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New Log-Domain First-Order Multifunction Filter Using MOSFETs in Weak Inversion

Manoj Kumar Jain, Vinod Kumar Singh

Department of Electronics Engineering, Institute of Engineering and Technology, Lucknow, India
Email: mkjain71@gmail.com, vksingh@ietlucknow.edu

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Abstract

A new current-mode first-order log-domain multifunction filter is presented in this paper. This filter has single input and provides three outputs (low-pass, high-pass and all-pass) using a first-order low-pass filter and five of current mirrors as building blocks. The proposed filter employs only MOSFETs and a grounded capacitor. The first-order filters are used in audio and video applications extensively. The MOSFETs of the core section are operated in weak inversion thereby making the circuit suitable for low-voltage, low-power applications. The SPICE simulations have shown good performance of the proposed filter.

Keywords

Log-Domain Filters, Multifunction Filter, Translinear Circuits

1. Introduction

In 1979, Adams [1] proposed the concept of log-domain signal processing but this concept did not receive much attention of the researchers at that time. The power of log-domain technique came into popular focus only when Frey [2] [3] gave a generalized method to synthesize log-domain filters by using state-space technique. The principle of log-domain signal processing is to first compress (logarithmic) the input signal and then process it and finally expand (exponential) the signal at output stage. The working nature of log-domain filters is the same as that of companding circuits which were proposed by Tsividis, Gopinathan and Toth [4] independently in 1990. Thus, the log-domain circuits fall into the class of externally linear and internally nonlinear (ELIN) circuits. Adams circuit was the first ELIN circuit. The log-domain filters are also recognized as translinear (TL) filters (or dynamic translinear filters). The TL filter concept was reinvented by Seevinck [5] in 1990.

Initially, log-domain filters were synthesized by using the exponential nature of bipolar transistor, but in 1994 Toumazou, Ngarmnil and Lande [6] proposed the first log-domain filter for implementation in MOS technology in which the MOS transistors were operated in subthreshold (or weak inversion) region. The literature survey up till 2014 shows that the log-domain filters have received more attention of the researchers during more than three decades [7].

The first-order filters have been extensively used in audio and video applications where circuit simplicity and power consumption are important parameters. Thus, during the last few decades, voltage-mode and current-mode first-order filter circuits have found significant place in literature. Among the voltage-mode and current-mode circuits, the latter fulfill the contemporary requirements such as low-power consumption, low-voltage operation, large dynamic range etc.; therefore, current-mode (CM) circuits have received much attention and from time to time, a number of current-mode first-order multifunction (low-pass, high-pass and all-pass) filters [8]-[14] have been reported earlier in the literature by various researchers. Current-mode multifunction filters employing only bipolar junction transistors and a single grounded capacitor have been proposed by Kircay and Cam [8] [9] in 2006 and Arslanalp, Tola and Yuce [10] [11] in 2011. In 2014, Kircay [12] again proposed a multifunction[1] filter using MOS transistors and single grounded capacitor. In this circuit [12], the MOS transistors have been operated in saturated region.

This paper proposes a MOS based multifunction first-order filter which is capable of realizing all possible first-order filters namely, low-pass, high-pas and all-pass from the same configuration. In the proposed circuit, the MOS transistors forming the core low-pass filter are operating in subthreshold region wherein MOS transistors have exponential characteristics. The validity of the proposed configuration has been confirmed through SPICE simulation results. The SPICE simulations show that the proposed circuit offers a performance which makes it suitable for low voltage, low power operation.

2. Proposed Multifunction Filter Circuit

The core block of the proposed circuit is a first-order low-pass filter which has been obtained by an appropriate modification of the four-MOSFETs translinear circuit used earlier as a normal product computation function [15]. The key concept to obtain multiple outputs from a single input signal is to subtract the low-pass signal from the input signal to get a high-pass response and then adding this high-pass output with the low-pass to get an all-pass output. In this sense, the methodology is similar to the one adopted in recent works [8] [9]. This is the first circuit of its kind in log-domain using CMOS technology.

The proposed circuit offers the advantage of the MOS transistors operating in subthreshold region [16]. This circuit includes a number of current steering circuits, at ap-

[1]Among other methods of creating first-order multifunction/ universal filters, which are based upon techniques other than log-domain/translinear/square-root domain approaches, one can count circuits of [13] [14]. But they have employed linear active building blocks named multiple output second generation current conveyor (MOCCII) and current differencing buffered amplifier (CDBA) respectively.

propriate locations for minimizing dc offset and producing correct outputs.

