Mixed-integrator biquad for continuous-time filters

Y. Chen, P.-I. Mak and Y. Zhou

A mixed-integrator biquad (MIB) combining the advantageous features of a g_m-C integrator and a source-follower-based (SFB) integrator is proposed. Unlike the conventional pure SFB biquad suffering from significant passband gain loss, the MIB employs a linearised g_m-C integrator at the front, overcoming the gain loss, and an SFB integrator at the back, guaranteeing good linearity and low-output impedance. The complex poles are synthesised through a negative feedback technique avoiding the need of a common-mode feedback circuit. An experimental fourth-order MIB-based Butterworth lowpass filter fabricated in 0.18 μm CMOS shows improved figure-of-merit with respect to the state-of-the-art, while occupying a small die area.

Introduction: Active filters without the need for operational amplifiers presents an attractive direction for minimising the power and area of wide types of integrated systems such as wireless transceivers. In this context, a discrete-time filter can be (partly) realised by comparator-based circuits [1], whereas a continuous-time filter using source-follower-based (SFB) biquads has demonstrated a high dynamic range (DR) with ultra-low power and compact area [2]. The key drawback of an SFB biquad is its passband loss, which becomes very severe when the filter order is increased. In this Letter, a mixed-integrator biquad (MIB) is proposed for continuous-time filters. Different from the typical SFB biquad [2] that uses a positive feedback between the differential branches to synthesise the complex poles, a negative feedback is employed between a linearised transconductance (g_m)-C integrator and an SFB integrator. In this way, a sufficient passband gain can be guaranteed while maintaining good linearity and low output impedance. The overall feasibility of the proposed MIB-based filter will be demonstrated through the implementation of a fourth-order Butterworth filter in a 0.18 μm CMOS technology.

Proposed MIB: Fig. 1 shows the proposed MIB. The front-stage is a linearised g_m-C integrator. The *primary* differential pair (M1-M3) is linearised by introducing a *secondary* cross-connected differential pair (M4-M6) that features a smaller g_m than that of the primary. In this way, the distortion induced by (M2-M3) can be reduced by (M5-M6) at the expense of a small reduction of passband gain, which can still be easily greater than unity. This technique is better in comparing with the source degeneration as no voltage headroom is consumed. The optimised total transconductance $g_{m,total}$ is 70% of $g_{m,M2}$.

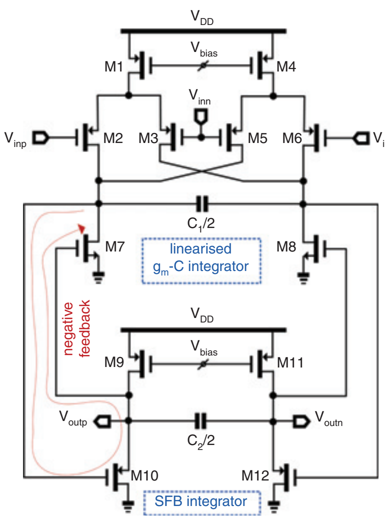

Fig. 1 *Proposed MIB*

The back stage is a first-order SFB integrator (M9-M12). A negative feedback applied between the front and back stages not only synthesises the complex poles, but also stabilises the output common-mode voltage of the linearised g_m-C integrator. The overall transfer function *H(s)* of the MIB can be derived using a half-circuit small-signal equivalent circuit as given by,

$$H(s) = \frac{(g_{m,total\text{-}half}\, g_{m,M10}/C_1C_2)}{s^2 + s(g_{m,M10}/C_2) + (g_{m,M7}\, g_{m,M10}/C_1C_2)} \qquad (1)$$

where g_{m_Mx} is the transconductance of the corresponding transistors and $g_{m,total\text{-}half} = 0.5g_{m,total}$. The filter parameters of the MIB can be obtained:

$$\omega_o = 2\pi f_o = \sqrt{\frac{g_{m,M7}g_{m,M10}}{C_1\ C_2}} \qquad Q = \sqrt{\frac{C_2}{C_1}\frac{g_{m,M7}}{g_{m,M10}}} \qquad K = \frac{g_{m,total\text{-}half}}{g_{m,M7}} \qquad (2)$$

where f_0 is the pole frequency, Q is the quality factor and K is the DC gain. Expressed as ratios of components, Q and K are highly insensitive to process and temperature variations.

The key advantages of the proposed MIB can be summarised as follows.

1. High gain: From (2), K can be sized to be much greater than unity to compensate the gain loss induced by the back-stage SFB integrator, lowering the input-referred noise of the MIB.
2. Accurate transfer function: At the first-order no parasitic pole is presented. It renders the MIB-based filter suitable for wideband high frequency filtering. For example, the −3 dB cutoff frequency can be sized beyond 1 GHz when small capacitors are applied.
3. No common-mode feedback circuit: Although the g_m-C integrator features high output impedance, the output common-mode voltage is stabilised through the negative feedback mechanism between the linearised g_m-C integrator and the SFB integrator (see Fig. 1).
4. High drive capability and extendibility: The MIB maintains high input impedance and low output impedance as the conventional SFB biquad. Thus, it is able to drive a wide range of load with no buffer, and the filter-order can be easily extended by cascading.

