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Shadow Bandpass Filter with Q-improvement

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Abstract **— A new architecture of the shadow bandpass filters with the quality factor improvement is proposed. The presented idea employs external amplifiers cooperating with the classical biquad cell resulting in convenient electronic tunability of the characteristic frequency and the quality factor. The scheme obtains the benefit of the quality factor–improvement via feedback gains of the external amplifiers. The theory is verified by PSPICE simulation using 0.18 μm CMOS technology model parameters.**

Keywords—High quality factor, VDTA, shadow filter.

I. INTRODUCTION

Since the concept of the shadow filters has been introduced [1], various improving designs have followed [3]–[5]. In the original work [1], the characteristic frequency of a bandpass filter and a lowpass filter are the center of attention. The outstanding feature is that the filters' characteristic frequencies can be electronically tuned by acting on the gain of an additional amplifier. In this paper, another new architecture of the shadow filters is presented. Like [1], the proposed shadow filter possesses the feature of electronic tunability. Both the characteristic frequency and the quality factor can be conveniently tuned by acting on the dc-bias current. The main advantage of the proposed scheme is that the improvement on the quality factor is possible via appropriately chosen circuit-parameters. Also, the circuit realization utilizes VDTA as active elements along with only grounded capacitors. Therefore, it is well-suited for IC implementation.

II. THEORETICAL CONCEPT

Fig.1 depicts a cell of the classical 2nd order biquad with the lowpass and bandpass transfer functions respectively given as follows

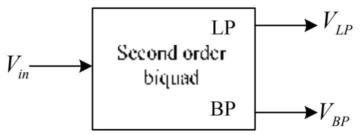

Fig.1 Classical biquad

$$\frac{V_{LP}(s)}{V_{in}(s)} = \frac{d}{1+as+bs^2} \tag{1}$$

$$\frac{V_{BP}(s)}{V_{in}(s)} = \frac{cs}{1+as+bs^2} \tag{2}$$

where *a, b, c* and d are positive real constants. The respective characteristic frequency and quality factor are

$$\omega_0 = \frac{1}{\sqrt{b}} \tag{3}$$

$$Q_0 = \frac{\sqrt{b}}{a} \tag{4}$$

The concept of the shadow bandpass filters with Q-improvement is illustrated in Fig.2.

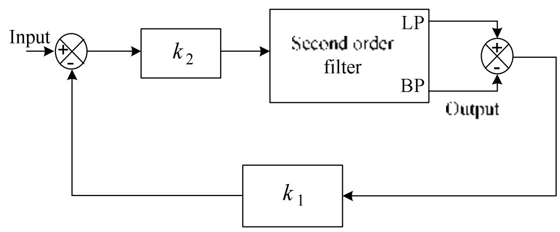

Fig.2 Topology of the proposed bandpass filters with Q-improvement

In the above Figure, the 2nd-order filter is the classical biquad with two outputs the transfer functions of which are given in (1) and (2). Simple analysis of Fig.2 yields the following transfer function

$$T(s) = \frac{k_2 cs}{(1+k_1 k_2 d)+(a-k_1 c)s+bs^2} \tag{5}$$

Where the gains k_1 and k_2 of the amplifiers are assumed positive values. Then the center frequency and the quality factor of this shadow bandpass filter are, respectively, found as

$$\omega'_{0(1)} = \omega_0\sqrt{1+k_1 k_2 d} = \omega_{0(1)} \tag{6}$$

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$$Q'_{0(1)} = Q_0 \frac{\sqrt{1+k_1k_2d}}{1-\frac{k_1k_2c}{a}} = \frac{Q_{0(1)}}{1-\frac{k_1k_2c}{a}} \tag{7}$$

Now, recalling the earlier version of the shadow bandpass filter introduced in [1] and depicting, once again, the circuit topology in Fig.3.

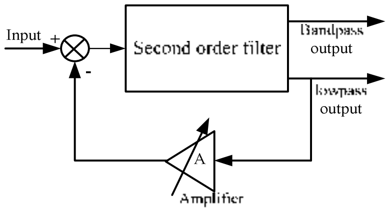

Fig.3 The general concept of shadow bandpass filters [1]

From the above figure, the respective center frequency and quality factor of the filter are found as follows:

$$\omega_{0(1)} = \omega_0\sqrt{1+Ad} \tag{8}$$

$$Q_{0(1)} = Q_0\sqrt{1+Ad} \tag{9}$$

Comparing (6) to (8), essentially both have the same patterns. Meanwhile, comparison of (7) with (9), it is seen that the quality factor in (7) can gain advantages over that in (9) by appropriate selection of the term $1-\frac{k_1k_2c}{a}$; that is choosing the parameters such that

$$0 < 1-\frac{k_1k_2c}{a} < 1 \tag{10}$$

III. Circuit Implementation

A. VDTA Description

The proposed architecture introduced in Section II can be conveniently implemented with the use of active elements so-called VDTA (Voltage Differential Transconductance Amplifier). Fig.4 shows the symbol of the building block VDTA.