In Figure 1 MOSFETs M_1-M_2-M_3-M_4 along with a capacitor C constitute the basic first-order low-pass core. The transfer function of this circuit can be determined as follows. For the translinear loop comprised of M_1-M_2-M_3-M_4, we have the following equation for the close loop containing of V_{GS} of the four-MOSFETs.

$$V_i + V_f = V_{GS3} + V_1 \tag{1}$$

If the MOS transistors are operated in weak inversion region they would have exponential relationship between drain current and gate source voltage [16] of the form

$$I_D = I_{d0} \mathrm{e}^{V_{GS}/nV_T} \tag{2}$$

where I_{d0} is the zero bias current, $n = 1.5$ is the subthreshold slope coefficient and $V_T = kT/q = 26$ mV at room temperature is known as thermal voltage.

Now Equation (2) can be rearranged as

$$V_{GS} = nV_T \ln\left(\frac{I_D}{I_{d0}}\right) \tag{3}$$

Therefore Equation (1) can be written as

$$nV_T \ln\left(\frac{I_{in}}{I_{d0}}\right) + nV_T \ln\left(\frac{I_f}{I_{d0}}\right) = nV_T \ln\left(\frac{sCV_1 + I_f}{I_{d0}}\right) + nV_T \ln\left(\frac{I_{out}}{I_{d0}}\right) \tag{4}$$

Equation (4) can be simplified as

$$\ln\left(\frac{I_{in}}{I_{d0}} * \frac{I_f}{I_{d0}}\right) = \ln\left(\frac{sCV_1 + I_f}{I_{d0}} * \frac{I_{out}}{I_{d0}}\right) \tag{5}$$

From Equation (5), we finally obtain

$$I_{in} * I_f = \left(C\dot{V}_1 + I_f\right) * I_{out} \tag{6}$$

The value of $\dot{V}$ can be obtained by differentiating Equation (2) and putting in Equation (6), thereby leading to

$$I_{in} * I_f = \left(sCnV_T + I_f\right) * I_{out} \tag{7}$$

Rearranging Equation (7), we get the transfer function of the circuit as

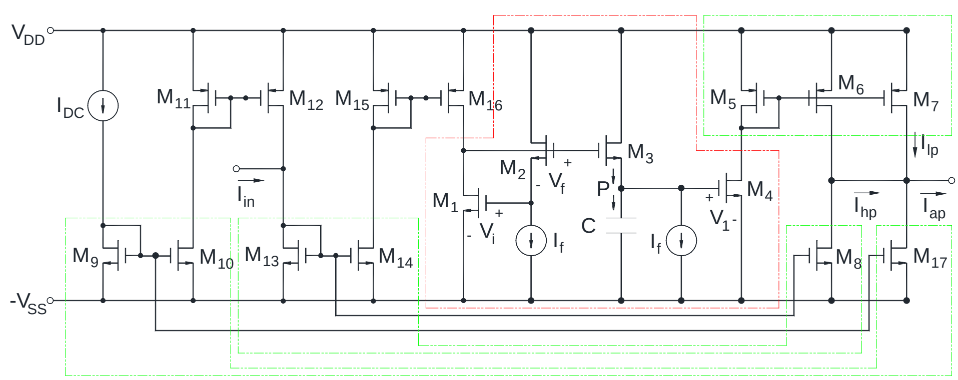


Figure 1. The proposed log-domain first-order multifunction filter.

$$\frac{I_{out}}{I_{in}} = \frac{I_f/(nCV_T)}{(s + I_f/(nCV_T))} \tag{8}$$

Equation (8) represents the transfer function of the first-order low-pass filter and can be expressed as:

$$H(s) = \frac{I_{out}}{I_{in}} = \frac{\omega_0}{s + \omega_0} \tag{9}$$

where $\omega_0 = I_f/(nCV_T)$ is the cutoff frequency of the low-pass filter.

Now the low-pass output is given by

$$I_{lp} = I_{out} \tag{10}$$

whereas the other two current outputs namely, I_{hp} and I_{ap} are obtained by

$$I_{hp} = I_{out} - I_{in} \tag{11}$$

$$I_{ap} = 2I_{out} - I_{in} \tag{12}$$

for which the required operations are carried out by the appropriate current mirrors and current repeaters as shown in **Figure 1**. The transistors M_9-M_{10}-M_{17}, M_{13}-M_{14}-M_8 and M_5-M_6-M_7 are current steering circuits and the MOSFET pairs M_{11}-M_{12} and M_{15}-M_{16} are simple current mirrors.

