On the design of micro power practical G_mC filters for biomedical applications

Jose Lasa
DIE - Universidad Católica del Uruguay
Av. 8 de Octubre 2801
Montevideo, Uruguay.
+598 24872717 *407
jlasa@ieee.org

Alfredo Arnaud
DIE - Universidad Católica del Uruguay
Av. 8 de Octubre 2801
Montevideo, Uruguay.
+598 24872717 *407
aarnaud@ucu.edu.uy

Matias Miguez
DIE - Universidad Católica del Uruguay
Av. 8 de Octubre 2801
Montevideo, Uruguay.
+598 24872717 *407
meyias@ieee.org

Joel Gak
DIE - Universidad Católica del Uruguay
Av. 8 de Octubre 2801
Montevideo, Uruguay.
+598 24872717 *407
jgak@ucu.edu.uy

ABSTRACT
Transconductor-capacitor or simply G_mC filters and amplifiers are an attractive option for the design of biomedical circuits because of their extremely low power consumption. G_mC filters for the analog processing of sensed outputs and biomedical signals, can be realized consuming as little as a few tens or hundreds nA current (a negligible power budget for a primary battery). Minimum or no external components are required, but there is always uncertainty in the transfer function of the filter. This paper shows the development of fully integrated G_mC filters for medical applications, emphasizing on the variability of their response with technology parameters that may change from an integrated circuit to another or from a fabrication batch to another. G_mC filters, amplifiers and rectifiers will be presented. Two examples are discussed: a G_mC band pass amplifier for a piezoelectric accelerometer to estimate physical activity and a robust G_mC cardiac sensing channel.

Categories and Subject Descriptors
B.7.1 [**Integrated Circuits**]: Types and design style – *Input/output circuits, VLSI.*

General Terms
Design.

Keywords
CMOS, low power, low noise, implantable medical devices, G_mC.

1. INTRODUCTION
Low power consumption is crucial in the case of active implants where batteries must last for years to extend the device's lifetime. The realization of complex but reliable circuits restricted to a few nano-Amperes of current consumption using a reduced number of external components is a major quest for manufacturers that normally incorporate custom integrated circuits for the task. Modern medical devices are complex electronic circuits that perform several sensing, control and stimulation functions. Although efficient and powerful microcontrollers are regularly employed to control the devices, there is still room for analog signal processing due to power consumption constrains, even at low frequencies. A low power microcontroller may consume from a few to several μAmperes to turn on its AD converter and implement a digital filter. In the analog domain for biological signal processing, switched capacitors (see for example [1][2]) has been for a long time the preferred technique because of its accurate transfer function based in the ratio between capacitors and a clock reference. But the use of multiple operational amplifiers and the charge/discharge of capacitors on each cycle is a limitation to ultra low power consumption. To reduce the power consumption of a filter to a few hundred of nA, a different technique must be employed. Regular R-C active filters are of limited use because of the maximum practical R, C values that can be integrated. To overcome this problem, continuous-time transconductor-capacitor G_mC filters [3] are an attractive option and several circuits have been developed using efficient nano power OTAs including examples for hearing aids, pacemakers, among others [4] [5] [6] [7]; even OTAs equivalent to tens GΩ are possible [8]. However, a major problem with G_mC filters/amplifiers is the degree of uncertainty in the transfer function. In effect, because of the fluctuation of transistor and capacitor parameters or in the bias current of the OTAs, not only from one chip to another but specially from an IC fabrication batch to another, the gain and the frequency of the poles may vary in a wide range. But while telecommunications filters for example shall be precise, those for biomedical applications can show variations due to the self variability of biomedical signal that have a very different behavior, depending the patient. Medical devices are normally adjusted one by one to each patient at the device level which helps to adopt G_mC filters as a first option. Semiconductors foundries can provide trimming services for ICs, but it is not a practical solution because of the low production volume of medical ASICs. Another possible solution is the automatic tuning of the filter based, for example, in a known time reference. While this is a well known technique, accurate trimming increases significantly the overall power consumption, circuit area and circuit complexity. This work shows the development of fully integrated G_mC filters for medical applications, particularly investigating the variability of their response with technology parameters. G_mC filters, amplifiers and rectifiers will be presented. Two examples are discussed: a G_mC band pass amplifier for a piezoelectric accelerometer to estimate physical activity, and a robust G_mC for a cardiac sensing channel.