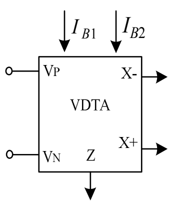

Fig. 4 Circuit symbol of the VDTA [6]

where V_P, V_N representing the input-terminal voltage terminals and Z, $X+$ and $X-$ are output-terminal currents. The terminal input-output relationship is described in the following expression

$$\begin{bmatrix} I_Z \\ I_{X+} \\ I_{X-} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ 0 & 0 & g_{m2} \\ 0 & 0 & -g_{m2} \end{bmatrix} \begin{bmatrix} V_{V_P} \\ V_{V_N} \\ V_Z \end{bmatrix} \tag{11}$$

One possible realization of practical VDTA is the usage of the CMOS-circuitry as demonstrated in Fig.5.

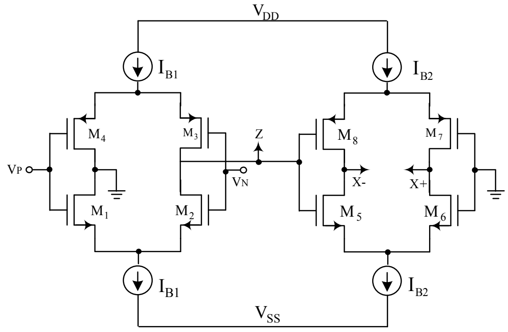

Fig.5 CMOS Realization of VDTA [6]

B. Circuit realization of the proposed shadow bandpass filter with Q improvement

Based on the proposed concept shown in Fig.2 and with VDTAs used as the active elements, the shadow filter is constructed as illustrated in Fig.6

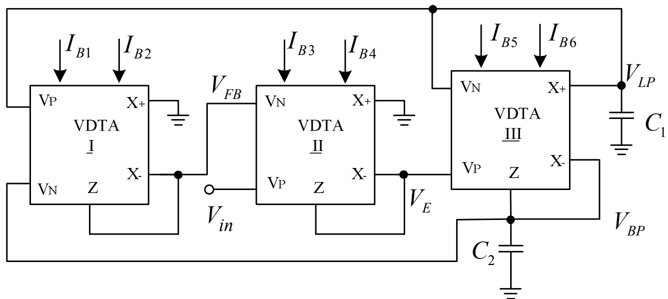

Fig.6 The proposed high Q-shadow bandpass filter

Note that the filter possesses a simple structure as only three VDTAs along with two grounded capacitors are employed in the circuit. With the characteristic described in (11), routine analysis results in the following expression

$$V_{FB}(s) = \frac{g_{m1}}{g_{m2}}\left(V_{LP}(s)-V_{BP}(s)\right) = k_1\left(V_{LP}(s)-V_{BP}(s)\right) \tag{12}$$

The transfer function of the 2nd differential amplifier, VDTA II can be found as

$$\frac{V_E(s)}{V_{in}(s)-V_{FB}(s)} = \frac{g_{m3}}{g_{m4}} = k_2 \tag{13}$$

In the Figure, VDTA III and the two capacitors functioning as the simple biquad. The transfer functions of the bandpass and lowpass responses with respect to V_E are, respectively, expressed as follows

$$\frac{V_{BP}(s)}{V_E(s)}=\frac{sC_1/g_{m6}}{1+s(C_1/g_{m5})+s^2C_1C_2/g_{m5}g_{m6}} \quad (14)$$

$$\frac{V_{LP}(s)}{V_E(s)}=\frac{1}{1+s(C_1/g_{m5})+s^2C_1C_2/g_{m5}g_{m6}} \quad (15)$$

Then the transfer function of the bandpass and lowpass responses with respect to the input V_{in} are derived as follows

$$\frac{V_{BP}(s)}{V_{in}(s)}=\frac{k_2\, sC_1/g_{m6}}{1+k_1k_2+s(C_1/g_{m5}-k_1k_2C_1/g_{m6})+s^2C_1C_2/g_{m5}g_{m6}} \quad (16)$$

$$\frac{V_{LP}(s)}{V_{in}(s)}=\frac{k_2}{1+k_1k_2+s(C_1/g_{m5}-k_1k_2C_1/g_{m6})+s^2C_1C_2/g_{m5}g_{m6}} \quad (17)$$

