A New OTA-C Electronically Tunable Orthogonal Universal Biquad

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***Abstract* – This paper presents a universal biquad, a core structure that provides, with minimum of adjustments, a wide range of transfer functions, from the usual low-pass, band-pass and all-pass to transfer functions with imaginary and complex zeroes. The biquad is tailored for silicon integration: it uses the Gm-C implementation technique, employing only grounded capacitors; the sizing equations allow the user to choose the capacitor values and result in relatively low spread of circuit component values. A design example suggests that these biquads can implement high-order filters operating in the tens of MHz frequency range.**

INTRODUCTION

Nowadays analog and mixed-signal systems require high performance continuous-time filters for interfacing digital processing cores with the real (analog!) world, from the simple anti-aliasing filters preceding ADCs to the high-spec channel-select and image-reject filters in integrated RF transceivers.

One of the most popular methods for the synthesis of high-order filters is the cascade of first- and second-order sections, particularly well suited for silicon integration due to its modularity and straightforward tuning of main parameters.

A large number of cascadable biquad structures have been reported in the literature and there are several criteria for classifying them, such as:

- the number of transfer function/filtering types provided: from "simple" - that is, one transfer function biquads - to "multiple" and "universal" biquads, that provide a wide range of transfer functions [1], [2].
- the circuit implementation techniques: from the traditional OpAmp–RC, effective up a few MHz [3], to the higher-frequency techniques Gm-C and Gm-C-OpAmp, used in commercial applications up to hundreds of MHz [4]. Or biquads implemented using less usual active devices, from current-conveyors [5], to current-mode unity-gain cells [6] and current differencing transconductors [7].
- voltage- or current-mode operation, or mixed-mode structures, with both voltage and current inputs and outputs [2].
- the availability of convenient ways to control the transfer function parameters. In complex systems and especially in IC design it is crucial that the system/designer can tune electrically the main parameters. The most sought after is the orthogonal tuning, that is the possibility to control each parameter independently, one at the time.

In this context the structure proposed in this paper is a Gm-C universal biquad, with voltage and current outputs, that allows electronic tuning for all the transfer function parameters and, in most cases, the independent control of these parameters.

Given the extensive literature in this area one needs to specify the differences between this work and similar ones, especially recent publications such as [2]. Main differencing factors are the possibility to realize transfer functions with imaginary and complex zeroes and the electronic tunability of the main parameters, including those related to the complex zeroes.

Section II presents the core of the proposed structure and discusses the possible effects of its main parasitics, along with ways of reducing/minimizing them. Section III gives examples of various transfer functions that can be realized using the core structure, with minimal adjustments. One such example is presented in detail: a biquadratic transfer function with complex zeroes. Section IV presents the design of a fourth-order low-pass elliptic filter with the -3dB corner frequency of 10.7MHz.

THE PROPOSED CORE STRUCTURE

Figure 1 shows the core structure from which all biquads proposed here can be derived. It contains eight transconductance amplifiers and two placed capacitors (**C_3** is a parasitic), a bill-of-materials similar to the one reported in [2]. It realizes the general transfer function:

$$V_{out}(s)=\frac{g_{m3}}{g_{m6}}\,\frac{V_{in3}s^2+V_{in2}s\dfrac{g_{m2}g_{m5}}{g_{m3}C_2}+V_{in1}\dfrac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}}{\dfrac{C_3}{g_{m6}}s^3+s^2+s\dfrac{g_{m5}g_{m8}}{g_{m6}C_2}+\dfrac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}} \quad (1)$$

This can be reduced to a biquadratic transfer function if the time constant given by capacitor **C_3** and transconductance **g_{m6}** is minimized so that the associated pole is pushed up in frequency, outside the intended operating frequency range. As the capacitor **C_3** does not appear in the expression of any other coefficient of the general transfer function in equation (1) the condition above can be conveniently met by reducing the value of **C_3**.

For most applications operating in the tens of MHz range this can be achieved by using the usual circuit and layout techniques; for higher frequencies and/or

