DESIGN OF A NEW LOG-DOMAIN DIFFERENTIATOR BASED UNIVERSAL ANALOG BIQUADRATIC FILTER

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Abstract *- A novel implementation of a continuous-time universal analog biquadratic filter is presented. Using two log-domain differentiators 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 and is electronically tunable over several decades of frequency by altering the magnitude of the current sources. Both the differentiators 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 demonstrated at circuit simulation level using the Saber simulator.*

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 and switched capacitors, the supply voltage restricts the attainable maximum dynamic range. Further the use of linear resistors in low-power environments demands large silicon area for on-chip integration and hence renders impractical. High frequency of operation and the requirement for tunablity of the filter complicates the situation further.

In the area of continuous-time filters, "Translinear (TL) filters" present a solution to the problems indicated above. The essence of Translinear filters 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 filters was proposed by Frey [3]. In all the above filters, currents, having an inherently large dynamic range, are compressed when transformed into voltages and expanded afterwards when transformed back to currents. Hence, the voltage swings across the integrator's capacitors are independent of the supply voltage and can be lowered to the minimum value required for current operation of the circuit. The log-domain principle exploits the properties of exponential functions which can be obtained from the relation between collector current and base-emitter voltage of a bipolar transistor or drain current of a MOS transistor in weak inversion region.

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

In this paper, we show how to combine two differentiators and a few current copier/summer blocks to realize an Universal Analog biquadratic filter in the log-domain. Usually, circuits that employ differentiators 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 differentiator (log-domain) constructed out of the part of the circuit reported in [10]. Further we propose a low voltage circuit working at 1.5 volts instead of 5 volts, which gives the low-pass, high-pass, band-pass, all-pass and band elimination filter outputs at different terminals. This circuit was simulated using the default Saber BJT model parameters. However when we use the BJT SPICE model parameters from TU Delft fabrication process we had to increase the working voltage to 2.5V.

II. CIRCUIT DESIGN AND ANALYSIS

The block diagram of the proposed Log-domain biquadratic filter consisting of two differentiators, two currents 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).

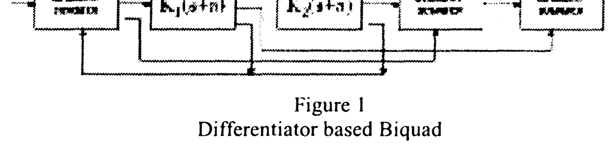

Figure 1
Differentiator based Biquad

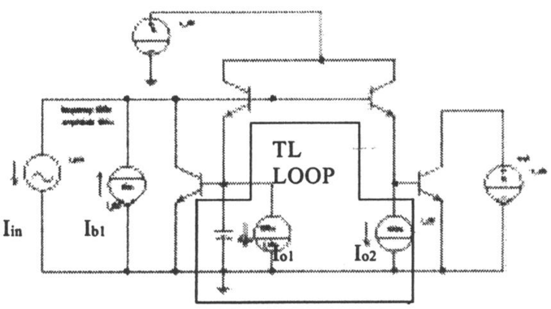

Figure 2
Lossy Differentiator

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.2. The Translinear loop formed by the four transistors in Fig.2 gives the following differential equation for the Lossy differentiator:

$$I_{out} \approx I_{in} I_{01} + \dot{I}_{in} (V_t \cdot C) / I_{02}$$

which, in the s-domain equals

$$I_{out} \approx I_{in} I_{01} + I_{in} (sV_t . C) / I_{02}$$

In the above equation V_t is the thermal voltage, C the capacitance in parallel to constant current source I_{01}; I_{out} and I_{in} are the output and input currents, respectively. The above equation gives the cutoff frequency of the differentiator, which equals $\varpi_o = \frac{I_{o2}}{V_t C}$ (rad/s). The block level analysis of the biquad structure indicated at Fig.1 gives the transfer characteristics of the universal biquad filter; the same is given in Table I. The constants k_1 and '**a**' define the transfer function of one differentiator, similarly the constants k_2 and '**b**' are used to define the transfer function of the other differentiator.

These transfer functions are related to the bias currents and capacitor values of the respective differentiators and are given by the following equations:

$$H(s)_{diff1} = k_1(s+a) \approx -(I_{o1A} + sC_A V_t)\frac{1}{I_{o2A}}$$

$$H(s)_{diff2} = k_2(s+b) \approx -(I_{o1B} + sC_B V_t)\frac{1}{I_{o2B}}$$

The current sources and capacitors used for the realization of both the differentiators indicated above will control the overall characteristics of the universal biquad using the log-domain differentiators. The complete circuit level realization of the universal biquad working at 1.5 volts is shown in Fig.3, this has been simulated using Saber default BJT model parameters. In Fig.4 an alternate circuit realization working at 2.5 volts is shown, this has been simulated using Delft university BJT model parameters..

