Int. J. Electron. Commun. (AEÜ) 70 (2016) 936–943

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular Paper

Electronically controllable bandpass filters with high quality factor and reduced capacitor value: An additional approach

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ARTICLE INFO

Article history:
Received 5 December 2015
Accepted 10 April 2016

Keywords:
Active filter
Bandpass filter
Amplifier
Analog circuit
High quality factor

ABSTRACT

In this paper, a new method is presented to increase the quality factor of bandpass filters employing active elements. Using the proposed method the values of the externally capacitors in filter structure are reduced. In this way chip area which is an important parameter in the integrated circuits can be minimized. Moreover, bandpass filters are investigated from the point of view of stability conditions and effects of the parasitic and non-ideal elements. Considering these effects, operating conditions and boundaries of the bandpass filter are calculated. To validate the feasibility of the method, an application example of bandpass filter used in intermediate frequency (IF) stage of AM receivers is given and the performance of the circuit is demonstrated by comparing the theory and simulation.

1. Introduction

Bandpass filters are mainly used in filtering signals as well as many applications in electronic circuits such as mixers, oscillators, etc. The most important parameter of the bandpass filters is the quality factor (Q) which determines the frequency selectivity of the filter. Generally, bandpass filters with high-Q value require high ratio of capacitances. However high-valued capacitors occupy large silicon area in integrated circuits (ICs).

In order to increase quality factor of active filters many researches have been presented in the literature [1–4]. However these filters are employed using several active and/or passive elements. Nevertheless, Lakys and Fabre [5] presented new method to increase pole frequency and quality factor at the same time which is the technique of shadow filters. The application areas of this method are such as cognitive and encrypted communications [6], frequency hopping circuit [7] and frequency agile filters [8]. Another method is presented to increase quality factor of the second order bandpass filter by Biolkova and Biolek [9]. The second order filter has lowpass, bandpass and highpass outputs. Both of lowpass and highpass outputs are added and applied to the input of the feedback circuit. The output of the feedback circuit is added to input signal. Therefore, quality factor is increased by factor of feedback gain without changing the pole frequency of the filter.

As mentioned, the capacitor being major used element in active filters occupies large area in IC fabrication. For this reason, the capacitance multiplier circuits [10–14] are also proposed in the literature to obtain high capacitance values. However, these presented circuits are employed more active and/or passive elements.

In this paper, we present a new method to increase the quality factor of the active bandpass filters. The high quality factor value can be obtained and tuned electronically by changing the gain of the feedback circuit. In fact, the proposed method decreases the values of the capacitor up to approximately square root of the feedback gain. The new method employs a feedback circuit and a second order filter which has two outputs, bandpass and highpass responses. The gain of the bandpass filter remains constant while the center frequency can be adjusted by electronically changing of the feedback gain. The active and passive sensitivities of the filter elements are no more than unity. Moreover, taking into account a single pole model for the two stages amplifier used in the feedback circuit, stability conditions are investigated. In addition, the effects of the parasitic elements in whole structure are investigated.

2. The proposed method

The proposed method depicted in Fig. 1b is built using second order filter structure and feedback circuit. In Fig. 1a second order filter structure called Class-0 has two filter outputs, bandpass and highpass responses. Highpass response of Class-0 is applied to the input of the feedback circuit. Then, output of the feedback

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http://dx.doi.org/10.1016/j.aeue.2016.04.009
1434-8411/

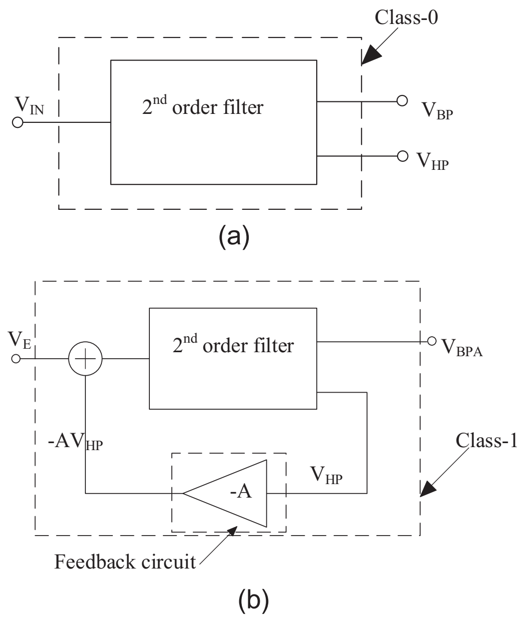

Fig. 1. (a) Class-0 and (b) Class-1 structure.

circuit is added into the input signal of the system. The whole structure is called Class-1. This is an interesting idea for the bandpass filter output of the Class-1.