Experimental results and performance comparison: A 10 MHz fourth-order Butterworth lowpass filter implemented by putting two MIBs in direct cascade has been fabricated in a 0.18 μm CMOS technology. The main parameters are summarised in Table 1 and the chip micrograph is shown in Fig. 2. The active area is 280 × 170 μm^2, which was optimised by minimising the sizes of the transistor and capacitors as shown in Table 1. The total capacitance involved is <12 pF.

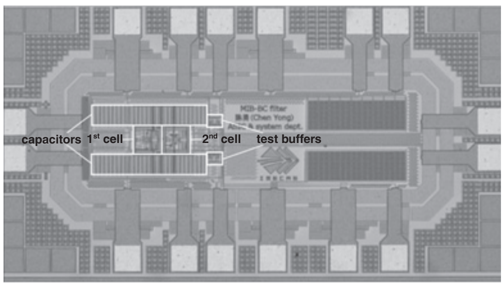

Fig. 2 *Chip micrograph of MIB-based filter*

Table 1: Summary of key filter parameters

	1st MIB	2nd MIB
$g_{m\ M2,6}$ (μA/V)	336	339
$g_{m\ M3,5}$ (μA/V)	101	102
$g_{m\ M7,8}$ (μA/V)	136	200
$g_{m\ M10,12}$ (μA/V)	223	224
C_1 (pF)	3.54	2.15
C_2 (pF)	1.71	4.12

Fig. 3 shows measured and simulated frequency responses. The −3 dB cutoff frequency is close to 10 MHz and the mid-band gain is +7 dB. The passband ripple is less than 0.5 dB. A two-tone test at 3 and 4 MHz shows a third-order inter-modulation distortion (IM3) of −46 dB under a input power of −16 dBm, which translates to an in-band IIP3 of +7 dBm. To calculate the DR, the linearity has been evaluated also in terms of third-harmonic distortion (HD3), which is -40 dB for a 0.15-V_{pp} input signal amplitude. The integrated input-referred spectral density noise is equal to 26 μV_{rms}. This translates to a 72 dB DR, for a HD3 of -40 dB. The total power consumption is 450 μW at 1.5 V.

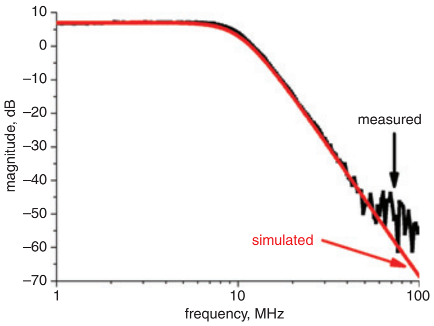

Fig. 3 *Simulated and measured frequency responses*

This work can be compared with the reported continuous-time filters by evaluating the figure-of-merit (FOM) defined as [2],

$$FOM = \frac{P_{\omega}}{8\,kT\,f_{-3\,\mathrm{dB}}\;N\;DR} \tag{3}$$

where P_{ω} is the total power consumption, $f_{-3\ \mathrm{dB}}$ is the cutoff frequency, N is the number of poles, and DR is the dynamic range. The performance comparison with recent works [2–4] is given in Table 2. It shows that most performance metrics of the proposed MIB-based filter are either competitive or superior in particular the power, area and overall FOM.

Table 2: Performance summary and comparison

Reference	[2]	[3]	[4]	This work
Process	0.18 μm CMOS	0.13 μm CMOS	0.13 μm CMOS	0.18 μm CMOS
Supply (V)	1.8	1.2	1.2	1.5
Power (mW)	4.1	14.2	5.6	0.45
Area (mm^2)	0.26	0.9	0.8	0.05
Order	4	4	4	4
Filter type	Bessel	Bessel	Bessel	Butterworth
DC-gain (dB)	-3.5	4	8	7
BW (MHz)	10	11	11	10
V_{in_noise} (μV_{rms})	24	36	118	26
In-band IIP3 (dBm)	+17.5	+21	+21.3	+7
DR (HD3 = -40 dB)	79	81	55	72
FOM	0.39×10^2	0.77×10^2	121×10^2	0.22×10^2

Conclusion: A novel MIB suitable for synthesising high-order continuous-time filters is proposed. A linearised g_m-C integrator followed by an SFB biquad balances the advantages of them in the front stage (i.e. high gain and high input impedance) and the back stage (good linearity and low output impedance), respectively. The feasibility has been validated by a 10 MHz fourth-order Butterworth lowpass filter showing good overall performance (FOM = 0.22×10^2) with low power (450 μW) and small die area ($280 \times 170\ \mu m^2$).

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One or more of the Figures in this Letter are available in colour online.

Y. Chen and Y. Zhou (*Institute of Microelectronics of Chinese Academy of Sciences, Beijing, People's Republic of China*)

P.-I. Mak (*Faculty of Science and Technology, University of Macau, Macao, People's Republic of China*)

E-mail: pimak@umac.mo

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