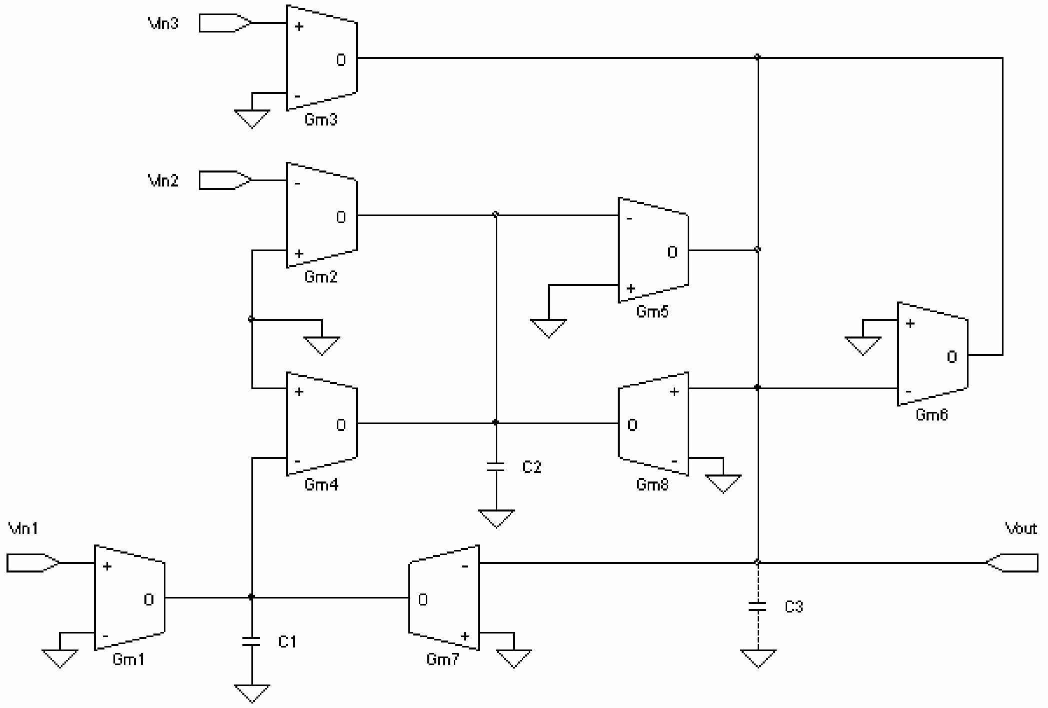

Figure 1. The core structure of the proposed universal biquad.
C_1 and C_2 are placed capacitors, C_3 illustrates parasitics.

special cases the circuit can be simplified by replacing the cells **Gm6**, **Gm7** and **Gm8** with one transconductor having three separate outputs, thus reducing the number of Gm cells from eight to six.

If the parasitic capacitance $\mathbf{C_3}$ can be neglected, the Figure 1circuit yields the general transfer function:

$$V_{out}(s)=\frac{g_{m3}}{g_{m6}}\frac{V_{in3}s^2+V_{in2}s\frac{g_{m2}g_{m5}}{g_{m3}C_2}+V_{in1}\frac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}. \qquad \textbf{(2)}$$

Note that the parasitic capacitances at the other nodes of this circuit appear in parallel with placed capacitances; therefore, the effect of these parasitics can be minimized by simply deducing their estimated value from the values calculated for $\mathbf{C_1}$ and $\mathbf{C_2}$.

Also worth noting is the fact that all the Gm cells in the circuit have one input connected to the ground (reference) line; this allows the direct derivation of a fully differential counterpart (not presented here), without topological changes.

An important property of the circuit is that all the voltage inputs are high-impedance while the voltage output is low-impedance; therefore all the biquads are fully cascadable in respect to the voltage in/outs.

Finally, the circuit can provide a current output by simply mirroring the output current of cell $\mathbf{G_{m6}}$; the transfer function for this current output is:

$$I_{out}(s)=-g_{m3}\frac{V_{in3}s^2+V_{in2}s\frac{g_{m2}g_{m5}}{g_{m3}C_2}+V_{in1}\frac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}. \qquad \textbf{(3)}$$

EXAMPLES OF ELECTRONICALLY TUNABLE BIQUADS

By analysing the general transfer functions (2) and (3) one can observe that various filter functions can be realized; several examples are summarized in Table 1.

The main parameters of the respective transfer functions can be electronically tuned through the values of transconductances $\mathbf{g_{m1}}$ to $\mathbf{g_{m8}}$. Moreover, independent control over most of these parameters is possible. Only one of these cases is analised in detail in this section: the implementation of a biquadratic transfer function with complex zeroes.

The relatively large number of Gm cells used by the proposed core appears as a shortcoming; however, it should be noted that similar universal structures [2] use at least the same number of Gm cells: the last two columns in Table 1 provide a direct comparison.

Biquadratic transfer function with complex zeroes

Transfer functions obtained using the classical approximations do not require biquads with complex zeroes. However, these biquads can be very useful in applications with stricter requirements, involving both frequency- and time-domain constraints.

Multiple-criteria filter optimization, that takes into account not only the magnitude and phase responses but also the peak overshoot, rise time and settling time often result in transfer functions containing imaginary and complex zeroes [3]. Reference [3] also presents biquads that realize such transfer functions and allow independent control over their parameters, circuits implemented using the OpAmp-RC approach.

