Payne, 2000). Square-root current-mode circuit and squarer/divider current-mode circuit are MOS translinear MTL circuits (Menekay et al., 2007; Yu et al., 2005). Fig. 1 shows the square-root circuit and Fig. 2 shows the squarer/divider circuit (Menekay et al., 2007; Yu et al., 2005). The second subcircuit block diagram has been given in Fig. 3.

The square-root-domain current-mode second order band pass filter has been actualized using Eqs. (12), (13) and (14) with a square-root circuit, a subcircuit made up of a square-root circuit and a squarer/divider circuit, current sources and two grounded capacitors. The band pass filter's central frequency given in Eq. (15) can be adjusted by changing the I_0 current value. Central frequency ω_0 is indirectly proportional with the capacitor value C and directly proportional with the square-root of the I_0 current:

$$\omega_0 = \frac{\sqrt{I_0 \beta}}{C} \qquad (15)$$

Fig. 1. Current-mode square-root circuit

Fig. 2. Current-mode squarer/divider circuit
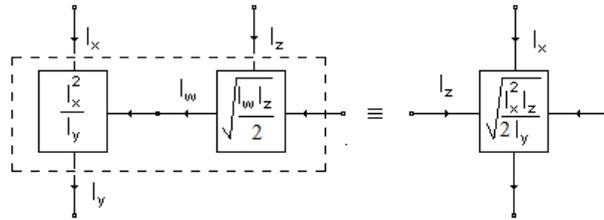
Fig. 3. Second subcircuit

3. Simulation Results

TSMC 0.25μm Level 3 CMOS transistor parameters have been used in the PSPICE simulations of the designed square-root-domain current-mode second order band bass filter. The transistor dimensions used in the second order band pass filter have been given in Table 1. The supply voltage of the filter circuit has been selected as $V_{DD} = 3V$, the values of the capacitors have been selected as $C = 200pF$ and the values of the dc current sources have been selected as $I_0 = 80\mu A$. The central frequency of the filter under these circumstances is 88kHz. The gain and phase responses of the second order band pass filter along with the theoretical results have been given in Fig. 5 and Fig. 6.
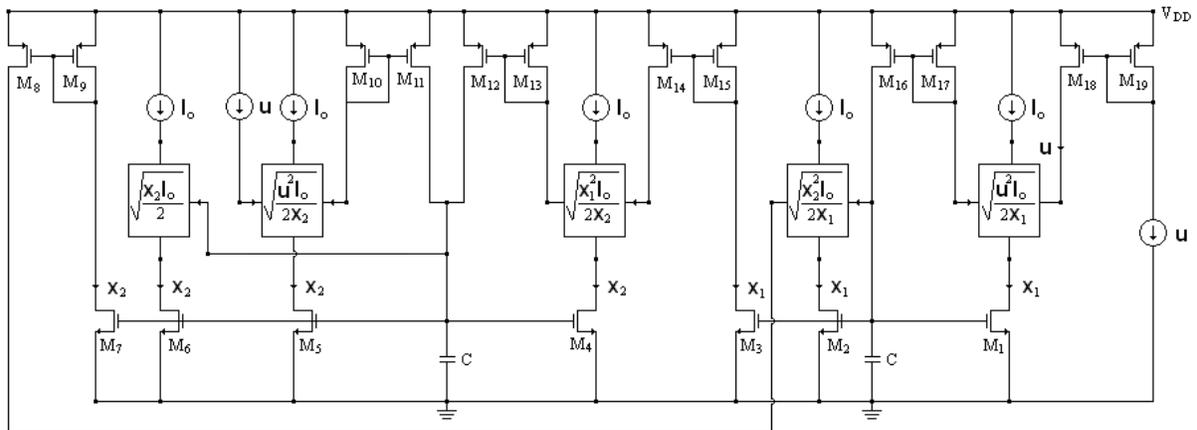
Fig. 4. Square-root-domain current-mode second order band pass filter circuit

Table. 1. Dimensions of MOS transistors.

	Transistor	ω (µm)	L (µm)
Square-root circuit	M_{11}	55	2
	M_1, M_{13}	60	2
	M_{10}	110	2
	M_2, M_3, M_4	120	2
	$M_5 - M_9, M_{12}, M_{14} - M_{17}$	220	2
Squarer/divider circuit	M_1, M_2, M_{13}	60	2
	M_{10}, M_{11}	110	2
	M_3, M_4	120	2
	$M_5 - M_9, M_{12}, M_{14} - M_{17}$	220	2
Band pass filter circuit	$M_1 - M_7$	20	2.0
	$M_8 - M_{19}$	22	8

It can be seen from the equations that the central frequency of the filter can be adjusted. Different gain responses have been attained for different central frequency values by changing the values of the dc current sources I_0 in second order band pass filter circuit. The central frequency varies between 20kHz-120kHz when the values of the I_0 dc current are changed between 3µA-160µA for the second order band bass filter. As a result, the central frequency of the filter can be adjusted in the 100kHz frequency range. The gain response obtained for the different values of the direct current sources I_0 of the filter circuit have been given in Fig. 7.

The time domain response obtained as a result of applying 88 kHz sinus wave with an amplitude of 10µA to the input of the second order band pass filter can be seen in Fig. 8. The output amplitude was greater than the input amplitude since the gain of the input at 88kHz was about 1dB.

