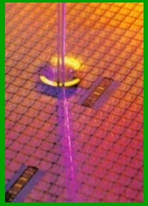


A 8.25-MHz 7th-order Bessel filter built with MOSFET–C single-amplifier biquads

Abstract of the paper — The 7th-order Bessel filter presented in this paper has an edge frequency that is continuously tunable from 4.5 MHz up to 10 MHz. It was fabricated with the 0.6-micron CMOS process by AMS, covers a chip area of0.24 mm^2, and consumes 49 mW from a 3.3-V supply. The SNR at −40 dB of harmonic distortion is between 48 dB and 50 dB over the whole tuning range. The comparatively low power consumption and chip area could be achieved by using single-amplifier biquadratic building blocks implemented as MOSFET–C filters and generating the control voltage of the MOSFET resistors with an on-chip charge pump. This paper briefly discusses design issues of such filters, sources of harmonic distortion, clock feed-through, and noise. Finally, it is shown that the filter can also be implemented using MOSFET capacitors instead of poly-poly capacitors with only 4 dB loss of SNR.

Hanspeter Schmid and George S. Moschytz, Signal and Information Processing Laboratory, ETH Zürich, Switzerland. E-Mail: h.p.schmid@ieee.org

Introduction

Why single-amplifier biquadratic filters (SABs)?

They need only one amplifier per complex pole pair. Compared to integrator-connected topologies (*at least* one amplifier *per pole*), they use less chip area, but their pole quality factor is also more sensitive to variations of the passive component values and the amplifier gain.

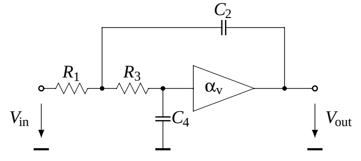
What is the purpose of this paper?

This paper gives an overview over the main design aspects of MOSFET-C SABs. It is essentially a short version of the author's dissertation.

Are these filters interesting for the industry?

Maybe not at the moment, the reason being that MOSFET resistors are MOSFETs that operate in a very special region: with a zero current in the operating point, and a quite high bulk-channel voltage. In order to simulate that properly, one needs bulk-referenced models and parameters extracted having this mode of operation in mind; neither is provided in standard design kits.

Single-amplifier biquadratic filters



Ideal transfer function

$$T(s) = \frac{\alpha_V\,\omega_p^2}{s^2 + \frac{\omega_p}{q_p}s + \omega_p^2}\,,$$

$$\text{with}\quad \omega_p = \frac{1}{RC}\,,\quad \frac{1}{q_p} = mn + \frac{m}{n} + \frac{1-\alpha_V}{mn}\,,$$

Properties of a Sallen-and-Key filter

Several important properties of this kind of single-amplifier biquads already follow from a theoretical discussion (see paper for references).

- The pole frequency and the pole Q are independently tunable.
- The maximum operating frequency of such a filter depends on the amplifier's non-idealities and is

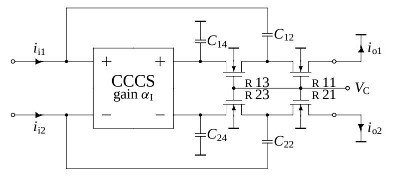
$$\omega_{p\,max} \approx \frac{1}{\max(m,1/m)\,C_{out}\cdot\max(n,1/n)\,R_{in}\cdot A_{stop}}\,,$$

- If the variance of the pole Q is minimised, the filter will *always* need an amplifier having a gain below two.

There are two possibilities of building a low-gain amplifier: either take a high-gain amplifier and apply local feedback, or build a low-gain amplifier without local feedback. The latter is faster, but generates a higher pole Q variance.

Second-order MOSFET–C filter

Schematic of a current-mode MOSFET–C SAB



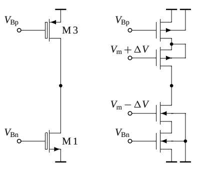
In a MOSFET–C SAB, all resistors are replaced by transistors operating in the triode region. The whole filter is built in balanced form, so that even-order harmonic distortion is reduced.

Tunability

Adjusting the voltage V_C changes the resistance of the MOSFET resistors and thus tunes the pole frequency. If this voltage is generated by a charge pump, as it is done in our example, then one can compute …

The optimum output signal swing for maximum SNR at a given level of distortion

The following schematic shows the output of our current amplifier.



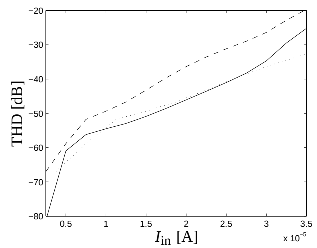
If ΔV is increased, the maximum signal swing at a given level of distortion also increases, but at the same time the transistor cascodes have less voltage margin, must become wider, and therefore also become noisier.

The optimum ΔV only depends on the threshold voltages of the CMOS process used to build the filter. It is

$$\Delta V = \frac{2}{7}V_{dd} - V_{T0}\,.$$

Second-order MOSFET-only filter

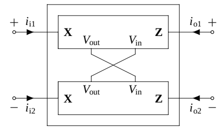
The same filters can be built on single-poly processes, with a 4 dB loss in the SNR. The following figure shows the simulated THD of a conventional MOSFET–C SAB (solid), of a MOSFET-only SAB (dashed), and the latter with I_{in} scaled by 1.5 (dotted).



