A Novel Log-Domain First-Order Multifunction Filter

Ali Kircay and Ugur Cam

ABSTRACT—A new log-domain first-order multifunction filter is proposed in this letter. The proposed filter is systematically derived using the state-space synthesis procedure from a corresponding block diagram. It provides low-pass (LP), high-pass (HP), and all-pass (AP) responses simultaneously for a single input signal. The filter circuit has a very simple structure since it uses only bipolar junction transistors (BJTs) and a grounded capacitor. It can be electronically tuned by changing an external current. The filter has a greater bandwidth due to its inherent current-mode and log-domain operations. PSPICE simulations are given to confirm the theoretical analysis.

Keywords—Log-domain filters, state-space synthesis, multifunction filter.

I. Introduction

The concept of log-domain signal processing was originally conceived by R.W. Adams [1] and was rigorously formulized by D.R. Frey [2], [3]. Frey's work shows that the synthesis of log-domain filters can be synthesized by state-space representation [2], [3]. Based on the translinear principle [4], these filters make explicit use of the exponential nature of bipolar junction transistors (BJTs) or the MOS transistor operating in the subthreshold region [5]. Log-domain filters are receiving interest in literature, mainly due to their suitability for low voltage, low power, large dynamic range, and high frequency applications, and because they are electronically tunable. Most interesting of all, they have opened the door to elegantly realizing a linear system with inherently nonlinear (logarithmic-exponential) circuit building blocks. Log-domain or dynamic translinear filters [6] inherit the advantages of conventional translinear circuits: insensitivity to variations in temperature, processing, current controllability, large bandwidth, and high functional density [7].

Due to the ongoing trends to lower supply voltages and maintain low power operation, the area of analog integrated filters is facing serious challenges [1], [8]. The maximal dynamic range achievable using conventional filter implementation techniques, such as opamp-MOSFET-C, transconductance-C, and a switched-capacitor, is becoming severely restricted by the supply voltage. In ultra-low-power environments, linear resistors have become too large for on-chip integration. Finally, the situation is complicated by high-frequency demands and the fact that the filter transfer function has to be tunable to compensate for process tolerances. In the area of continuous-time filters, a promising approach to meet these challenges is provided by the class of log-domain filters [3], [6], and [9]. An important property of log-domain filtering is that it uses companding [10], whereby the signals are compressed logarithmically at the input stage before being processed and then expanded exponentially at the output stage. This makes it possible for log-domain circuits to operate with very low supply voltage without sacrificing the dynamic range [11]. Also, these filters contain low impedance nodes along the signal path, which can be exploited to achieve greater bandwidths.

Unlike the conventional classes of filters, in which linear circuits are implemented using nonlinear devices, log-domain techniques directly exploit the nonlinear characteristic of the transistors to linearize the whole filter. Without the need for conventional circuit linearization techniques, log-domain filter circuits have a simple and elegant structure, and hold the potential to run at high frequencies and operate from low power supplies [12], [13].

The state-space synthesis method is a very powerful and efficient approach in the synthesis of log-domain filters. It provides a very general solution for realizing a filter function [2], [3]. A state-space formulation consists of a set of first-order differential equations. The state variables are equal to simple functions of the exponentials of node voltages. This facilitates systematic circuit implementation and makes debugging a simpler task. In addition, all of the capacitors in a current-mode implementation of a state-space filter have one

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terminal connected to ground. This makes the filter more suitable for IC implementation [12].

Many biquadratic and high-order log-domain filters are given in the literature [2], [5], [12], [14], and [15]. However, first-order filters are widely used in audio and video, as well as in many applications where simplicity and power consumption are important parameters. Up to now, several first-order low-pass filters have been presented in the literature [1], [2], [12], and [16]. A literature survey shows us that no log-domain first-order multifunction filters exist. Realization of a first-order all-pass filter using log-domain techniques is reported in [17], which introduced a systematic state-space synthesis method for designing a first-order all-pass log-domain filter. Two different external currents I_{f1} and I_{f2} were used to realize a filter function. The proposed filter has advantages with respect to other filter structures in that minimum components are used to realize a filter function. In this study, a new log-domain multifunction filter, which is systematically derived using the state-space synthesis procedure from a corresponding block diagram, can give first-order low-pass, high-pass, and all-pass responses simultaneously for a single input. Only one external current I_f is used to realize the filter circuit.