Thus, the transfer functions of the low-pass, high-pass and all-pass filters realized by the proposed circuit are given by

$$H_{lp} = \frac{I_{lp}(s)}{I_{in}(s)} = \frac{\omega_0}{s + \omega_0} \tag{13}$$

$$H_{hp} = \frac{I_{hp}(s)}{I_{in}(s)} = -\frac{s}{s + \omega_0} \tag{14}$$

$$H_{ap} = \frac{I_{ap}(s)}{I_{in}(s)} = \frac{-s + \omega_0}{s + \omega_0} \tag{15}$$

From Equations (13)-(15), it turns out that the cutoff frequency (in case of low-pass and high-pass) and phase (in case of all-pass) can be electronically tuned by changing the value of I_f since $\omega_0 = \frac{I_f}{nCV_T}$.

3. SPICE Simulations

The proposed circuit was simulated in SPICE employing TSMC 0.35 µm Level 3 CMOS process parameters [17]. The selected parameters were $V_{DD} = -V_{SS} = 0.5$ V, $C = 3$ pF, $I_f = 70$ nA, $I_o = 0.3$ µA and $I_{in} = 0.2$ µA. The aspect ratios of the transistors were taken as shown in **Table 2**. From SPICE simulation, it has been verified that the condition required for weak inversion operation (of all the four MOSFETs M_1-M_2-M_3-M_4 of the basic low-pass core) *i.e.* $V_{GS} < V_T$ is satisfied.

The result of SPICE simulations of the circuit of **Figure 1** using TSMC 0.35 µm level 3 CMOS process parameters as given in **Table 1** with aspect ratios of the MOSFETs as given in **Table 2**, are shown in **Figures 2-5**. **Figure 2** shows the frequency response of

Table 1. TSMC 0.35 µm Level 3 CMOS process parameters.

Parameters	NMOS	PMOS
L	1U	1U
W	6U	6U
TOX	7.9E−9	7.9E−9
NSUB	1E17	1E17
GAMMA	0.5827871	0.4083894
PHI	0.7	0.7
VTO	0.5445549	−0.7140674
DELTA	0	0
UO	436.256147	212.2319801
ETA	0	9.999762E−4
THETA	0.1749684	0.2020774
KP	2.055786E−4	6.733755E
VMAX	8.309444E4	1.181551E5
KAPPA	0.2574081	1.5
RSH	0.0559398	30.0712458
NFS	1E12	1E12
TPG	1	−1
XJ	3E−7	2E−7
LD	3.162278E−11	5.000001E−13
WD	7.04672E−8	1.249872E−7
CGDO	2.82E−10	3.09E−10
CGSO	2.82E−10	3.09E−10
CGBO	1E−10	1E−10
CJ	1E−3	1.419508E−3
PB	0.9758533	0.8152753
MJ	0.3448504	0.5
CJSW	3.777852E−10	4.813504E−10
MJSW	0.3508721	0.5

Table 2. Aspect ratios.