Here we assumed that Class-0 and Class-1 structure operate in voltage mode. Nevertheless, the same method can be applied to all different filter modes. The general transfer functions of the Class-0 can be defined the following as

$$T_{BP} = \frac{V_{BP}}{V_{IN}} = \frac{sa_1}{s^2 + sb_1 + b_0} \tag{1}$$

$$T_{HP} = \frac{V_{HP}}{V_{IN}} = \frac{a_2 s^2}{s^2 + sb_1 + b_0} \tag{2}$$

where, b_1 and b_0 are real positive constants to ensure stability of the second order filter. a_1 can be real positive or negative constants while a_2 is real positive constant. The routine analysis of the Class-1 filter yields the following voltage-mode bandpass transfer function,

$$T_{BPA} = \frac{V_{BPA}}{V_E} = \frac{\frac{sa_1}{(1+Aa_2)}}{s^2 + \frac{sb_1}{(1+Aa_2)} + \frac{b_0}{(1+Aa_2)}} \tag{3}$$

Here, A is gain of the feedback circuit and is positive constant. From (3) the expressions for pole frequency and quality factor of the Class-1 are given by

$$\omega_{0A} = \sqrt{\frac{b_0}{(1+Aa_2)}} \tag{4}$$

$$Q_A = \frac{\sqrt{(1+Aa_2)b_0}}{b_1} \tag{5}$$

It can be clearly seen from Eqs. (4) and (5) that quality factor increases by factor of $\sqrt{1+Aa_2}$ while pole frequency decreases by factor of $\sqrt{1+Aa_2}$ in Class-1 topology with respect to Class-0. This result is the main aim of the proposed method. Sensitivity analyses of the proposed method with respect to gain of the feedback circuit yields

$$S_A^{\omega_{0A}} = -\frac{1}{2} + \frac{1}{2(1+Aa_2)} \tag{6}$$

$$S_A^{Q_A} = \frac{1}{2} - \frac{1}{2(1+Aa_2)} \tag{7}$$

As it is evident from the above analysis, the sensitivity of the pole frequency and quality factor of the proposed method in regard to gain of the feedback circuit do not exceed unity. Note that, to avoid the stability problem, in Eq. (3) the term $(1 + Aa_2)$ should ensure to be positive by virtue of Routh Hurwitz criterion [15]. Consequently, both feedback gain and highpass filter gain of the Class-0 must be chosen simultaneously positive or negative.

A summary of the specific parameters of the Class-0 and Class-1 are shown in Table 1. The gain of the bandpass filter remains the same in Class-0 and Class-1. It is obvious from Table 1 that pole frequency of the Class-1 diminishes amount of $\sqrt{1+Aa_2}$ as quality factor of the Class-1 rises by factor $\sqrt{1+Aa_2}$ with respect to Class-0.

3. Application example

In order to show the feasibility of the proposed method, the voltage mode filter, proposed by Chen [16], is selected. However, this filter is modified input terminal and some connections. The modified filter (Class-0) is shown in Fig. 2. Thanks to the modification in filter, it is not necessary to use adder circuit. The filter in Fig. 2 can simultaneously realize voltage mode bandpass and highpass filters employing two DDCCs and four grounded passive elements.

The port relations of the DDCC can be characterized by $V_X = V_{Y1} - V_{Y2} + V_{Y3}$ and $I_Z = I_X$. Routine analysis of the filter shown in Fig. 2 gives the following filter transfer functions:

$$\frac{V_{HP}}{V_{IN}} = \frac{s^2}{s^2 + s\frac{1}{C_2R_2} + \frac{1}{C_1C_2R_1R_2}} \tag{8}$$

$$\frac{V_{BP}}{V_{IN}} = \frac{s\frac{1}{C_1R_1}}{s^2 + s\frac{1}{C_2R_2} + \frac{1}{C_1C_2R_1R_2}} \tag{9}$$

Gain of the bandpass filter, the natural frequency and quality factor are obtained as:

$$G_{BP} = \frac{C_2R_2}{C_1R_1} \tag{10}$$

$$\omega_0 = \sqrt{\frac{1}{C_1C_2R_1R_2}} \tag{11}$$

$$Q = \sqrt{\frac{C_2R_2}{C_1R_1}} \tag{12}$$

It can be seen that the natural frequency and quality factor cannot be tuned electronically. Moreover, buffer circuit is required for bandpass output due to possessing high and frequency-dependent output impedance. The Class-1 circuit is shown in Fig. 3 which is the combination of the Class-0 and a feedback circuit (amplifier). The input terminal of the feedback circuit is connected to highpass output of the modified filter. Then, the output of the feedback

Table 1
The specific parameters of the Class-0 and Class-1 in Fig. 1.

	Class-0	Class-1
Gain BP filter at pole frequency	$\frac{a_1}{b_1}$	$\frac{a_1}{b_1}$
Pole frequency	$\omega_0 = \sqrt{b_0}$	$\omega_{0A} = \frac{\sqrt{b_0}}{\sqrt{1+Aa_2}}$
Quality factor	$Q = \frac{\sqrt{b_0}}{b_1}$	$Q_A = \sqrt{1+Aa_2}\frac{\sqrt{b_0}}{b_1}$