II. Proposed Log-Domain First-Order Multifunction Filter

A multifunction first-order log-domain circuit is derived from the first-order low-pass transfer function. The block-diagram realization can be obtained by combining the low-pass block with two arithmetic blocks as shown in Fig. 1. The arithmetic block represents a node where the currents are being summed or substracted depending on the direction of current flow at that node.

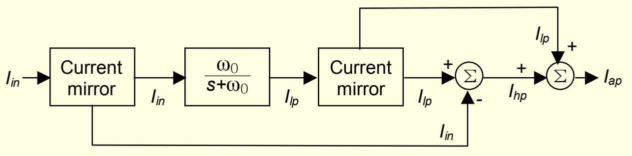

Fig. 1. Corresponding block-diagram for the proposed circuit.

A first-order low-pass filter transfer function can be written as follows,

$$H(s)=\frac{I_{lp}(s)}{I_{in}(s)}=\frac{Y(s)}{U(s)}=\frac{\omega_0}{s+\omega_0}, \qquad (1)$$

where ω_0 is the cut-off frequency of the filter. A transfer function was transformed to the following equation [2], [3]:

$$\dot{y}=-\omega_0 y+\omega_0 u\ . \qquad (2)$$

Its state variables are determined by using the companion form.

State variable x_1 is $x_1=y$. (3)

Equation (2) can be arranged to form the following equation,

$$\dot{x}_1=-\omega_0 x_1+\omega_0 u\ . \qquad (4)$$

The output equation is $y=x_1$, (5)

where u is the input, y is the output, and x_1 is the state variable. Equation (4) can be transformed into a set of nodal equations by using exponential mappings on the input and state variables. The following mappings can, therefore, be applied to quantities [2], [3] in the following equation (infinite β condition):

$$x_1=I_s e^{V_1/V_t}\ ,\quad u=I_s e^{V_0/V_t}\ , \qquad (6)$$

where I_s is the saturation current, V_t is the thermal voltage, and $V_t=kT/q$. The derivatives of u and x are

$$\dot{x}_1=I_s\frac{1}{V_t}\dot{V}_1 e^{V_1/V_t}\ ;\quad \dot{u}=I_s\frac{1}{V_t}\dot{V}_0 e^{V_0/V_t}\ . \qquad (7)$$

The above relationship was applied to (4), and scaling factors are multiplied through the equation with $CV_t/I_s e^{V_1/V_t}$, when it is then arranged to form the following nodal equations:

$$C\dot{V}_1=-\omega_0 CV_t+\omega_0 CV_t e^{\frac{V_0-V_1}{V_t}}\ , \qquad (8)$$

where I_f are positive constants that are defined in

$$I_f=\omega_0 CV_t\ ,\quad \text{and} \qquad (9)$$

$$C\dot{V}_1=-I_f+I_f e^{\frac{V_0-V_1}{V_t}}\ . \qquad (10)$$

If I_f is equal to $I_s e^{V_f/V_t}$, (10) can be arranged as

$$C\dot{V}_1=-I_f+I_s e^{\frac{V_0+V_f-V_1}{V_t}}\ . \qquad (11)$$

The output equations are

$$I_{lp}=y_{lp}=x_1\ , \qquad (12)$$

$$I_{hp}=y_{hp}=x_1-u\ , \qquad (13)$$

$$I_{ap}=y_{ap}=2x_1-u\ . \qquad (14)$$

The realization of the filter circuit using (11), (12), (13) and (14) is shown in Fig. 2.

