Design of a Log-domain Differentiator And Integrator Based Universal Analog Biquadratic Filter

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***Abstract*-A novel implementation of a continuous-time universal analog biquadratic filter is presented. Using a log-domain differentiator and integrator along with a few current mirrors and current copiers, the low pass, high pass, band pass, band elimination (notch) and all pass filter transfer functions are realized. The filter has been designed using a purely current-mode approach. The filter realized is electronically tunable by altering the magnitude of the bias/control current sources. Both the differentiator and the integrator used here have been designed using bipolar junction transistors. The design can be extended and realized with MOSFETs operating in the weak inversion region. The concept has been validated by circuit simulations.**

I. INTRODUCTION

The on-going trend towards lower supply voltages and lower-power operations has brought the area of analogue integrated filters into limelight. In conventional filter implementation techniques using opamp–MOSFET–C, transconductance–C or switched capacitors, the supply voltage restricts the attainable maximum dynamic range. Further the use of linear resistors in low-power environment demands a large silicon area for on-chip integration and hence renders impractical. High frequency operation and the requirement for tunability of the filter complicates the situation further.

In the area of continuous-tune filters, "Translinear (TL) Filters" presents a solution to the problems indicated above. The essence of a translinear filter was originally presented by Adams [1], however, he introduced the term "Log-Domain Filters" based on the logarithmic relation between the voltages and currents as he had not observed the TL nature of these circuits. Seevinck [2] independently reinvented the TL filter concept and called it "Current-mode Companding". The filters reported by Adams and Seevinck were of first order; a synthesis method enabling the design of high-order log-domain filter was proposed by Frey [3]. In all the above methods, current having an inherently large dynamic range, is compressed when transformed into voltage and expanded afterwards when transformed back to current. Hence, the voltage swing across the integrator's capacitor is independent of the supply voltage and can be lowered to the minimum value required for current-mode operation of the circuit. The log-domain principle exploits the properties of an exponential function which can be obtained from the relation between collector current and the base-emitter voltage of a bipolar transistor or drain current of a MOS transistor in weak inversion.

Conventionally, cascading integrators or differentiators normally construct continuous-time filters. In the log domain, 'log-domain' integrators [1-7] and 'log-domain' differentiators [8] can be used. A band pass filter is usually implemented by putting two integrators in a loop. Agrawal et al [9] proposed a design of a biquad filter using log-domain techniques in which low pass, high pass, band pass, band elimination and all pass filter functions were realized by using two integrators and 3 current summer blocks, however this circuit operated at 5V supply.

It is observed that a log-domain differentiator consumes less power than a log-domain integrator. Keeping this in mind, in this paper, we show how to combine an integrator, a differentiator and few current copier/summer blocks to realize a Universal Analog Biquad Filter in the log domain. Usually, circuits that employ differentiator suffer from instability caused by the unavoidable poles that accompany the zero in the transfer function. However, a simple stable differentiator would not create this instability. For this purpose, we have used the (log-domain) differentiator constructed out of part of a circuit reported in [10]. Further, a transistor level implementation of a low-voltage, circuit working at 1.5V supply, which gives low pass, high pass, band pass and Notch filter output at different terminals and also consumes lesser power has also been proposed.

II. CIRCUIT DESIGN AND ANALYSIS

The block diagram of the proposed log-domain biquadratic filter comprising a differentiator, an integrator, two current copiers and two current summers is shown in Fig. 1. The summer block represents a node where the currents are added (or subtracted depending on the direction of current flow at that node).

While designing, the circuit at transistor level we have used the integrator circuit proposed by Seevinck [2]. This integrator is shown in Fig. 2.