MOS Transistors	W/L (µm)
M_1-M_7, M_9-M_{17}	6/1
M_8	5.87/1

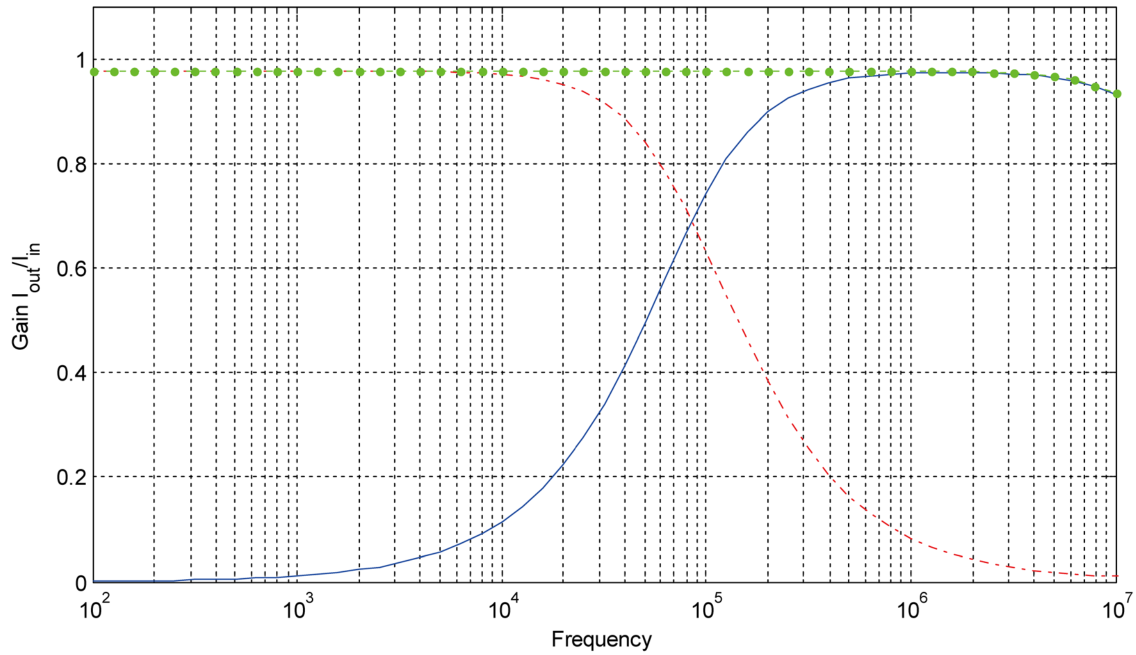
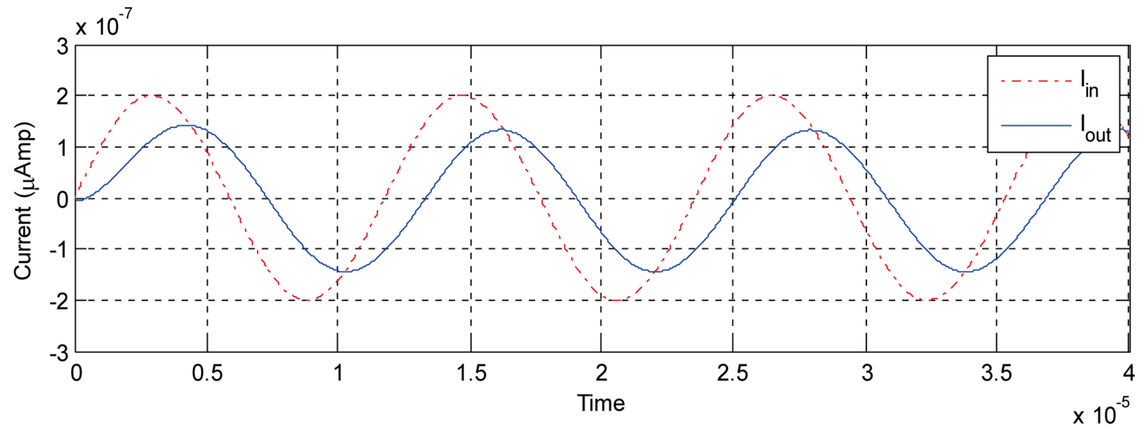
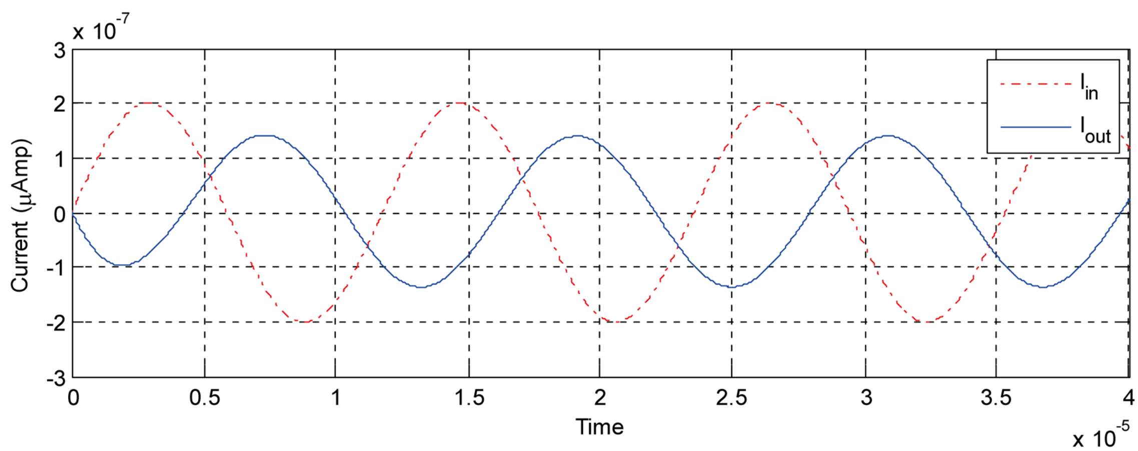


