วงจรกรองความถี่แบบ KHN ในโหมดกระแสด้วย VDTA เพียงตัวเดียว
Current-mode KHN Filter Using Single VDTA

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บทคัดย่อ

บทความนี้นำเสนอวงจรกรองความถี่แบบ KHN โหมดกระแสที่สามารถให้ผลตอบสนองได้ 3 แบบ ในวงจรเดียวกัน ได้แก่ กรองความถี่ต่ำผ่าน สูงผ่าน และแถบความถี่ผ่าน ด้วยอุปกรณ์วงจรขยายผลต่างแรงดันส่งผ่านความนำกระแส (VDTA) เพียงตัวเดียว มีลักษณะเด่นของวงจร คือ สามารถปรับค่าความถี่โพลและค่าควอลิตี้แฟกเตอร์ได้ด้วยวิธีทางอิเล็กทรอนิกส์โดยการปรับกระแส I_B ได้อย่างอิสระ โครงสร้างของวงจรไม่ซับซ้อนประกอบไปด้วย VDTA เพียง 1 ตัว ร่วมกับตัวเก็บประจุที่ต่อลงกราวนด์อีก 2 ตัว ปราศจากตัวต้านทานและใช้กับอุปกรณ์พาสซีสแบบต่อลงกราวนด์ วงจรที่นำเสนอนี้ สามารถนำไปพัฒนาเป็นวงจรรวม ผลการจำลองการทำงานของวงจรโดยใช้โปรแกรม PSpice พบว่าให้ผลสอดคล้องกับที่คาดการณ์ไว้ตามทฤษฎี วงจรมีอัตราดึงกำลังงาน 1.76mW ที่แหล่งจ่ายไฟฟ้า ±1.5V

คำสำคัญ : วงจรกรองความถี่แบบ KHN; วงจรขยายผลต่างแรงดันส่งผ่านความนำกระแส (VDTA)

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Abstract

This article presents a current-mode KHN universal biquadratic filter performing 3 standard functions at the same time: low-pass, high-pass and band-pass functions, based on only a single voltage difference transconductance amplifier (VDTA). The features of the circuit are that: the pole frequency and quality factor can be electronically tuned via the input bias currents I_B. The circuit topology is very simple, consisting of merely single VDTA and 2 grounded capacitors. Without any external resistor and using only grounded elements, the proposed circuit is very suitable to further develop into an integrated circuit. The PSpice simulation results are shown. The given results agree well with the theoretical anticipation. The maximum power consumption is approximately 1.76mW at ±1.5V power supply voltages.

Keywords : KHN filter; VDTA

Introduction

An analog filter is an important building block, widely used for continuous-time signal processing. It can be found in many fields: including communications, measurement, instrumentation and control systems (Sedra and Smith, 2003; Ibrahim et al., 2005). One of the most popular analog filters is the multifunction filter, since it can provide several functions at the same time. It has been accepted that the Kerwin–Huelsman–Newcomb (KHN) biquad filter is also the more popular multifunction filter structure. Because this structure offers several advantages such as low passive and active sensitivity performance, low component spread and good stability behavior (Kerwin et al., 1998; Deliyannis et al., 1999). The KHN filters have been realized by employing different high performance active building blocks. The voltage-mode KHN filters based on CCIIs (Soliman, 1994; Senan and Singh, 1995), CDBAs (Khaled and Soliman, 2000), DVCC (Minnae and Ibrahim, 2008), DDCC (Ibrahim and Kuntman, 2004), VDTA (Satansup et al., 2013) and op-amps have been developed. These reported circuits provide good performances but they suffer from some disadvantages for example, excessive use of the passive elements especially external resistors, lack of electronic adjustability, limitation at high frequency performance due to gain-bandwidth of op-amp. The CCCII