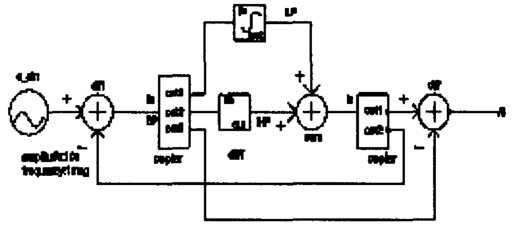

Fig. 1: Block Diagram of the Log Domain Biquad Filter

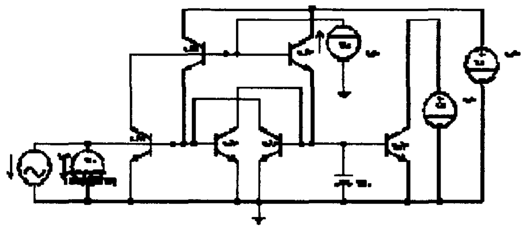

Fig. 2: Log-domain Integrator

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The transfer function of the integrator is given by

$$I_{out} = \frac{I_o}{V_t C_1} \int I_{in} dt \qquad (1)$$

and the unity gain bandwidth follows from

$$f_{ug} = \frac{I_o}{2\pi C_1 V_t} \qquad (2)$$

I_o being a bias/control current, V_t being the thermal voltage kT/q, C_1 being the capacitance value and I_{in} being the integrator's input signal. In the s-domain, the transfer function of the integrator is given by

$$H(s)_{\text{int}} = \frac{k_2}{s+b} = \frac{I_{bias_1}}{sC_1 v_t}\ ; b = 0 \qquad (3)$$

In order to get a stable differentiator for realizing our circuit, we have used a portion of the circuit proposed in [10]. The circuit for the (lossy) differentiator is depicted in Fig. 3. The translinear loop formed by the four transistors in Fig. 3 gives the following differential equation for the lossy differentiator:

$$I_{out} = I_{in} + \dot{I}_{in}(V_t \cdot C_2)/I_{0l} \qquad (4)$$

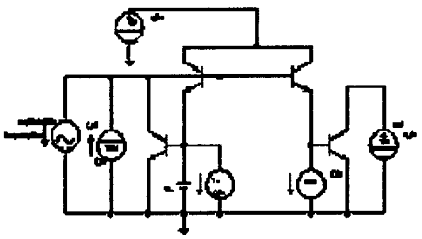

Fig. 3. Lossy Differentiator

Which, in the s-domain, equals

$$I_{out} = I_{in} + I_{in}(sV_t . C_2)/I_{0l} \qquad (5)$$

In the above equation V_t is the thermal voltage, C_2 the capacitance in parallel with constant current source I_{0l}; I_{out} and I_{in} are the output and input currents, respectively.

We can write the generalized transfer function of the differentiator as below:

$$H(s)_{diff} = k_1(s+a) = \frac{V_t \cdot C_2}{I_O}(s + \frac{I_{O_1}}{V_t \cdot C_2}) \qquad (6)$$

A block level analysis of the proposed biquad in Fig. 1 gives the transfer characteristics of the universal biquad, which is given in Table I. The constants k_1 and 'a' define the transfer function of the differentiator, similarly the constants k_2 and 'b' defines the integrator transfer function. These are controlled by the current sources and the capacitances used in the differentiator and integrator. Hence, the current sources and capacitors used for the realization of the individual integrator and differentiator indicated in Fig. 2 and 3 will control the overall transfer characteristics of the universal biquad. The complete transistor level realization of the universal biquad is shown in Fig. 4. This circuit operates at 5V supply. The integrator & the differentiator used here are shown in Fig. 2 and 3 respectively. A subset of the universal biquad giving low pass, high pass, band pass and band elimination filter characteristic at various terminals of the circuit and operating at 1.5V supply is shown in Fig. 5. It may be noted that the floating voltage sources used in this circuit are for simulation purposes only.

Table I Transfer Functions of the Biquad

Band Pass	$\dfrac{((s+b)/k_1)}{(s^2+(a+b+1/k_1)s+ab+(k_2+b)/k_1)}$
Low Pass	$\dfrac{k_2/k_1}{(s^2+(a+b+1/k_1)s+ab+(k_2+b)/k_1)}$
High Pass	$\dfrac{s^2+(a+b)s+ab}{(s^2+(a+b+1/k_1)s+ab+(k_2+b)/k_1)}$
Notch	$\dfrac{s^2+(a+b)s+ab+k_2/k_1}{(s^2+(a+b+1/k_1)s+ab+(k_2+b)/k_1)}$
All Pass	$\dfrac{s^2+(a+b-1/k_1)s+ab+(k_2-b)/k_1)}{(s^2+(a+b+1/k_1)s+ab+(k_2+b)/k_1)}$