SBCCI'11, September, 2011, Joao Pessoa, Brazil.

2. A 0.5Hz-15Hz G_mC FILTER AND RECTIFIER FOR PHYSICAL ACTIVITY ESTIMATION.

The first G_mC circuit to be presented in this work is the signal conditioning of a piezoelectric accelerometer to estimate physical activity. Piezoelectric sensors are preferred because they fulfill size and power consumption requirements for implantable devices. A miniature single axis accelerometer was selected; the charge sensitivity and capacitance of the sensor are 1.5pC/g, and 550pF respectively [9], which is equivalent to 3.5mV/g sensitivity in the connection scheme of Fig1.

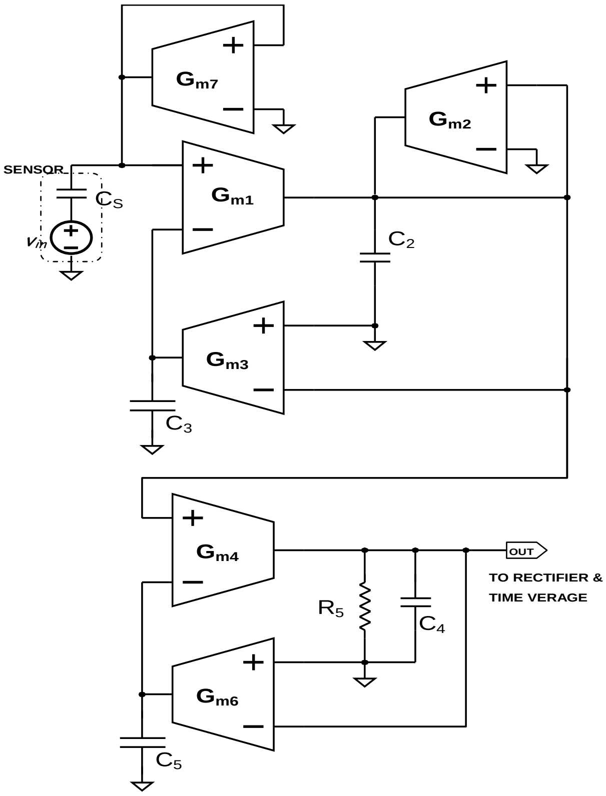

Figure 1: A schematic of the fabricated G_mC filter for a piezoelectric accelerometer.

The circuit topology and design procedure closely follows the one presented in [7], but the current circuit was fabricated in a 0.6µm technology. The circuit was developed to:

- Study the variability of the transfer function of the G_mC.
- Validate a rectifier topology.
- Extend the bandwidth in comparison to [7] for better physical activity estimation according to different experiments carried with a discrete version of the circuit.

The circuit shall implement a 50dB gain, 40dB/dec roll-off band pass filter-amplifier in the 0.5 to 15Hz band followed by a fully integrated voltage to current rectifier, and a 0.2Hz time average. The circuit must operate in the range of 2 to 4.2V either to be powered by a lithium-iodine primary battery or a lithium rechargeable battery [10], with power consumption below 500nA. Input referred noise shall be preserved below 25µV_{rms} to detect a minimum relevant physical activity.

2.1 Circuit Description

The selected band pass filter topology is shown in Fig.1 and Table I. Two cascaded single-ended stages are connected with a total gain of G=320 and 40dB/dec roll-off. The preamplifier stage is formed by G_{m1}, G_{m2}, G_{m3}, G_{m7}, C_3 (external), C_2, and the second gain stage formed by G_{m4}, R_5, G_{m6}, C_5 (external) and C_4. Each stage is composed of a low pass gain structure similar to the proposed in [5] for a capacitive microphone, and a DC cancellation loop. G_{m7} is an extremely small transconductance OTA, equivalent to a 3GΩ resistor to DC bias the sensor input.