Hence the center frequency $\omega'_{0(1)}$ of the proposed shadow bandpass filter is found as

$$\omega'_{0(1)}=\sqrt{(1+k_1k_2)}.\sqrt{\frac{g_{m5}g_{m6}}{C_1C_2}}=\sqrt{(1+k_1k_2)}.\omega_0 \quad (18)$$

It is seen from (18) that controlling the center frequency is flexibly possible through a number of parameters, i.e., k_1, k_2 and the two dc bias currents, not mention the two capacitors. Meanwhile, the quality factor of the shadow bandpass filter response is found as follows:

$$Q'_{0(1)}=\left(\frac{\sqrt{1+k_1k_2}}{1-k_1k_2\dfrac{g_{m5}}{g_{m6}}}\right).\sqrt{\frac{C_2g_{m5}}{C_1g_{m6}}}=\frac{Q_{0(1)}}{1-k_1k_2\dfrac{g_{m5}}{g_{m6}}} \quad (19)$$

Note that it is effortless to arrange k_1 and k_2 in the above equation so as to be in the same form as that in (18) of the earlier developed work [7]; resulting in having $Q_{0(1)}$ of the above equation the quality factor of the work presented in [7]. Comparison of the above quality factor with that given in (18) of [7], the obvious term $1-\frac{k_1k_2g_{m5}}{g_{m6}}$ can be observed and properly selected. Hence the quality factor $Q'_{0(1)}$ can be enhanced provided that

$$0 < k_1k_2\frac{g_{m5}}{g_{m6}} < 1 \quad (20)$$

Note that the condition in (20) also ensures the system stability.

In addition, the parameter sensitivities of the proposed filter are analyzed and obtained as follows:

$$S_{C_1}^{\omega'_{0(1)}}=S_{C_2}^{\omega'_{0(1)}}=-\frac{1}{2},\ S_{g_{m5}}^{\omega'_{0(1)}}=S_{g_{m6}}^{\omega'_{0(1)}}=\frac{1}{2}$$

$$S_{k_1}^{\omega'_{0(1)}}=S_{k_2}^{\omega'_{0(1)}}=\frac{k_1k_2}{2(1+k_1k_2)},$$

$$S_{k_1}^{Q'_{0(1)}}=S_{k_2}^{Q'_{0(1)}}=\frac{k_1k_2g_{m5}}{g_{m6}}\frac{Q'_{0(1)}}{Q_{0(1)}} \quad (21)$$

Clearly, the center frequency of the proposed filter yields satisfactory sensitivities the values of which are less than unity. In the meantime, the sensitivities of the quality factor with respect to the two gains can also be managed so that their values are kept within unity.

IV. Simulation Results

In order to verify the above concept, the circuit depicted in Fig. 6 is simulated by PSPICE. Each VDTA utilizes the CMOS circuitry shown in Fig.5, with TSMC CMOS 0.18 µm as the model parameters. The CMOS dimension used in the simulation are given in table 1. The voltages $V_{DD}=-D_{SS}=1V$ are supplied throughout the simulation.

Table I.CMOS dimension of VDTA

Transistors	W(µm)	L(µm)
M_1 , M_2 , M_5 , M_6	3.60	0.36
M_3 , M_4 , M_7 , M_8	16.64	0.36

Firstly, the frequency response of the proposed bandpass filter in Fig.6 is investigated. The dc biased currents $I_{B5}=I_{B6}=100\,\mu$A and $C_1=C_2=20$ pF are provided for the circuit. The gain k_1 is adjusted via the ratio of dc bias currents I_{B1} and I_{B2}. The gain k_2 can be controlled through the bias currents I_{B3} and I_{B4}. For simplicity in tuning the center frequency, the gain k_1 is varied while the gain k_2 is kept unity by setting $I_{B3}=I_{B4}=100\,\mu$A . The current I_{B1} is a fixed value of 50 µA. In the meantime, I_{B2} (the dc bias current of VDTA I) is chosen as I_{B2}=80 µA , 100 µA , and 120 µA in accordance with k_2 = 0.63, 0.50, and 0.41 respectively. These dc bias currents correspond with different transconductance gains of the VDTA at 407 µA/V, 480 µA/V, and 555 µA/V, respectively. The frequency response of the bandpass filter accordingly to (16) is illustrated in Fig.10.

Relating to the above examination, other parameters involving the performance of the filter are summarized in Table II.

In addition, enhancement of the quality factor is investigated. The initial quality factor of biquad cell is unity by setting $I_{B5}=I_{B6}=100\mu$A , $C_1=C_2=20$pF. Then, the proposed shadow bandpass filter is simulated with I_{B2}=100 µA and the gain k_1 is varied from 0.1-1 by selecting $I_{B1}=10\mu\text{A}-100\,\mu$A .