Table I.
TRANSFER FUNCTIONS OF THE BIQUAD

All-Pass	$\dfrac{s^2+(a+b-1/k_2)s+ab-a/k_2+1/k_1k_2}{s^2+(a+b+1/k_2)s+(ab+a/k_2+1/k_1k_2)}$
Band -Pass	$\dfrac{(k_1+1/k_2)s+k_1a+a/k_2}{s^2+(a+b+1/k_2)s+(ab+a/k_2+1/k_1k_2)}$
Band - Elimination	$\dfrac{s^2+(a+b)s+ab+1/k_1k_2}{s^2+(a+b+1/k_2)s+(ab+a/k_2+1/k_1k_2)}$
High- Pass	$\dfrac{s^2+(a+b)s+ab}{s^2+(a+b+1/k_2)s+(ab+a/k_2+1/k_1k_2)}$
Low –Pass	$\dfrac{1/k_1k_2}{s^2+(a+b+1/k_2)s+(ab+a/k_2+1/k_1k_2)}$

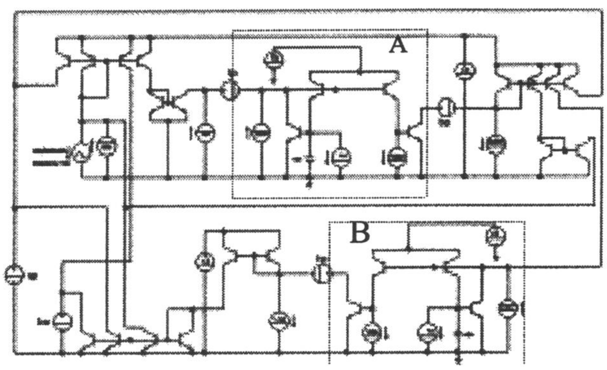

Figure 3
Differentiator based Biquad Filter working at 1.5 volts supply.

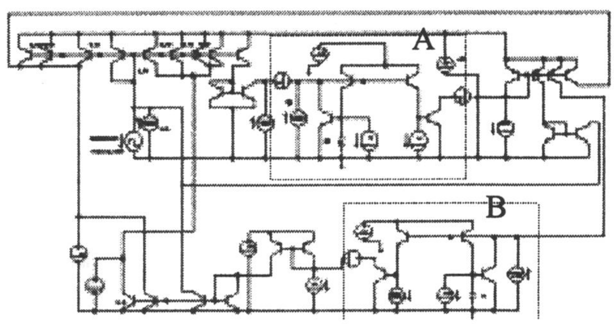

Figure 4
Differentiator based Biquad Filter working at 2.5 volts supply.

III. SIMULATION AND RESULTS

The simulation of the Lossy differentiator at Fig. 2 is shown in Fig. 5 for three different capacitance value of 0.1nF, 1nF, and 10nF respectively, the value of the current sources being I_{b1}=5uA, I_{01}=100uA,and I_{02}=1uA respectively.

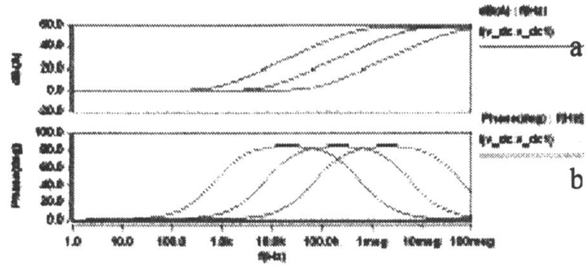

Figure 5
Gain-Frequency and Phase-Frequency Response of Lossy Differentiator for C= 0.1nF, 1nF, 10nF.

The biquad filter circuit at Fig. 3 has been simulated using the Saber default BJT model parameters 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)

For differentiator-A the values of the capacitor and the current sources are C_{1A}=1nF, I_{b1A}=230uA, I_{01A}=1uA and I_{02A}=100uA while for Differentiator-B the corresponding values are C_{1B}=12nF, I_{b1B}=230uA, I_{01B}=1uA and I_{02A}=100uA, using the same nomenclature as that of Fig.2. Other values of current sources used in the circuit are 20uA, 1mA, 0.035mA and 1.1mA.The LP and BP filter outputs are across dummy voltage sources, while BP, BE and AP are across voltage sources of 1V, 0.5V, and 0.8V respectively.