Table I. 0.5-15Hz band-pass filter OTA's, R's and C's description

	Value	Comments
G_{m1}	100nS	Standard Symmetrical OTA
G_{m2}	15nS	Standard Symmetrical OTA, input pair in moderate inversion for wider linear range
G_{m3}	4nS	Standard Symmetrical OTA, input pair in moderate inversion for wider linear range
G_{m4}	500nS	Standard Symmetrical OTA, input pair in moderate inversion for wider linear range
G_{m6}	150nS	Resistor-linearized OTA, ±0.5V linear range
G_{m7}	0.3nS	Symmetrical OTA w/1nA bias current
C_1, C_3	470nF	External Capacitor
C_2	15pF	Poly1-Poly2 capacitor
C_4	400pF	450µm x 450µm Poly1-Poly2 capacitor.
R_5	20MΩ	High resistivity poly resistor

The capacitors, and OTAs G_{m1} to G_{m6}, where designed with the following criteria:

- Noise is critical, mostly determined by the input OTA G_{m1}, thus G_{m1} is a standard symmetrical OTA designed to minimize noise, according to the area and the current consumption budget. G_{m1} input pair is biased in weak inversion with only 12.5nA current.
- OTAs G_{m2} to G_{m4} are also standard symmetrical OTAs designed using the methodology proposed in [8] according their required transconductance and linear range. G_{m2}, G_{m3} share the same differential input pair that is biased with only 12.5nA current in moderate to strong inversion. Different current dividers/multipliers are used at the output of each OTA to achieve the desired 4nS, 15nS and 500nS transconductance.
- R_5 is a high resistivity poly resistor, G_{m6} has a minimum offset oriented design and C_3= 470nF is an external capacitor. G_{m6} is a resistor linearized OTA similar to the one used in Fig.2 but with a single output.
- C_5 is an external capacitor to preserve a reduced area. The rest of the capacitors are standard double poly ones.
- A unity gain buffer was included at the filter's output for test purposes.

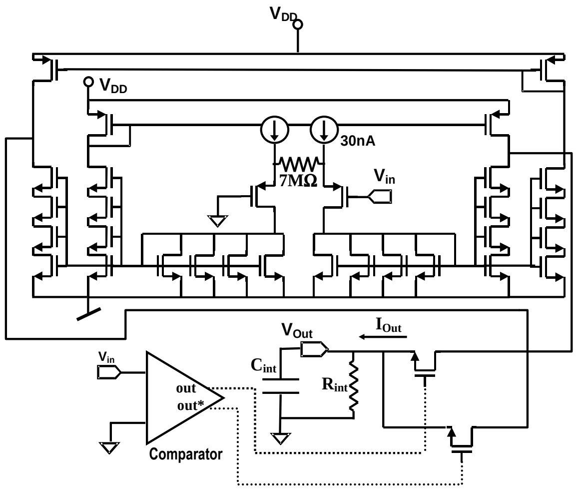

Figure 2: A schematic of the fabricated G_mC rectifier following the band pass filter.

An integrated rectifier and a time average circuit using a single capacitor was designed, using the same circuit blocks of the band pass amplifier. The circuit is shown in Fig.2. It is composed of a modified transconductor, which incorporates a second output branch toggling the connections of the mirrors. A comparator and two MOS switches select which of the outputs will be the active output of the transconductor with an effective value $I_{out} = |G_{m6} \cdot V_{in}|$. This rectifying OTA will be referred to as G_{mR} and is connected to an integrating resistor – capacitor network. R_{int} is a 10MW resistor and C_{int} is an external 470nF capacitor. The total power consumption of the rectifier is 120nA and the estimated input offset, which is closely related to the overall circuit precision [7], is only 1mV.

2.2 Measurement results, variability analysis and discussion.

The previously described band pass filter-amplifier was fabricated (in a 0.6µm CMOS technology) and tested. In Fig.3 a microphotograph of the circuit occupying only 0.8mm^2 is shown. Fig.4 shows the expected and measured transfer function of the filter. The center frequency was measured at 3Hz and the gain at G=50db, while the 3dB decays were measured at .45Hz and 13Hz.

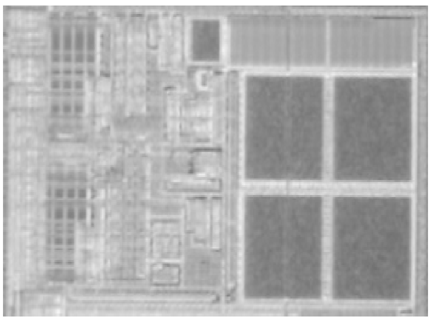

Figure 3: G_mC filter and rectifier microphotography.

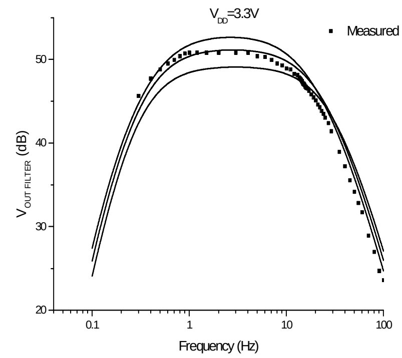

Figure 4: G_mC filter simulated (lines, using typical and corner transistor models) and measured (dot) transfer function.