(Altuntas and Toker, 2002) and OTA (Shah and Bhaskar, 2002) based voltage-mode KHN filter enjoy electronic tunability. Unfortunately, the circuit (Shah and Bhaskar, 2002) requires the use of large number of CCCIIs (5 CCCIIs). Moreover, the OTA-based circuities known to be restrained by limited operating range and output voltage swing. Recently, the multifunction filters working in current-mode have been more popularly used than the voltage-mode type. Since the last decade, there has been much effort to reduce the supply voltage of analog systems. This is due to the demand for portable and battery-powered equipment. Since a low voltage operating circuit becomes necessary, the current—mode technique is ideally suited for this purpose. Actually, a circuit using the current-mode technique has many other advantages, such as, larger dynamic range, higher signal bandwidth, greater linearity, simpler circuitry and lower power consumption (Toumazou et al., 1990). The current-mode KHN filter based on different high performance current-mode active components are reported in literature (Altuntas and Toker, 2002; Toker et al., 1999; Keskin et al., 2006; Biolek et al., 2007). However, some of these circuits require more active elements which make the circuit becoming more complicated and consumes more power.

Therefore, the aim of this paper is to propose a single active element based CM resistorless universal filter. For this purpose, the voltage differencing transconductance amplifier (VDTA) (Biolek et al., 2008) is a recently introduced active element. The VDTA device is composed of current source controlled by the difference of two input voltages and a multiple-output transconductance amplifier, providing electronically controlled ability through its transcontance gains. Therefore, the VDTA device is very suitable for electronically tunable active circuit synthesis. Another advantage feature of the use of the VDTA as an active element is that compact structures in some application can be achieved easily (Biolek et al., 2008).

The aim of this paper is to propose a current-mode KHN filter, emphasizing on use of single VDTA and grounded capacitors. The features of the proposed circuit are as follows: It can provide 3 transfer functions such as low-pass, high-pass and band-pass without changing the circuit topology. The circuit configuration is very simple, employing only grounded capacitors as passive components, thus it is suitable for fabricating in monolithic chip. The quality factor and pole frequency can be electronically adjusted.

Circuit Principle

Description of the VDTA

In 2008, the conceptual of the VDTA was firstly suggested by Biolek (Biolek et al., 2008) The schematic symbol of the VDTA is represented in figure 1, where the port relations can be defined by the following expression (Yesil et al., 2011).

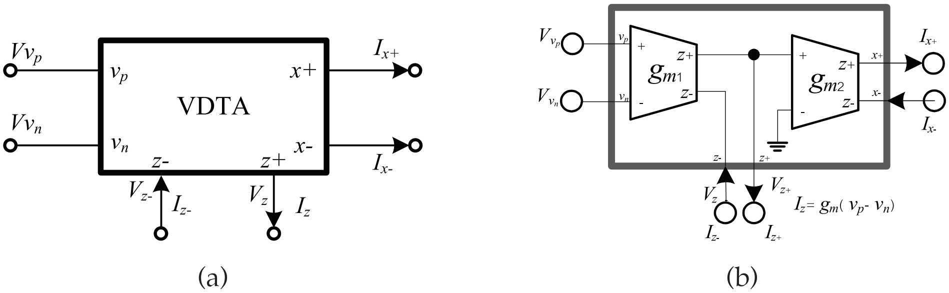


Figure 1. (a) Symbol of the VDTA and (b) its implement by OTAs.

$$\begin{bmatrix} I_z \\ I_{x+} \\ I_{x-} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ 0 & 0 & g_{m2} \\ 0 & 0 & g_{m2} \end{bmatrix} \begin{bmatrix} Vv_p \\ Vv_n \\ V_z \end{bmatrix} \tag{1}$$