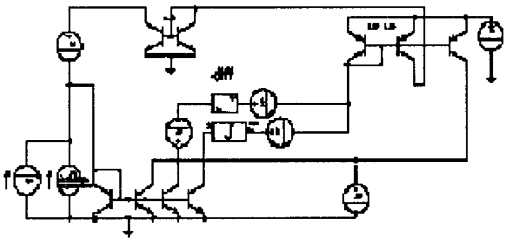

Fig. 4. Differentiator-Integrator Biquad

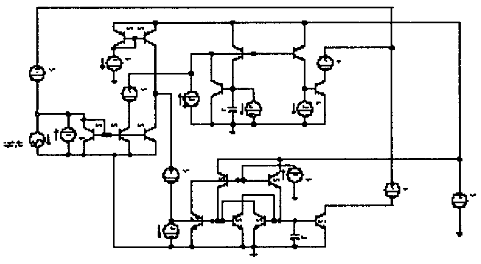

Fig. 5. Log-Domain Circuit for Low-Pass, High pass, Band-pass, Notch filter at 1.5V supply

III. SIMULATION AND RESULTS

The simulation of the log-domain integrator-differentiator biquad at Fig. 4 has been carried out using Saber Simulator. The input bias current is 2mA. The values of capacitor and current source for the differentiator are 0.1uF and 0.002 A. The values of capacitor and current source for the integrator are 1 uF and 1 mA. Saber default BJT model parameters that were used in the simulation are given below:

(type n, is=100a, bf=100, nf=1, ise=0, ne=1.5, br=1, nr=1, isc=0, nc=2, rb=0, rbm=0, re=0, rc=0, cje=0, vje=0.75, mje=0.33, tf=0, xtf=0, itf=0, ptf=0, cjc=0, vjc=0.75, mjc=0.33, xcjc=1, tr=0, cjs=0, vjs=0.75, mjs=0, xtb=0, eg=1.11, xtb=3, kf=0, af=1, fc=0.5, gmin=1p, tnom=27)
(type p, is=100a, bf=100, nf=1, ise=0, ne=1.5, br=1, nr=1, isc=0, nc=2, rb=0, rbm=0, re=0, rc=0, cje=0, vje=0.75, mje=0.33, tf=0,xtf=0, itf=0, ptf=0, cjc=0, vjc=0.75, mjc=0.33, xcjc=1, tr=0,cjs=0, vjs=0.75, mjs=0, xtb=0, e.g.=1.11, xtb=3, kf=0, af=1, fc=0.5, gmin=1p, tnom=27)

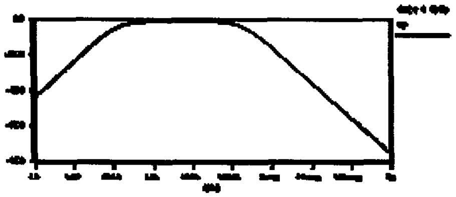

Fig. 6. Frequency Response (Magnitude)-Band Pass

The plot at Fig.6 shows magnitude response of the biquad for Band Pass filter configuration. The bandwidth for the above simulation is in excess of 100 kHz.

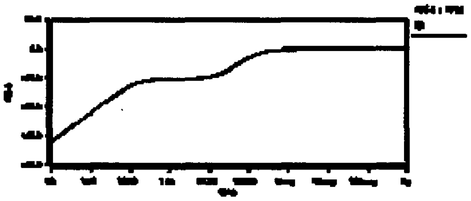

Fig. 7. Frequency Response (Magnitude)-High Pass

The plot at Fig. 7 shows magnitude response of the biquad for High Pass filter configuration. The plot shows existence of two different poles.