Five circuit samples were measured showing a very similar transfer function. The measured input referred noise was 20µV_{rms} and the measured total current consumption was 530nA. The circuit properly operated in a wide range from 1.7 to 5.5V. Fig.5 shows the total transient output of the circuit (band pass + rectifier + time average) of 5 circuit samples to a 1mV, 5Hz sine wave that is suddenly applied to the input. Note in the picture that all the samples show a similar response, the difference can be associated to an offset in the DC bias voltage of each measurement.

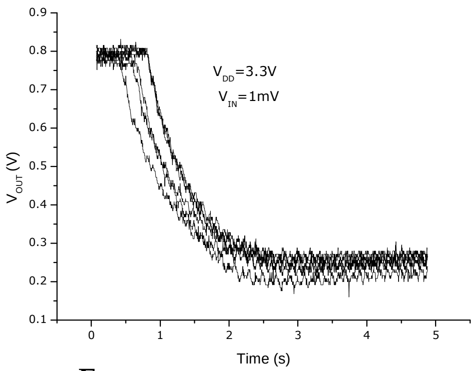

Figure 5: Transient circuit output (bandpass + rectifier + time average) of 5 circuit samples

A summary of the band pass filter-amplifier characteristics is shown in Table II.

Table II. G_mC band pass filter measured characteristics

Parameter	Value
V_{DD}	1.6V-5.5V
Power Consumption	530nA
Gain	50dB
Bandwidth	0.45Hz-13Hz

Fig.4 shows a high degree of agreement between the measured and the expected transfer function for the filter. Moreover, it should be pointed that the circuit in this work was biased with currents derived from a 50nA-nominal integrated current source, designed following the topology and guidelines in [11]. But the results are limited to chips from two MPW runs, and it is necessary to estimate how much the spread in the technology parameters affect the transfer function of the system. From the datasheet of the target CMOS process and simulations using corners, capacitors are expected to spread ±10% around their typical value, and OTAs transconductance and self bias current a larger ±20%. Fluctuations affect the center frequency, gain, and Q of the filters; in the plot of Fig.4 different transfer functions using typical and corner transistor models are shown. Examining the gain, a 6dB (equivalent to roughly ±50% amplitude) variation may be associated to inaccurate physical activity estimation if the filter is not trimmed. But the human body itself also shows wide fluctuations when measuring different parameters from one individual to another. In rate responsive pacemakers, physicians calibrate the pacing rate algorithm according to the physical activity (making the patient rest, walk or run). Even the sensors are specified with a large uncertain in sensitivity [9]. This adjustment is a kind of trimming at the device level once in use. For a first order trimming at circuit level, to avoid saturation and to put the system output in the range of the following AD converter, the circuit includes a two bit current reference adjustment. By varying the 50nA reference current from 35nA to 65nA, the filter's gain is close to 50dB for all the corners. A fine tuning adjustment can be performed later at digital level.

3. A 70Hz-200Hz G_mC FILTER FOR A CARDIAC SENSING CHANNEL

While biological signals to be registered in medical devices show a high variability, sometimes the filter accuracy is limited because of regulations. For example according to EN45502 standard [12], the cardiac activity sensitivity shall be measured with ±5% absolute voltage error. This kind of constrain may result in a major limitation for untrimmed G_mC filters. The second G_mC circuit presented in this work is a cardiac sensing channel [1][2][13-ch.8]. A cardiac sensing channel consists in a band pass amplifier, a programmable level detector using a low offset comparator and a DAC to trigger cardiac activity detection. The preamplifier can be shared for example in the case of intracavital electrocardiogram (ECG) recording. A scheme of the complete signal chain is shown in Fig.6; a rectifier is used to compare both signal peaks (positive, negative). The focus in this work will be in the filter but simulations include an ideal preamplifier at the input.