The three filtering transfer functions, (LP), (HP), and (AP) are obtained as follows:

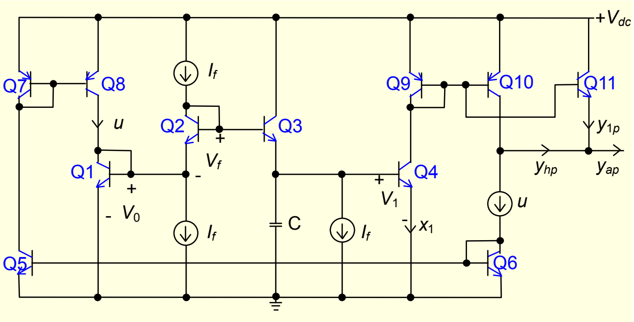

Fig. 2. Circuit schematic of the proposed log-domain first-order multifunction filter.

$$T_{lp}=\frac{I_{lp}(s)}{I_{in}(s)}=\frac{Y_{lp}(s)}{U(s)}=\frac{\omega_0}{s+\omega_0}, \tag{15}$$

$$T_{hp}=\frac{I_{hp}(s)}{I_{in}(s)}=\frac{Y_{hp}(s)}{U(s)}=-\frac{s}{s+\omega_0}, \tag{16}$$

$$T_{ap}=\frac{I_{ap}(s)}{I_{in}(s)}=\frac{Y_{ap}(s)}{U(s)}=\frac{-s+\omega_0}{s+\omega_0}. \tag{17}$$

The cut-off frequency of the filter is $\omega_0 = I_f / CV_t$. (18)

Phase responses for AP output is $\varphi(\omega)=-2\arctan(\frac{\omega}{\omega_0})$. (19)

It should be noted that ω_0 and the phase can be electronically tuned by changing I_f.

III. Simulation Results

The proposed filter was simulated by using both ideal and AT&T CBIC-R (NR200N-2X NPN), (PR200N-2X PNP) transistors. The circuit parameters are chosen as V_{cc}= 3 V, I_f= 50 µA, and C = 300 pF. The cut-off frequency of the filter is f_0=1 MHz. The gain response of the multifunction first-order log-domain filter is shown in Fig. 3. The tuning characteristics were observed by changing the external current as shown in Fig. 4. The phase response of the multifunction first-order log-domain for all-pass output is shown in Fig. 5.

The parasitic pole/zeros can be seen in the transfer function due to non-ideal behavior of the BJT. This result caused a peak in the gain response of the proposed circuit. These non-idealities are a parasitic emitter and base resistance, finite β, early voltages, and area mismatches. If the value of grounded capacitor C is increased, this peak will be smaller. Another solution is an electronic compensation approach. Up to now, several simple electronic compensation schemes were proposed to correct for transistor non-idealities in the literature [9], [12], and [18].

The time-domain response of the all-pass filter is shown in Fig. 6. A sine-wave input at a frequency of 1 MHz was applied to the filter. This causes a 0.26 µs time delay at the output of the all-pass filter corresponding to a 93 degree phase difference, which is close to the theoretical value (90 degree).

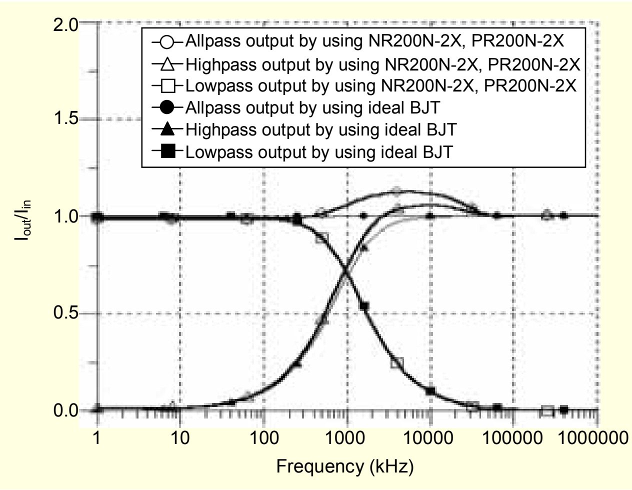

Fig. 3. The gain response of multifunction first-order log-domain filter.