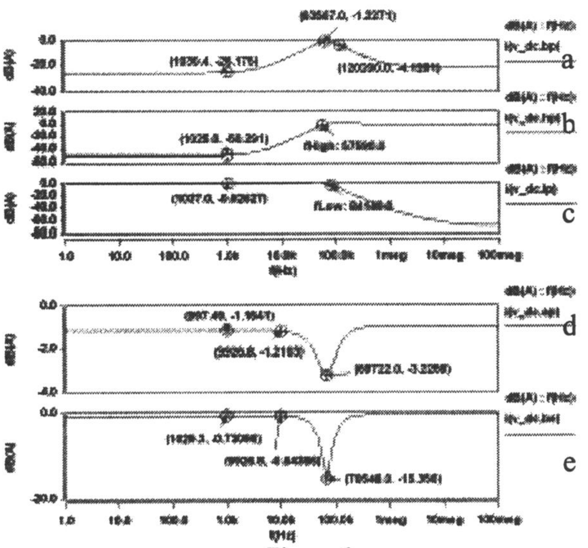

Figure 6
Gain-Frequency Response of: a) Band-Pass b) High-Pass c) Low-Pass d) All-Pass and e) Band-Elimination filter respectively

Fig, 6 show the Gain-Frequency response of all the filter configuration of the differentiator based biquad filter. In case of all-pass filter at Fig. 6 d) the dip in the gain-frequency response is of the order of 2dB and can thus be neglected for all practical purpose.

The transient response of the circuit at Fig. 3 is shown in Fig. 7 for an input AC signal current of amplitude 20nA at 1000Hz and the input DC bias current is 20uA. The transient response shows the maximum attenuation in case of HP filter output, which is confirmed from the gain-frequency plot.

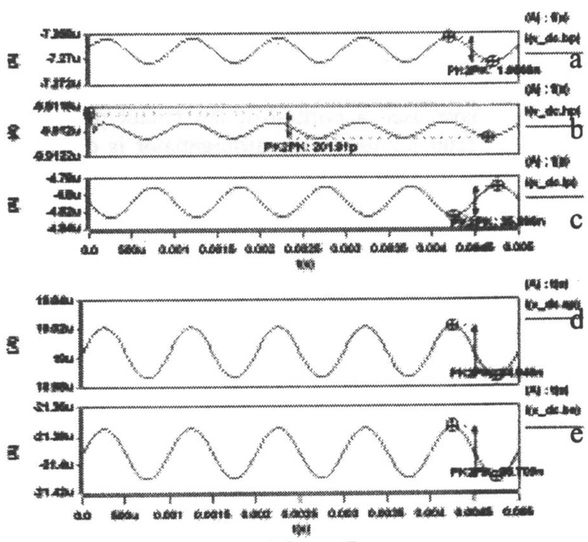

Figure 7
Transient Response of: a) Band-Pass b) High-Pass c) Low-Pass d) All Pass and e) Band-Elimination filter respectively

The filter circuit at Fig. 4 has been simulated using the Delft University BJT SPICE model parameters given below: type= n, is=0.061a, bf=195, nf=1.0080, vaf=45, ikf=10.000E-3, ise=1.30E-18, ne=1.9, br=9, var=1.6, ikr=10.0E-3, isc=2.1E-18, nc=1.6, rb=600, irb=8E-6, rbm=1000, re=60,rc=250, cje=11.0E-15, vje=1, mje=.6, tf=10E-12, xtf=25, vtf=2, itf=8.0E-3, ptf=60, cjc=16E-15, vjc=0.4, mjc=0.2,tr=1.0E-9, cjs=123E-15, vjs=.5,mjs=.1) type= p, is=0.5a, bf=55, nf=1.2, vaf=20, ikf=10E-6, ise=500E-18, ne=2, br=17, var=10, ikr=10E-3, isc=1.4E-15, rb=80,re=25, rc=150, cje=65E-15, vje=0.67, mje=0.34, tf=2E-9, xtf=25, vtf=2, itf=6E-3, ptf=60, cjc=160E-15, vjc=0.7, mjc=0.4, tr=10E-9, cjs=350E-15, vjs=0.5, mjs=0.1, xtb=1.5, eg=1.2, xti=2.5)

For differentiator-A the values of the capacitor and the current sources are C_{1A}=2nF, I_{b1A}=0.03mA, I_{01A}=1uA and I_{02A}=0.1uA while for Differentiator-B the corresponding values are C_{1B}=1nF, I_{b1B}=0.47mA, I_{01B}=10uA and I_{02A}=300uA, other values of current sources used in the circuit are 100uA, 0.8mA, 0.001uA and 1uA. The LP filter output is taken across dummy voltage source, while HP, BP, BE and AP is taken across voltage sources of 1V, 0.5V, 1.2V, and 0.9V respectively.