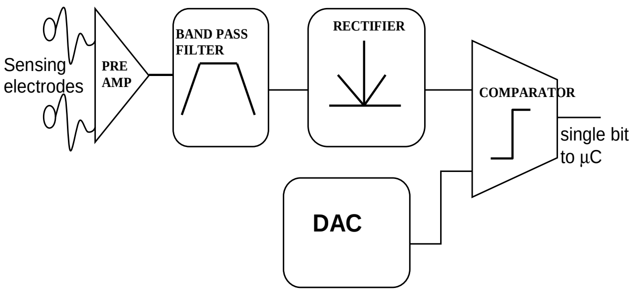

Figure 6: A scheme of the cardiac sense channel.

In [1][2] a discrete time switched capacitors (SC) filter is proposed for the task while in [13][14] a continuous time filtering is proposed requiring precise external components. But G_mC filters may result in a minimum power and a fully integrated solution. Regarding the accuracy of the filter, cardiac sensing level is adjusted by the physician in a pacemaker therapy, but the standards may require certain accuracy in the response of the circuit. Because it is desirable to avoid individual trimming of the devices the G_mC filter shall be precise. The standard in [12] uses the so called CENELEC (or Tokyo) waveform shown in Fig.7 as the normalized test.

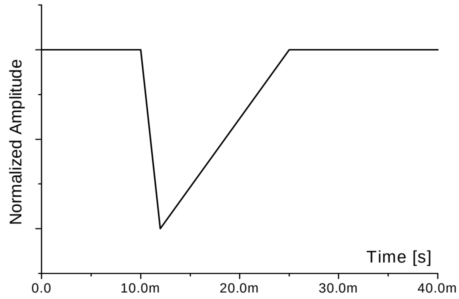

Figure 7: The usual 2ms-13ms test signal.

Note from its Fourier transform in Fig.8 and the sweep in Fig.9, that the high frequency pole does not necessarily have to be accurate (a 10% variation in it, results in much less than ±5% variation of the signal amplitude at the output) and the position of the low frequency pole has a limited yet still significant impact (around 8% for a maximum expected 15% variation of the integrated time constant). From our previous experience it is possible to conclude that the effort in the design shall be in the adjustment of an accurate gain within 5%, and secondly in the accurate determination of the low-frequency pole .

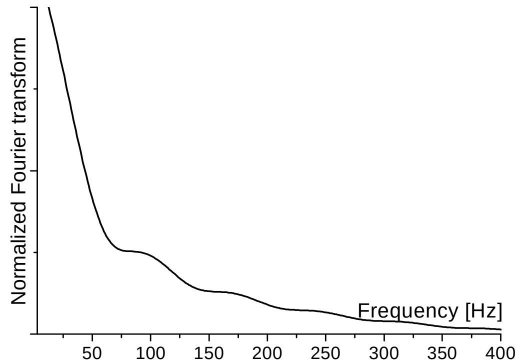

Figure 8: The Fourier transform of the CENELEC test signal.

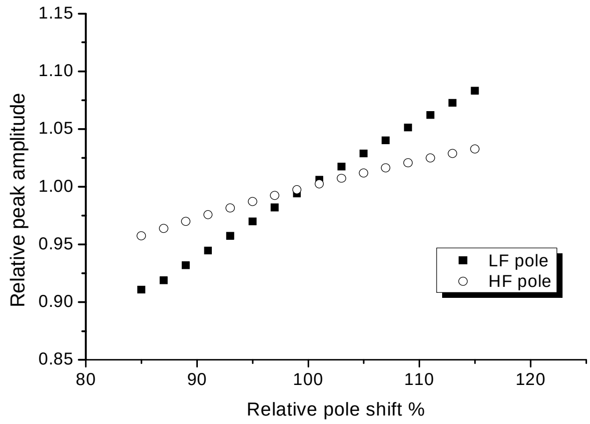

Figure 9: Estimated channel inaccuracy: a unitary gain test signal Fourier transform of Fig.8 is filtered varying the LF and HF poles.