The total harmonic distortion of the output signals have been measured for different current values. The total harmonic distortion was measured as %3.4 when a 88kHz sinus with an amplitude of 10µA is applied to the input. The properties and performances of the suggested second order band pass filter have been given in Table 2.
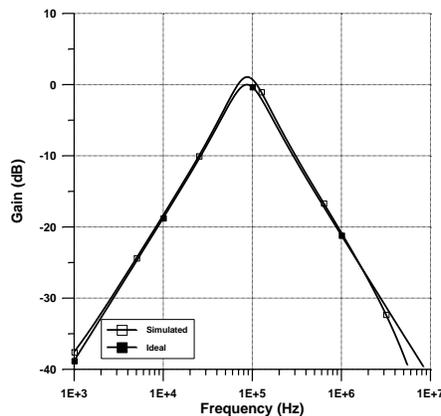
Fig. 5. Gain response of second order band pass filter
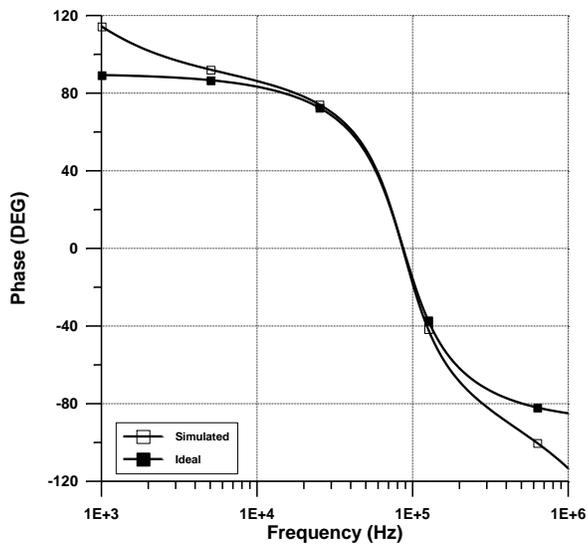
Fig. 6. Phase response of second order band pass filter
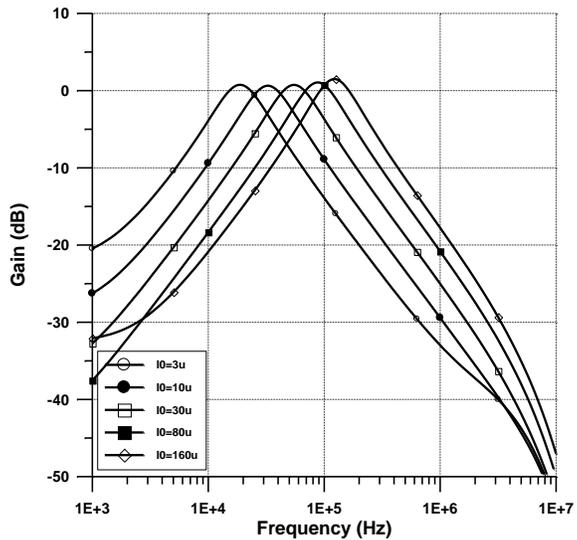
Fig. 7. Electronically tunable gain response of second order band pass filter
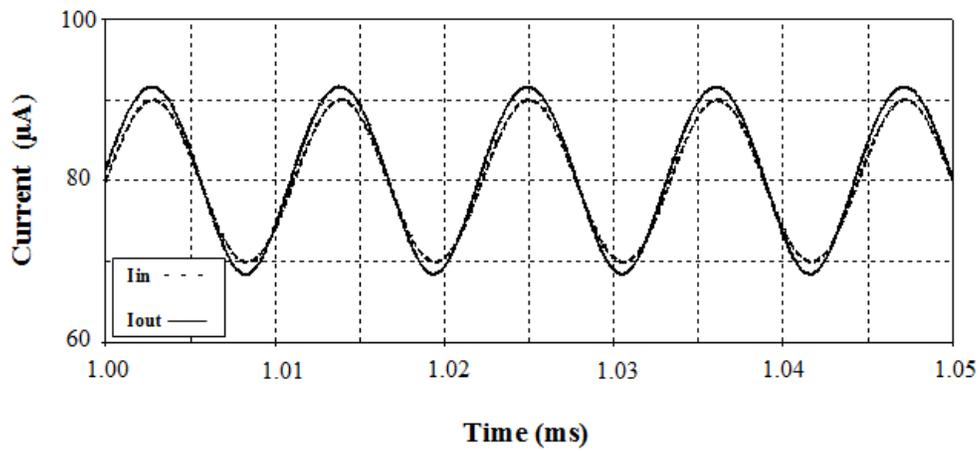
Fig. 8. Time domain response of second order band pass filter

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Table. 2. Properties and performances of suggested second order band pass filter.

Parameters	Simulation Conditions
Technology	TSMC 0.25µm
Order of filter	2
Supply voltage	3V
Capacitor value	200pF
I_0	5µA, 10µA, 30µA, 80µA, 160µA
Parameters	**Simulation Results**
f_0 (I_0= 10µA, 30µA, 80µA)	33kHz, 55kHz, 88kHz
THD (I_0= 10µA, 30µA, 80µA)	1.53%, 2%, 3.4%

4. Conclusion

In this study, square-root-domain current-mode second order band pass filter circuit for low frequency applications has been presented. State-space-synthesis method was used to generate the filter circuit. PSPICE simulations have been given in order to verify the theoretical analysis. The presented filter circuit has various advantages such as the ability to be adjusted electronically, requiring only MOS transistor and grounded capacitor, suitability to VLSI (Very Large Scale Integration) technologies, suitability to low voltage/power applications and the ability to operate at high frequencies. It is expected that the suggested square-root-domain current-mode second order band pass filter circuit will be beneficial for the design of signal processing application design.

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