In equation (1), g_{m1} and g_{m2} are the first and second transconductance gains of the VDTA respectively. The differential input voltage from the terminals p and n (v_p-v_n) is transformed into output currents at the terminals z and $z-$ with first transconductance g_{m1}. The voltage drop at the terminal z (v_z) is transformed into output currents at the terminals $x+$ and $x-$ with second transconductance g_{m2}. For a BJT VDTA, the g_m can be expressed as

$$g_m = \frac{I_B}{2V_T} \tag{2}$$

where I_B and V_T are the bias current and the thermal voltage (V_T), respectively. Generally, VDTA can contain an arbitrary number of x terminals, providing currents I_B of both directions. In the same way, the number of z terminals can be arbitrarily included by using the internal current mirror to provide a copy of the current flowing out of the z terminal to the other z terminals (called z_c terminal). As an example, the symbol of the VDTA with a pair of $x+$, $x-$, z and $z-$ terminals are illustrated in figure 1, respectively.

General structure of KHN biquad filter

A KHN structure consists of two integrator blocks and a summer block as shown in figure 2. From block diagram in figure 2, the transfer functions of HP, BP and LP can be respectively expressed as follows:

$$HP(s) = \frac{s^2}{s^2 + s\frac{1}{\tau_1} + \frac{1}{\tau_1\tau_2}}, \tag{3}$$

$$BP(s) = \frac{s\frac{1}{\tau_1}}{s^2 + s\frac{1}{\tau_1} + \frac{1}{\tau_1\tau_2}}, \tag{4}$$

$$LP(s) = \frac{\frac{1}{\tau_1\tau_2}}{s^2 + s\frac{1}{\tau_1} + \frac{1}{\tau_1\tau_2}}. \tag{5}$$

The pole frequency and quality factor can be expressed as

$$\omega_O = \sqrt{\frac{1}{\tau_1\tau_2}} \tag{6}$$

and

$$Q_O = \sqrt{\frac{\tau_1}{\tau_2}}\ . \tag{7}$$

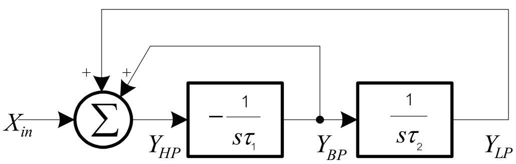


Figure 2. Fundamental KHN structure.

The proposed current-mode KHN filter

As mentioned in the last section, the proposed KHN filter is based on current summer and lossless integrators. In this section, these circuits will be described. The current summer based on VDTA is shown in figure 3. The output current of this circuit can be written as

$$I_O = I_{x+} = I_1 + I_2 + I_3 \tag{8}$$

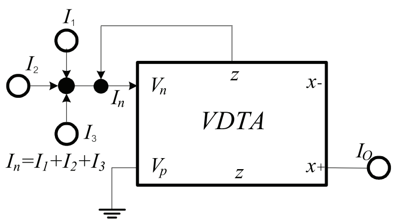


Figure 3. Current summer.

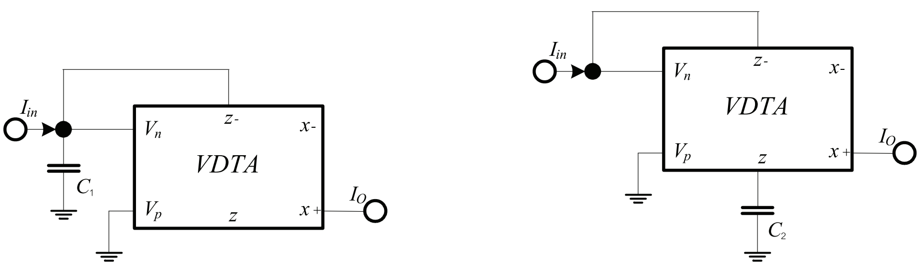
Figure 4 shows the lossless integrator employing VDTA. Considering the circuit figure 4 (a) and (b) using VDTA properties, we will receive

$$\tau_1 = \frac{g_{m1}}{sC_1} \tag{9}$$

and

$$\tau_2 = \frac{g_{m2}}{sC_2} \tag{10}$$

where τ is the time constant.