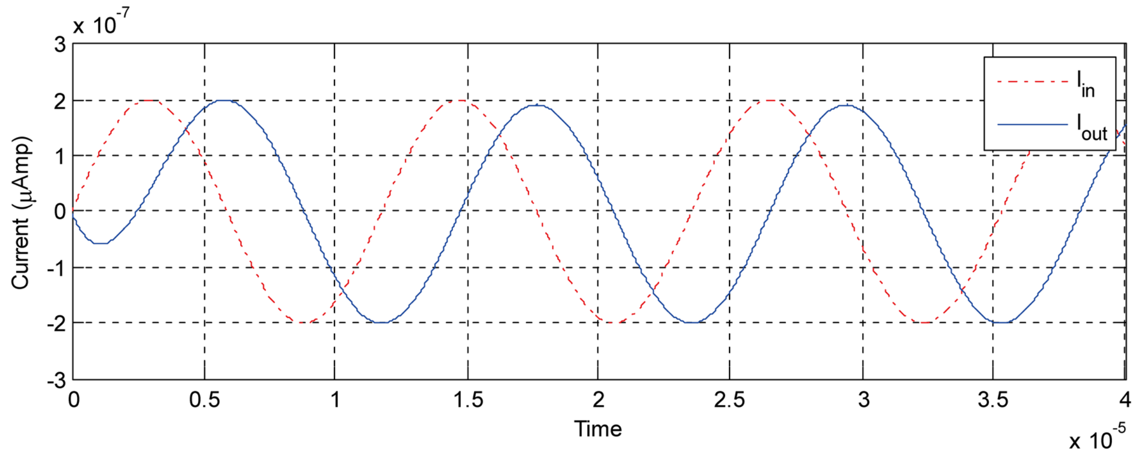
Figure 2. SPICE generated frequency response for the circuit of **Figure 1** for $I_f = 70$ nA.



(a)



(b)



(c)

Figure 3. Transient response of various circuits: (a) Transient response of low-pass filter (f_0 = 85 KHz); (b) Transient response of high-pass filter (f_0 = 85 KHz); (c) Transient response of all-pass filter (f_0 = 85 KHz).