3.1 Circuit Description

The topology of the proposed G_mC is shown in Fig. 10 and Table III. A 0.6µmHV (high voltage) technology was employed in the design, and two different low and high supply voltages V_{DD} and HV_V_{DD} were used to allow the G_mC to be connected to a high voltage input signal (for example to sense at voltages above the battery [15]). Only half the input transconductor G_{m1} (see Fig.11) is connected to a high voltage supply. The complete circuit of Fig.10 is a differential input, common mode output, single stage formed by G_{m1}, G_{m2}, G_{m3}, C_1, and C_2 similar to the previously presented G_mC for the accelerometer. The stage has a total gain of G=45dB (including the preamplifier). The circuit is fully integrated. G_{m1}, is a double input 1µS OTA, the circuit is shown in Fig.11, separated in two parts: the HV input part is a HV-NMOS differential pair implemented using NISO transistors (a special HV-NMOS isolated one) biased in Weak Inversion (WI) with a 80nA current; the LV input part is a standard PMOS differential pair also biased in WI with a 80nA current. Three types of transistors were used: NMOS and PMOS are regular nmos and pmos low-voltage ones; HV-PMOS (the M2 transistors in Fig.11) uses thick gate oxide and a diffused drain to withstand V_{GS} and V_{DS} voltages up to 18V and 40V respectively; NISO that is a completely isolated HV-NMOS transistor that can withstand VGS voltages up to 18V and VDS voltages up to 50V.

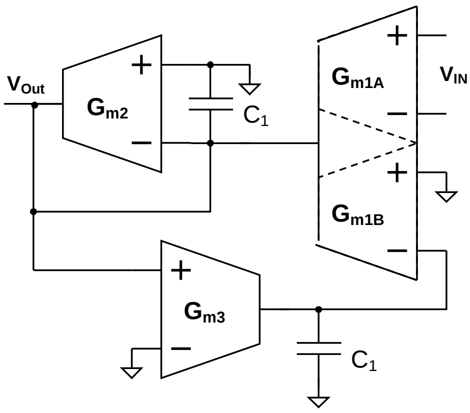

Figure 10: A schematic of the designed GmC filter for the cardiac sensing channel.

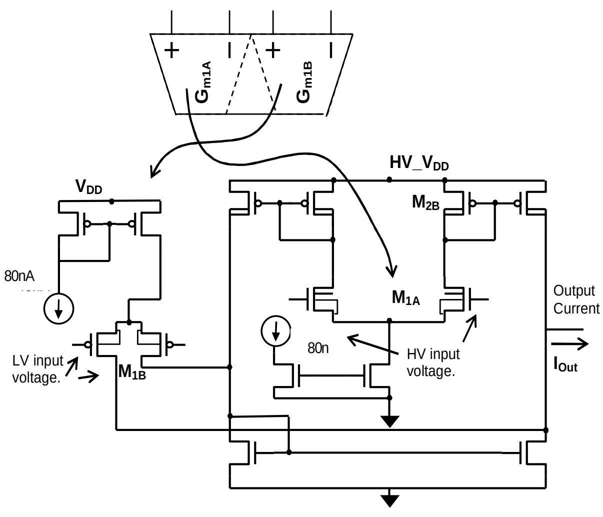

Figure 11: A schematic of the designed G_{m1}.

The remaining capacitors and OTAs where designed with the following criteria:

- G_{m2} and G_{m3} are resistor-linearized OTAs similar to the one used in the rectifier of Fig.2 but with a single output. The input pair is biased in moderate inversion (MI), while the resistor is also a 7MΩ one. The simulated linear range is ±500mV.
- C_1 and C_2 are standard double poly capacitors.
- An ultra low power unity gain buffer is included at the output to drive the rectifier and comparator. These stages are not discussed for the sake of simplicity.

The circuit was designed for VDD in the range of 2 to 4.2V and a HV_V_{DD} of up to 15V can be used

Table III. 70-200Hz band pas filter OTA's, C's description

	Value	Comments
G_{m1}	1µS	Dual input. HV input capacity on one side.
G_{m2}	80nS	Resistor-linearized OTA. ±500mV range
G_m3	1.6nS	Resistor-linearized OTA. ±500mV range
C_1	105pF	Poly-Poly Capacitor
C_2	45pF	Poly-Poly Capacitor

3.2 Simulation Results

In Fig.12, the simulated AC transfer function of the band-pass filter is shown while varying the transistor model (tm, ws, wp), resistor model, and capacitors values within the range provided by the manufacturer. In Fig.12, the AC transfer function of the band-pass filter is presented while varying the transistor model (tm, ws, wp), resistor model, and capacitors values within the range provided by the manufacturer. Only a 2dB gain difference is observed between the worst case curves. In Fig.13 the response of the filter to a test wave is shown. Different simulations like the one in Fig.13 were performed for input amplitudes from 200mV to 8mV and the output peak voltage shown a high degree of linearity with the input.