Video-frequency current amplifier

Block diagram

In order to reduce the even-order harmonic distortion as far as possible, the amplifier should be perfectly symmetrical.

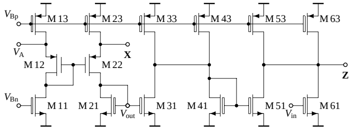


This amplifier is ideally described by

$$i_{o1} = \alpha_I\,(i_{i1} - i_{i2}) \qquad i_{o2} = -\alpha_I\,(i_{i1} - i_{i2})\,.$$

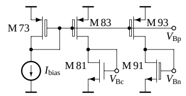
It consists of two instances of the same …

Half circuit



… and one …

Bias circuit



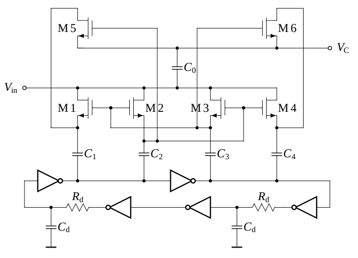
Transistor dimensions

	main transistors	cascode transistors
M [1–6]1	45 × 1.8 µm	95 × 0.6 µm
M 81	14 × 0.6 µm	—
M 91	45 × 1.8 µm	95 × 0.6 µm
M [1–2]2	120 × 0.6 µm × 2	—
M 13	87 × 1.8 µm	140 × 0.6 µm
M [2–8]3	70 × 1.8 µm	140 × 0.6 µm
M 93	87 × 1.8 µm	140 × 0.6 µm

Properties of the amplifier

- Supply: 160 µA per branch at 3.3 V.
- X input resistance: $R_{in} \approx 1/g_{m22} \approx 500\,\Omega$
- nCurrent gain: $\alpha_I \approx -2$

Self-oscillating charge pump



Charge pump components	
All *n*MOSTs	10 × 0.6 µm
All *p*MOSTs	33 × 0.6 µm
R_d	4.8 kΩ
C_d, C_2, C_3	0.5 pF
C_1, C_4	1 pF
C_0	20.5 pF

Properties of the charge pump

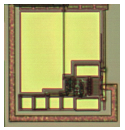
- Operation: 1.3 V … 3.3 V
- Output: 1.5 V … 5.0 V
- Oscillation Frequency: 62 … 71 MHz
- Power consumption: ≈ 5 mW

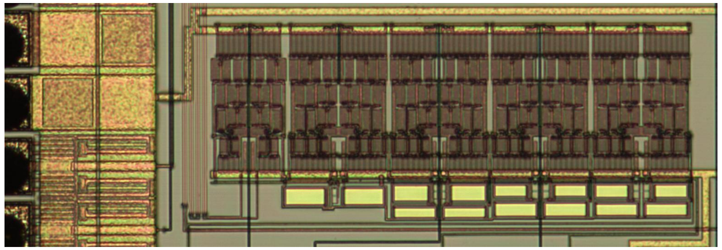
Chip photos

The two chip photos have the same scale.

Right: Charge pump.

Below: 7th-order filter cascade.





7th-order Bessel filter

Filter Sections

Biquadratic filter sections			
(f_p, q_p)		element dimensions	capacitance
(1.687, –)	C [1–2]4	68.9 × 28 µm	1.68 pF
	R [1–2]3	12 × 8 µm	
(2.053, 1.13)	C [1–2]2	60 × 26.75 µm	1.40 pF
	C [1–2]4	72.2 × 16.6 µm	1.05 pF
	R [1–2][1,3]	12 × 6 µm	
(1.719, 0.53)	C [1–2]2	55.5 × 19.1 µm	0.93 pF
	C [1–2]4	72.2 × 22.2 µm	1.40 pF
	R [1–2][1,3]	12 × 10.5 µm	
(1.825, 0.66)	C [1–2]2	56.5 × 21.25 µm	1.05 pF
	C [1–2]4	72.2 × 19.5 µm	1.23 pF
	R [1–2][1,3]	12 × 9.5 µm	

Process Parameters

Process parameters			
	*n*MOS	*p*MOS	
V_{T0}	0.85	−0.85	[V]
$\mu \cdot C_{ox}$	120	40	[µA/V^2]
γ	0.8	0.5	[$\sqrt{V}$]
ϕ_0	0.94	0.91	[V]

Measurement Results

Measured performance	
Charge pump supply	2.7 … 3.3 V
V_C	4.4 … 5.0 V
Edge frequency	4.5 … 10 MHz
SNR for 1 % THD	48 … 50 dB
Supply voltage	3.3 V
Power consumption	53 mW
Chip area	0.28 mm^2

Main advantage

Compared to other filters with similar electrical properties, filters basing on MOSFET–C biquads only use 15 % to 30 % of the chip area.

The author's future

From December 1 on, Hanspeter Schmid will work as an analogue-IC designer for Bernafon AG, Bern, Switzerland, a company that produces a wide range of hearing aids. He will also continue giving his lecture "Analogue Signal Processing and Filtering" at the Swiss Federal Institute of Technology (ETH Zürich).