(a) Integrator type a (b) Integrator type b

Figure 4. Lossless integrator employing VDTA.

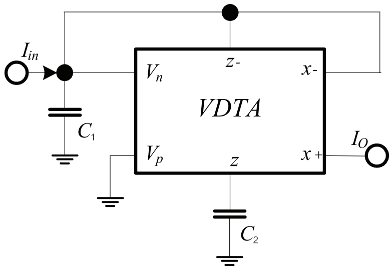


Figure 5. The proposed current-mode KHN filter.

As mentioned in the above section, the proposed KHN filter is based on two integrator blocks and a summer block. The operation of this filter can be achieved very conveniently with the combination of figure 3 and figure 4 together. As can be seen, this topology can be realized using a single VDTA and two grounded capacitors as shown in figure 5. The current transfer functions can be obtained as follows:

$$HP(s) = \frac{I_{HP}(s)}{I_{in}(s)} = \frac{s^2}{s^2 + s\frac{g_{m1}}{C_1} + \frac{g_{m1}g_{m2}}{C_1C_2}}, \quad (11)$$

$$BP(s) = \frac{I_{BP}(s)}{I_{in}(s)} = \frac{s\frac{g_{m1}}{C_1}}{s^2 + s\frac{g_{m1}}{C_1} + \frac{g_{m1}g_{m2}}{C_1C_2}}, \quad (12)$$

$$LP(s) = \frac{I_{LP}(s)}{I_{in}(s)} = \frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + s\frac{g_{m1}}{C_1} + \frac{g_{m1}g_{m2}}{C_1C_2}}, \quad (13)$$

from equations (11)-(13), the pole frequency and quality factor can be expressed as

$$\omega_O = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \quad (14)$$

$$Q_O = \sqrt{\frac{g_{m2}C_1}{g_{m1}C_2}} \; . \quad (15)$$

Substituting the intrinsic resistance and transconductance as depicted in equations (9) and (10) into equations (14) and (15), it yields pole frequency and quality factor as follows:

$$\omega_O = \frac{1}{2V_T}\sqrt{\frac{I_{B1}I_{B2}}{C_1C_2}} \tag{16}$$

and

$$Q_O = \sqrt{\frac{C_1 I_{B2}}{C_2 I_{B1}}} \tag{17}$$

from equations (16) and (17), by maintaining the ratio I_{B1} and I_{B2} to be constant, it can be remarked that the pole frequency can be adjusted by varying I_{B1} and I_{B2} without affecting the quality factor. Moreover, the circuit can provide high Q_0 by setting value of C_1 more than value of C_2. The filter bandwidth (BW) can be expressed as follows:

$$BW = \frac{\omega_O}{Q_O} = \frac{2V_T I_{B1}}{C_1} \tag{18}$$

Note that the bandwidth can be linearly controlled by I_{B1}.

Tracking Errors and Sensitivity Analysis

Considering the non-ideal characteristics of VDTA, the relation of current and voltage in equation (1) can be rewritten as:

$$\begin{bmatrix} I_z \\ I_{x+} \\ I_{x-} \end{bmatrix} = \begin{bmatrix} \beta_1 g_{m1} & -\beta_1 g_{m1} & 0 \\ 0 & 0 & \beta_2 g_{m2} \\ 0 & 0 & -\beta_2 g_{m2} \end{bmatrix} \begin{bmatrix} Vv_p \\ Vv_n \\ V_z \end{bmatrix} \tag{19}$$

where β_1 and β_2 are the tracking errors for the first and second stages of the VDTA respectively. Reanalysis of the proposed circuit in figure 5 employing equation (19) yields the following non-ideal filter parameters.

$$\omega_O = \sqrt{\frac{\beta_1\beta_2 g_{m1} g_{m2}}{C_1C_2}} \tag{20}$$

and

$$Q_O = \sqrt{\frac{\beta_2 g_{m2} C_1}{\beta_1 g_{m1} C_2}} . \qquad (21)$$

It is evident that the values of ω_O and Q may be slightly changed by the effect of the VDTA tracking errors. However, the small deviation in equations (20) and (21) can be minimized by properly adjusting the VDTA transconductance values. Hence, the desired parameter values can still be satisfied.