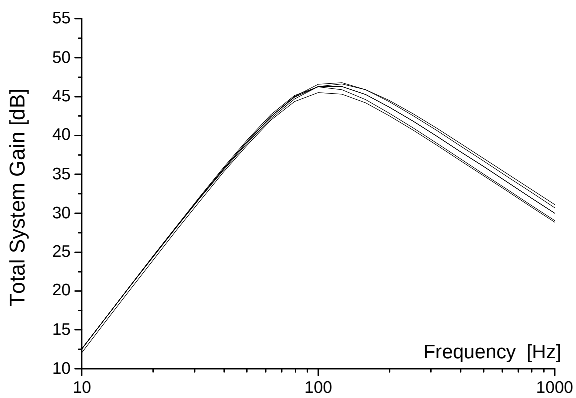

Figure 12: Simulated AC transfer for the proposed total filter (GmC filter +preamplifier) varying transistor, capacitor, and resistor models in the filter.

Although the designed filter is likely to be close enough to the typical curve, if it is still necessary to tune the circuit at the G_mC level, it can be easily adjusted varying the global reference current of the OTAs (the global reference is a current copied with different weights to bias all the OTA's). In effect, Fig.14 shows the peak response of Fig.13 while varying the global reference current, the result being a monotonic gain increase. Thus to make the filter compliant with the standards it is necessary to adjust a single parameter.

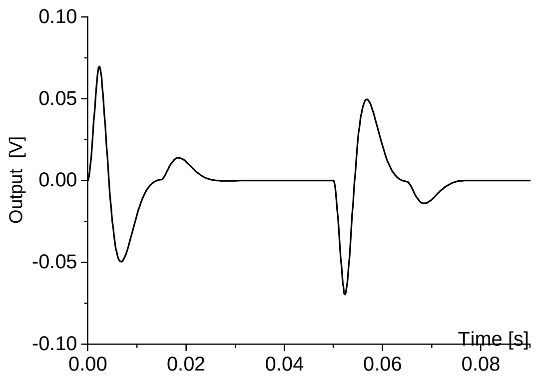

Figure 13: Transient simulation of the complete circuit, to a successive positive and negative CENELEC test signal.

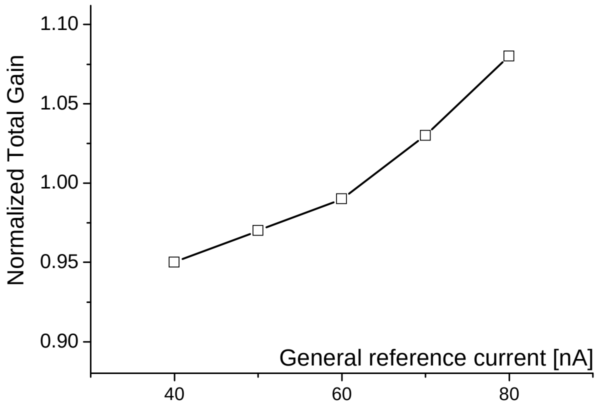

Figure 14: Relative amplitude at the output .

4. CONCLUSIONS

Several issues on the design of G_mC filters for real medical applications, particularly implantable medical devices were studied. Fully integrated G_mC circuits offer an excellent power consumption option but on the other hand the transfer function may present a certain degree of inaccuracies. First a 0.5Hz - 15Hz G_mC filter and rectifier for physical activity estimation using known circuit techniques was presented. The circuit was fabricated in a 0.6µm technology, and tested. The measured transfer function shows a high degree of agreement between the measured and expected (typical transistor model) transfer function. The circuit allowed also validating a low power OTA-based rectifier. Although it is a single experiment, considering also other reported measurements, it is possible to affirm that a G_mC is likely to fit the expected transfer function quite far from the worst case of simulations (worst case corners). Since most medical devices are trimmed at the device level because of the variability of biological signals, G_mC remains a valuable circuit technique. Secondly a 70-200Hz G_mC filter for a cardiac sensing channel was presented. It was designed in a 0.6µm HV technology but not yet fabricated. It incorporates the ability to filter input signals with a high common mode input up to 15V. Simulations show an excellent linearity for the filter and in a worst case the circuit response is within the 5% barrier. The circuit will be fabricated to test the transfer function at least in a single fabrication batch. If still necessary for a real application to tune the filter it can be done by just changing a single parameter: the global reference current of the OTAs. Finally it should be noted that most of the design (most transistor operate in deep weak inversion) was carried with LT-Spice [16], a free CAD tool. BSIM foundry models were adapted without major problems, and the results were validated with measurements and other available tools.

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