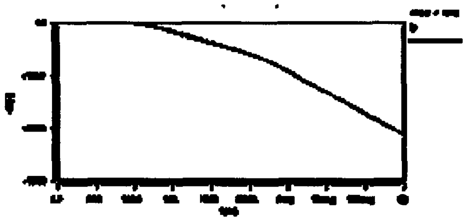

Fig. 8. Frequency Response (magnitude)-Low Pass

The plot at Fig. 8 shows magnitude response of the biquad for Low Pass filter configuration. It can be seen from the Fig.8 that we get two different slopes in the transfer curve; these are due to the existence of multiple poles

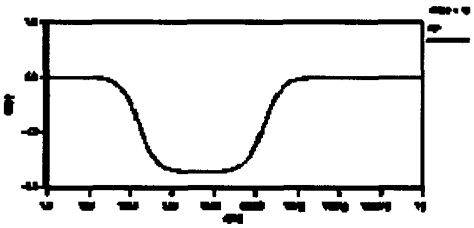

Fig. 9. Frequency Response (magnitude)-All Pass

The plot at Fig. 9 shows magnitude response of the biquad for All Pass filter configuration. The response is almost constant as the dip in the output is of extremely small magnitude and can be neglected.

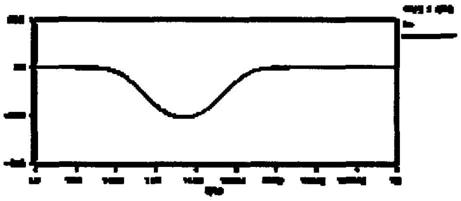

Fig. 10. Magnitude Response -Band Elimination

The plot at Fig. 10 shows magnitude response of the biquad for Band Elimination filter configuration. The notch approximately extends to about 20db

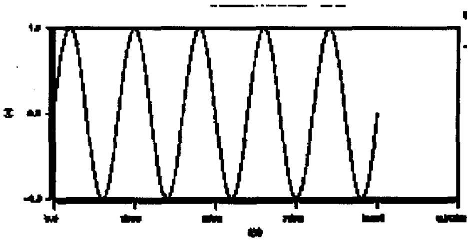

Fig. 11. Input Signal used for the transient response

The Transient response of the above filter configurations were done and the results were as expected. For the sake of completeness the Transient Response of one of the cases (all pass filter) for sinusoidal input signal depicted at Fig. 11 is shown in Fig. 12. This has just been included to show the signal integrity/linearity

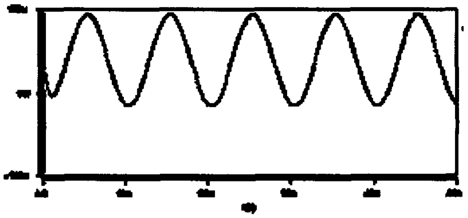

Fig. 12. Transient response of the All Pass filter

The simulation of the circuit at Fig. 5, a subset of the circuit at Fig. 4, giving low pass, high pass, band pass and notch filter outputs at various terminals has been carried out using the Saber Simulator employing realistic transistor models of the DIMES-03 1-micron bipolar IC process of DIMES (Delft Institute for Microelectronics and Submicron Technology). Typical transistor parameters used are: $f_{T,npn}$ = 17 GHz, $BF_{,npn}$ = 195, $f_{T,pnp}$ = 80 MHz, $BF_{,pnp}$ = 55. The input bias current is 50 micro-amps. The values of capacitor and current sources for the integrator are 100nF, 10uA and 10uA, respectively and the values of capacitor and current sources for the differentiator are 10nF, 50uA, 100uA, and 150uA. This simulation shows that biquad at Fig. 5 can indeed be operated at a reduced power supply voltage of 1.5V.

The plot in Fig. 13 shows the magnitude frequency response of the biquad shown in Fig. 5 for a band-pass filter configuration. The bandwidth is in excess of 20 kHz. The limited attenuation at low and high frequencies is due to second-order effects, such as the Early effect and base currents.

The plot in Fig. 14 shows the magnitude frequency response of the biquad at Fig. 5 for a high-pass filter configuration. The plot clearly shows the two different time constants.