The sensitivities of the proposed circuit can be found as

$$S_{I_{B1}}^{\omega_0} = S_{I_{B2}}^{\omega_0} = \frac{1}{2},$$
$$S_{C_1}^{\omega_O} = S_{C_2}^{\omega_O} = -\frac{1}{2},$$
$$S_{V_T}^{\omega_O} = \frac{1}{2} \qquad (22)$$

and

$$S_{I_{B2}}^{Q_0} = S_{C_1}^{Q_O} = \frac{1}{2},$$
$$S_{I_{B1}}^{Q_0} = S_{C_2}^{Q_O} = -\frac{1}{2}. \qquad (23)$$

Therefore, all the active and passive sensitivities are equal or less than unity in magnitude.

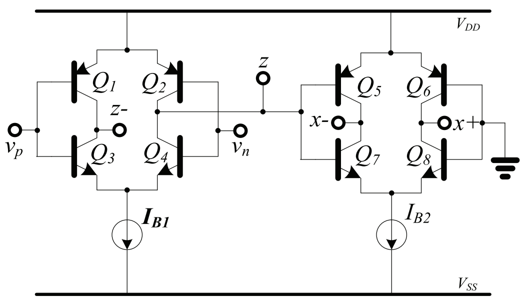


Figure 6. Internal construction of VDTA

Results

To prove the performances of the proposed filter, a PSpice simulation was carried out. The PNP and NPN transistors employed in the proposed circuit were simulated by respectively using the parameters of the PR200N and NR200N bipolar transistors of ALA400 transistor array from AT&T (Frey, 1993). Figure 4 depicts schematic description of the VDTA used in the simulations. The circuit was biased with $\pm 1.5V$ supply voltages. The circuit was connected to a 1Ω load resistor. $C1=C2=1nF$ and $I_{B1}=50\mu A$ and $I_{B2}=150\mu A$ are chosen. It yields the pole frequency of 198.39kHz. The results shown in figure 5 are the gain responses of the proposed KHN biquad filter. It clearly shows that this circuit can provide simultaneously low-pass, high-pass and band-pass responses without modifying the circuit topology. Figure 6 displays gain responses of band-pass function with different I_B values. It is shown that the bandwidth of the responses can be adjusted by the input bias current I_B. figure 7 shows gain responses of band-pass function where I_{B1} and I_{B2} are equally set to keep the ratio to be constant and changed for several values. It is found that pole frequency can be adjusted without affecting the quality factor.

In order to investigate a time-domain response of the proposed current-mode universal filter, a 198.39kHz sinusoidal input current of 20mA is applied to the filter. The results obtained are shown comparing input and output waveforms of the LP, HP and BP responses in figure 8. (a), (b) and (c) respectively. It can be seen from simulations that in case of BP response, the total harmonic distortion (THD) of about 1.61% approximately at the total power consumption of 1.76mW can be obtained.

Conclusion

A current-mode KHN biquad filter based on single VDTA has been presented. The features of the proposed circuit are that: pole frequency and quality factor can be electronically adjusted via input bias currents. The circuit description comprises only single VDTA and 2 grounded capacitors. With mentioned features, it is very suitable to realize the proposed circuit in monolithic chip to use in battery powered, portable electronics equipment such as wireless communication system devices.