The gain k_2 is selected to values between 0.2-0.8 with 0.2 increase 0.2 step-increments. This corresponds to setting $I_{B4} = 100\,\mu A$ and $I_{B3} = 20\mu A - 80\,\mu A$. The graphs of quality factor values with respect to different gains are illustrated in Fig.11.

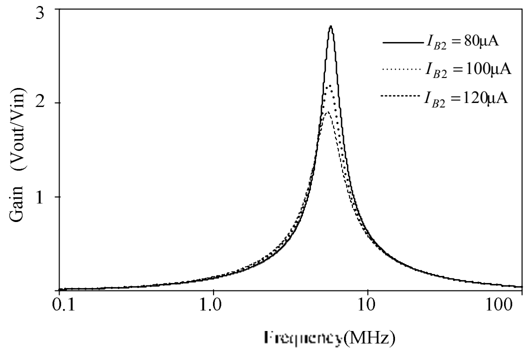

Fig.10 Frequency responses of the proposed filter; I_{B1} = 50 μA

Table II Performance characteristic of the proposed filter

Parameters	I_{B2} = 80μA	I_{B2} = 100 μA	I_{B2} = 120 μA
Center-Frequency	5.77MHz	5.63MHz	5.55MHz
Quality factor	3.80	2.90	2.40
Bandwidth	1.52MHz	1.95MHz	2.26MHz
Power dissipation	1.06mW	1.10mW	1.14mW
Maximum output noise voltage	32nV@ 6.28MHz	25nV@ 4.99MHz	23nV@ 4.99MHz
THD	0.50%	0.32%	0.24%

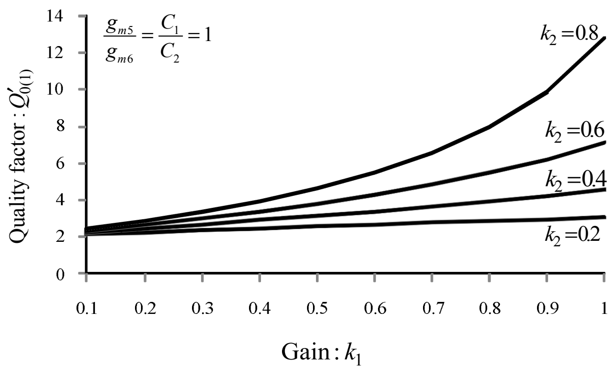

Fig. 11 The quality factor value of the proposed filter when gain k_1 and k_2 are varied.

The time domain response of the proposed filter is also simulated by feeding the system an input of 10 mVpp at 6 MHz. The dc bias currents for each VDTA, I_{B3} = 80 μA and the rest are of 100 μA. The two capacitors remain the same value of 20 pF. The time domain response of output in the steady-state, including input signal, is depicted in Fig.12. The total harmonic distortion (THD) of the output signal is about 0.7%.

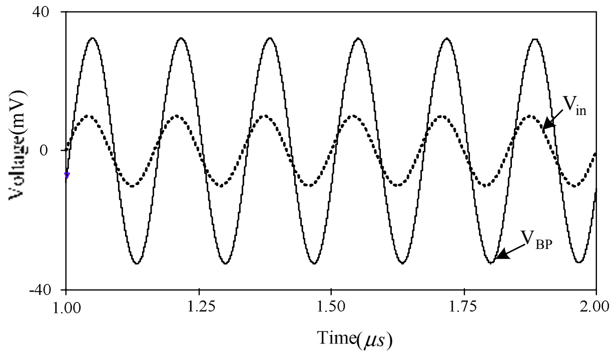

Fig.12 The time domain response

V. CONCULSIONS

This paper presents a new topology of the shadow bandpass filters with improvement of the quality factor. The proposed filter is capable of scaling up the quality factor as well as the center frequency. The CMOS practical circuit is implemented for the active building blocks VDTAs. Simulation results confirm the feasibility of concept and circuitry.

Table III. Properties-comparison of the reported shadow filters with the proposed circuit

Parameter	This work	Ref[4]	Ref[7]
Number of component	3VDTAs	2DDCCs +1AMP	3VDTAs
Resistor	0	2	0
Capacitor	2	2	2
Electronically tuning	Yes	Yes	Yes
Power consumption	1.2mW	-	1.4mW
Frequency scale	Scale up	Scale down	Scale up
Gain of amplifier	Less than 1	More than 1	More than 1
Q-Improvement	Yes	Yes	No

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