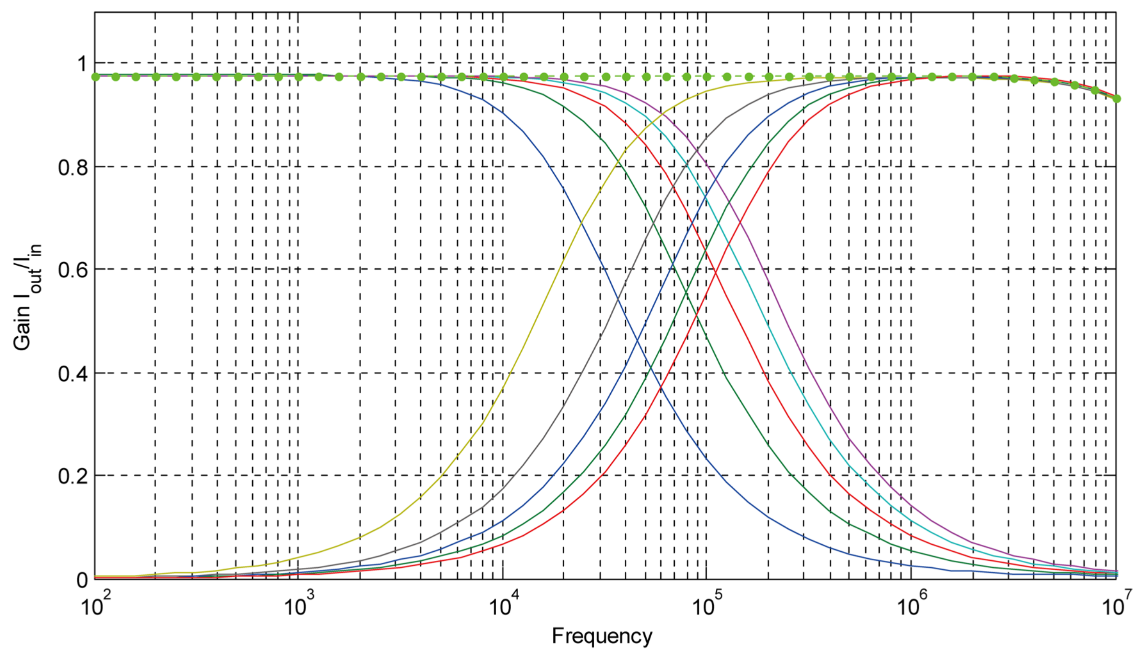


Figure 4. Electronically tuning characteristics observed by varying the current I_f (20 nA, 45 nA, 70 nA, 95 nA and 200 nA).

low-pass, high-pass and all-pass. **Figures 3(a)-(c)** shows the transient response of the low-pass, high-pass and all-pass filters designed for cutoff frequency of f_0 = 85 KHz by taking I_f = 70 nA. **Figure 4** shows the electronic controllability of the cutoff frequency by change of dc bias current (I_f = 20 nA, 45 nA, 70 nA, 95 nA and 120 nA) and **Figure 5** shows the phase response of the all-pass filter. The proposed circuit has been tested in 0.35 μm technology has also been tested in 0.18 μm technology as per the reviewer one. The results obtained where almost similar to results obtained by 0.35 μm technology. In the all-pass response the cutoff frequency has been found better.

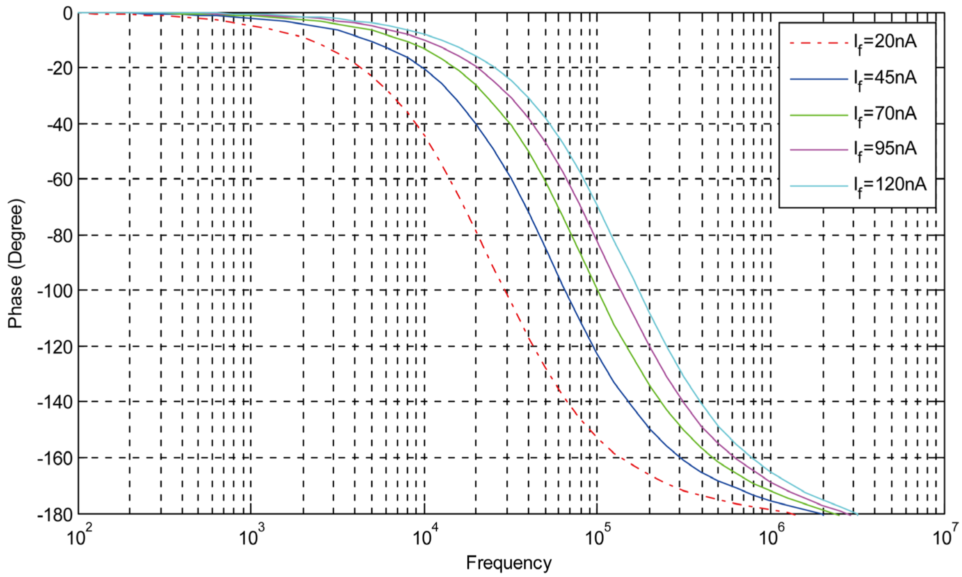


Figure 5. Phase response of the all-pass filter.

The SPICE simulation results, thus confirm the validity of the proposed filter.

4. Concluding Remarks

This paper presented a log-domain multifunction first-order filter using only MOSFETs and grounded capacitor. The circuit is capable of realizing all first-order filters namely, low-pass, high-pass and all-pass from the same configuration with electronic tunability of the radian frequency ω_0. The circuit was simulated in SPICE employing TSMC 0.35 µm Level 3 CMOS process parameters. The SPICE simulation results have confirmed the workability and performance of the proposed MOS circuit. The proposed circuit which is operated from ±0.5 volt DC power supply and consumes only 2.62 µW power at I_f =120 nA, appears suitable for low voltage, low-power applications. This paper has therefore, added a new CMOS multifunction first-order filter to the existing repertoire of log-domain filters (as in [1]-[9] [16] and references cited therein).

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