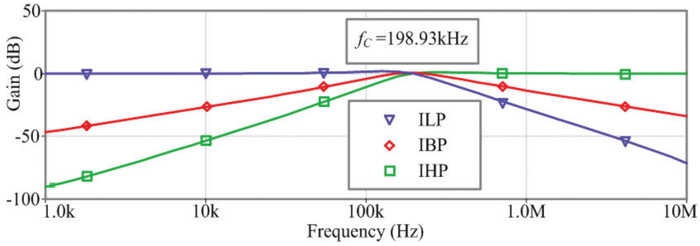


Figure 7. Gain responses of the proposed circuit

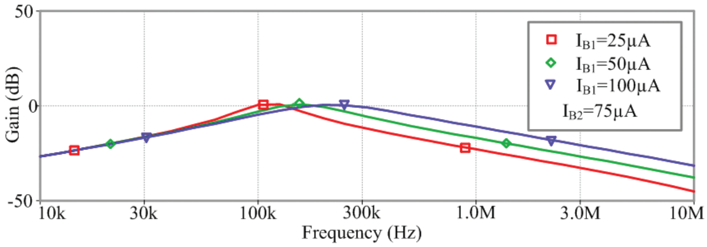


Figure 8. Band-pass responses for different values I_{B1}

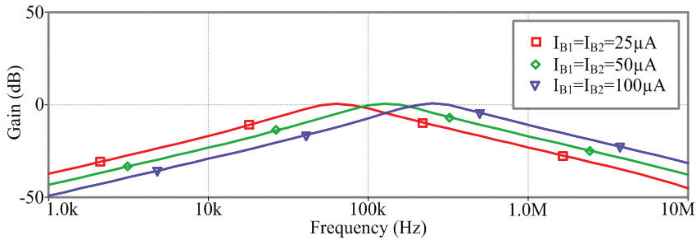
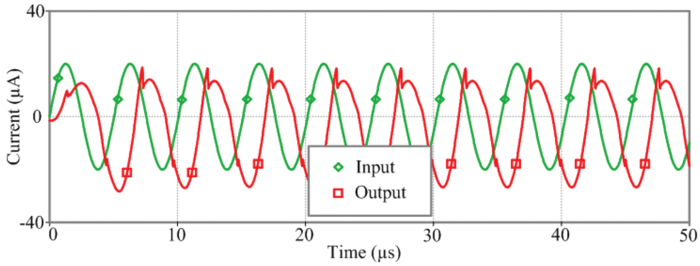
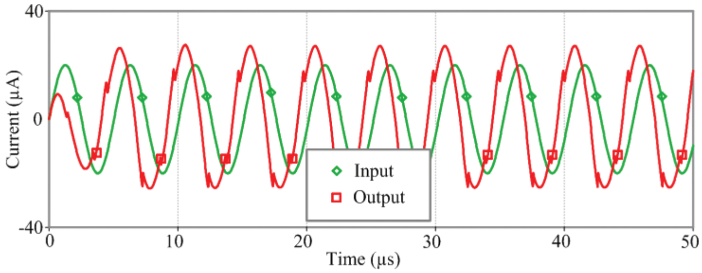


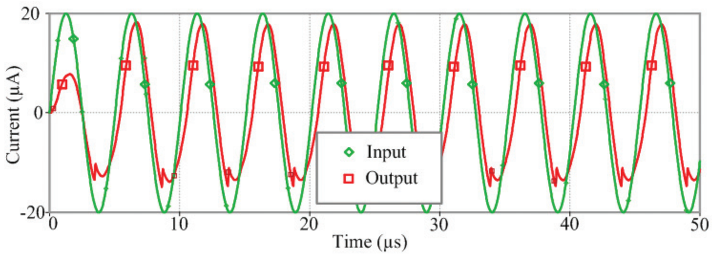
Figure 9. Band-pass responses for different values of I_{B1} and I_{B2} with keeping their ratios constant



(a) LP



(b) HP



(c) BP

Figure 10. Input and output waveforms of the LP, HP and BP responses for a 198.39kHz sinusoidal input current of 20mA

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