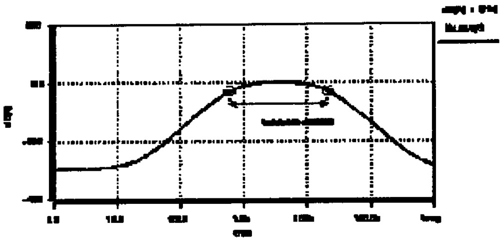

Fig.13. Frequency Response (Magnitude): BandPass

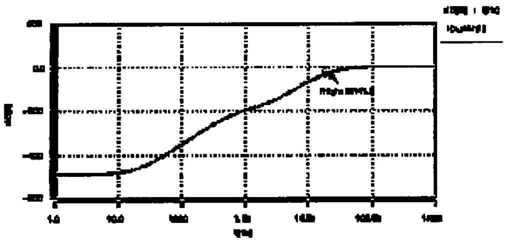

Fig. 14. Frequency Response (Magnitude): High Pass

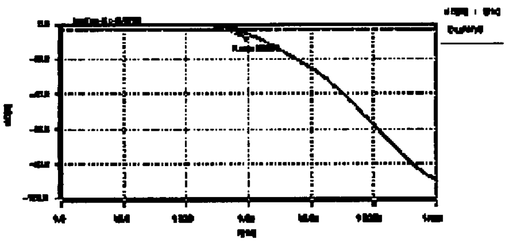

Fig. 15. Frequency Response (magnitude): Low Pass

The plot in Fig. 15 shows the magnitude frequency response of the biquad for a low-pass filter configuration. It can be seen from Fig. 15 that there are two different slopes in the transfer curve. These are due to the existence of two poles.

The plot in Fig. 16 shows the magnitude frequency response of the biquad for a band-elimination filter configuration. The notch approximately extends to about 9dB with a bandwidth of approximately 15kHz

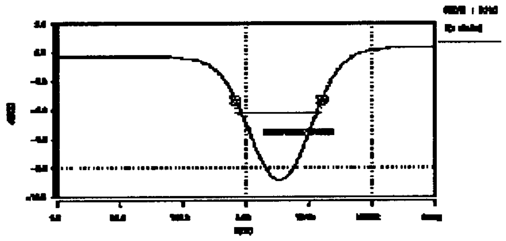

Fig.16. Magnitude Response: Band Elimination

A transient analysis of the above filters was done and the results were as expected. For the sake of completeness, the transient response of the low pass and high pass filter configurations is shown in Fig. 17 along with the sinusoidal input signal of 100Hz. It has been included to show the signal integrity/linearity.

Finally, in order to get a feel of the distortion in the circuit we show in Table II the total harmonic distortion (THD), in %, for input signal magnitudes of 25nA, 250nA and 5uA.

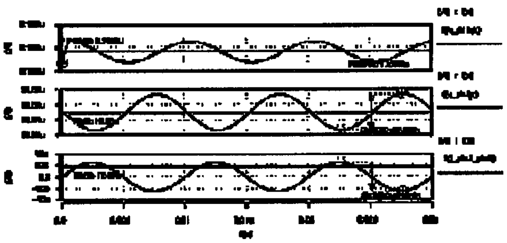

Fig. 17. Transient Response of the Low Pass and High Pass filters to 100Hz sinusoidal input signal

Table II THD at various magnitudes of input current

Input current Output	25 nano amp	250 nano amp	5 micro amp
i(v_dc.lp)	0.02257	0.01301	0.009391
v_dc.lp/m	0.185	0.07727	0.05274
v_dc.lp/p	0.185	0.07727	0.05274

IV. CONCLUSION

A new approach for the design of a continuous-time universal biquad filter based on the combination of a log-domain integrator and a differentiator has been proposed. In published literature, only integrator based design of biquad are discussed. The proposed architecture based on integrator and differentiator has been shown to be stable and gives a new approach to the design of biquad filters. Preliminary estimation of the power consumption shows that the proposed filter consumes about 60% less power than the integrator-integrator biquad configuration presented at [9]. Further it may be noted that the analog biquadratic filter in the log-domain at [9] was operated at 5V supply, however, in our log-domain biquad at Fig.5 we have used 1.5V supply. The noise aspect of the proposed filter is under study.

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