The gain-frequency response of the differentiator based biquad for the alternate circuit at Fig. 4 is depicted in Fig. 8.

In case of all-pass filter output at Fig. 8 d) the dB variation (of 5 dB) in gain-frequency response is almost negligible.
Fig.9 shows the Transient Response of the circuit at Fig, 4 for an input AC signal of 20nA at 1KHz. and has been included to show the signal integrity/linearity. Here too the HP output is attenuated maximum.

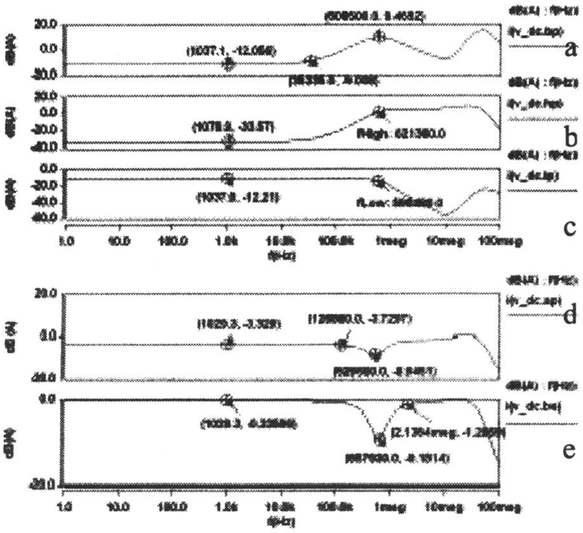

Figure 8:
Gain-Frequency Response (Magnitude) of: a) Band-Pass b) High-Pass c) Low-Pass d) All Pass and e) Band-Elimination filter respectively.

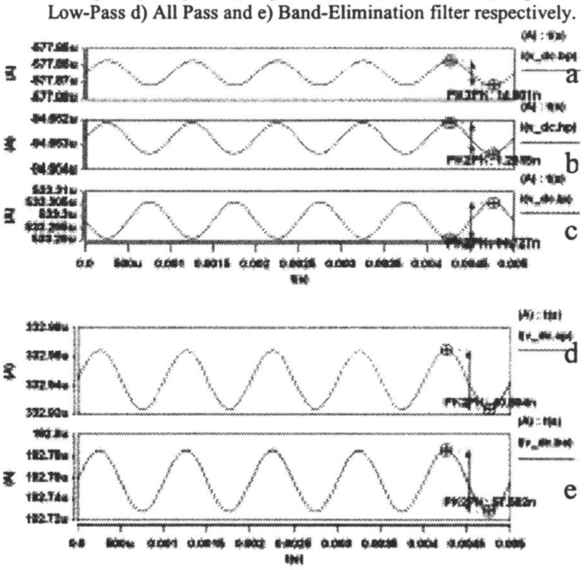

Figure 9
Transient Response of: a) Band-Pass b) High-Pass c) Low-Pass d) All -Pass and e) Band-Elimination filter respectively.

In order to compare the proposed architecture of the differentiator based log-domain filter with the integrator-based filter reported at [9], the Band-Pass outputs of both the configuration were compared to ascertain the power consumption. We used the Saber default BJT model parameters for both the circuits. Further the circuit proposed at [9] was operated at 1.5V instead of 5V. The results are summarized in Table II.

Table II
Comparison between Integrator and Differentiator based Biquad Filters

	Integrator-Based filter	Differentiator-Based filter
Mid-freq.	205.3KHz	204.4KHz
Band Width	135KHz	150Khz
Q-Factor	1.52	1.36
Power	325mW	12.24mW
Capacitances	C_A=6nF, C_B=8uF	C_A=1nF,C_B =12nF
BJT-count	32	26

IV. Conclusion

A new approach for the design of a continuous-time universal biquad filter based on log-domain differentiators has been proposed. In published literature, only integrator-based designs of biquads are discussed. However, the proposed architecture based on differentiators and implemented using BJTs has been shown to be stable and works at 1.5V supply consuming less power than that in the integrator based filter [9] as it uses lesser number of transistors. The design can be improved further by using loss less Differentiators, which is likely to improve the frequency response of the filter at higher frequencies.

V. References

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