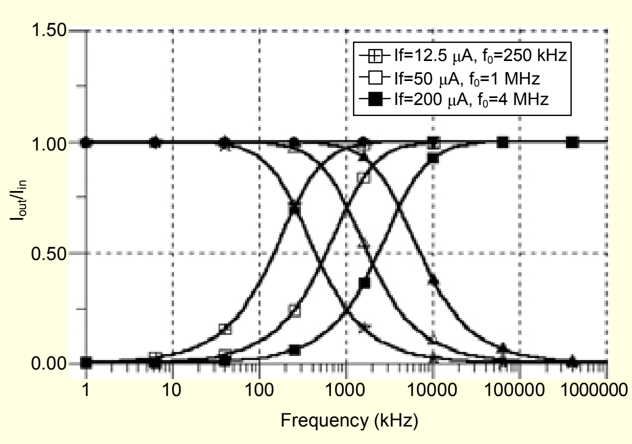

Fig. 4. The tuning characteristics were observed by changing the current I_f.

The output signal's total harmonic distortion (THD) in % was measured with a different input current value by using both ideal and AT&T CBIC-R (NR200N-2X NPN), (PR200N-2X PNP) transistors. The filter was set to a 1 MHz cut-off frequency with I_f= 50 µA, and the input frequency was also set to this value. Then, a sinusoidal signal was applied to the filter with different input currents, 10 µA, 20 µA, 40 µA, and 80 µA, and the THD results obtained were 0.0002, 0.0003, 0.0006, and 0.0019 for ideal BJTs, and 0.212, 0.383, 0.781, and 1.37 for real BJTs, respectively. THD results point out a good linearity response of this type of filter structure. Tolerable differences are observed and the realization of this filter in simulation has provided satisfactory results.

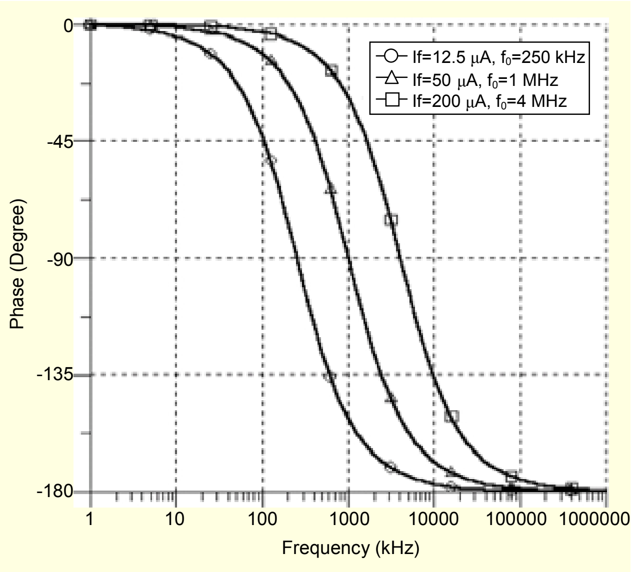

Fig. 5. The phase response of first-order log-domain all-pass filter.

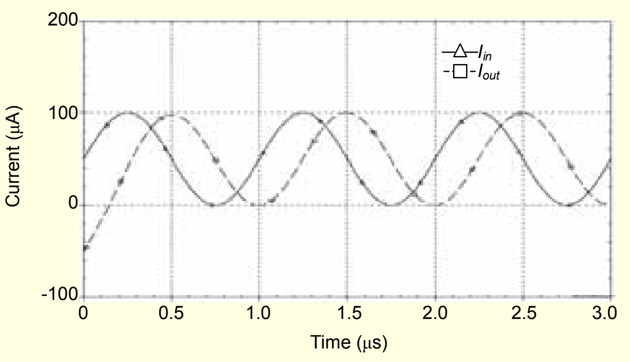

Fig. 6. Time-domain response of the proposed all-pass filter.

IV. Conclusion

In this work, a new log-domain first-order multifunction filter structure is presented. A systematic synthesis procedure to derive the filter circuit is also given. PSPICE simulations are provided to confirm the theoretical analysis. The proposed filter has the following advantages: i) It can be electronically tuned, ii) has a wide bandwidth, iii) employs only BJTs and a capacitor, iv) has a very simple structure, v) is suitable for very large-scale integration technologies, and vi) is suitable for low voltage/power applications. It is expected that the proposed current-mode multifunction first-order log-domain filter will be useful in the design of analog signal processing applications.

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