Figure 2 presents the schematic of a Gm-C biquad derived from the core structure shown in Figure 1

Transfer Function Type	Conditions (refered to the core in Figure 1)	Transfer Function Expression	No Gm Cells used	
			Fig.1	In [2]
With complex zeroes	$Vin_1=Vin_2=Vin_3=Vin$	$V_{out}(s)=\frac{g_{m3}}{g_{m6}}\frac{s^2+s\frac{g_{m2}g_{m5}}{g_{m3}C_2}+\frac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}$	8	Not imple-mented
With purely imaginary zeroes	$Vin_1=Vin_3=Vin$; $Vin_2=0$	$V_{out}(s)=\frac{g_{m3}}{g_{m6}}\frac{s^2+\frac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}$	7	7
Low-pass	$Vin_2=Vin_3=0$; $Vin1=Vin$	$V_{out}(s)=\frac{g_{m1}}{g_{m7}}\frac{\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}$	6	7
High-pass	$Vin_1=Vin_2=0$; $Vin_3=Vin$;	$V_{out}(s)=\frac{g_{m3}}{g_{m6}}\frac{s^2}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}$	6	7
Band-pass	$Vin_1=Vin_3=0$; $Vin_2=Vin$;	$V_{out}(s)=\frac{g_{m2}}{g_{m8}}\frac{s\frac{g_{m8}g_{m5}}{g_{m6}C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}$	6	7
All-pass	$Vin_1=Vin_2=Vin_3=Vin$; inverted $\mathbf{G_{m2}}$ cell and $g_{m2}=g_{m8}$; $g_{m1}=g_{m7}$	$V_{out}(s)=\frac{g_{m3}}{g_{m6}}\frac{s^2-s\frac{g_{m2}g_{m5}}{g_{m3}C_2}+\frac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}}$	8	7

Table 1. Examples of transfer function implemented with biquads derived from the structure shown in Figure 1.

with the adjustments described in the first position in Table 1. It realizes a biquadratic transfer function containing complex zeroes:

$$V_{out}(s)=\frac{g_{m3}}{g_{m6}}\frac{s^2+s\frac{g_{m2}g_{m5}}{g_{m3}C_2}+\frac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}}{s^2+s\frac{g_{m5}g_{m8}}{g_{m6}C_2}+\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}} \quad (4)$$

The expressions of the canonical parameters - $\mathbf{H_0}$, $\boldsymbol{\omega_p}$, $\boldsymbol{\omega_z}$, $\mathbf{Q_p}$ and $\mathbf{Q_z}$ - result as follows:

$$H_0=\frac{g_{m3}}{g_{m6}};\ \omega_p=\sqrt{\frac{g_{m4}g_{m5}g_{m7}}{g_{m6}C_1C_2}};$$
$$\omega_z=\sqrt{\frac{g_{m1}g_{m4}g_{m5}}{g_{m3}C_1C_2}};$$
$$\frac{1}{Q_p}=g_{m8}\sqrt{\frac{g_{m5}}{g_{m4}g_{m6}g_{m7}}\frac{C_1}{C_2}}; \quad (5)$$
$$\frac{1}{Q_z}=g_{m2}\sqrt{\frac{g_{m5}}{g_{m1}g_{m3}g_{m4}}\frac{C_1}{C_2}}.$$

Several sizing strategies can be devised; for example, one can set the values of $\mathbf{C_1}$, $\mathbf{C_2}$, $\mathbf{g_{m4}}$, $\mathbf{g_{m5}}$ and $\mathbf{g_{m6}}$ (the later according to the requirement to minimize the effect of the parasitic capacitance at the output node). The sizing equations for the remaining circuit elements result as follows:

$$g_{m3}=g_{m6}H_0;$$
$$g_{m1}=\omega_z^2\frac{g_{m6}H_0C_1C_2}{g_{m4}g_{m5}};$$
$$g_{m7}=\omega_p^2\frac{g_{m6}C_1C_2}{g_{m4}g_{m5}}; \quad (6)$$
$$g_{m2}=\frac{\omega_z}{Q_z}\frac{g_{m6}H_0C_2}{g_{m5}};$$
$$g_{m8}=\frac{\omega_p}{Q_p}\frac{g_{m6}C_2}{g_{m5}}.$$

By inspecting these expressions it results the following transfer function parameter – controlling element pairs: $\mathbf{H_0} \leftrightarrow \mathbf{g_{m3}}$; $\boldsymbol{\omega_p} \leftrightarrow \mathbf{g_{m7}}$; $\boldsymbol{\omega_z} \leftrightarrow \mathbf{g_{m1}}$; $\mathbf{Q_p} \leftrightarrow \mathbf{g_{m8}}$; $\mathbf{Q_z} \leftrightarrow \mathbf{g_{m2}}$.

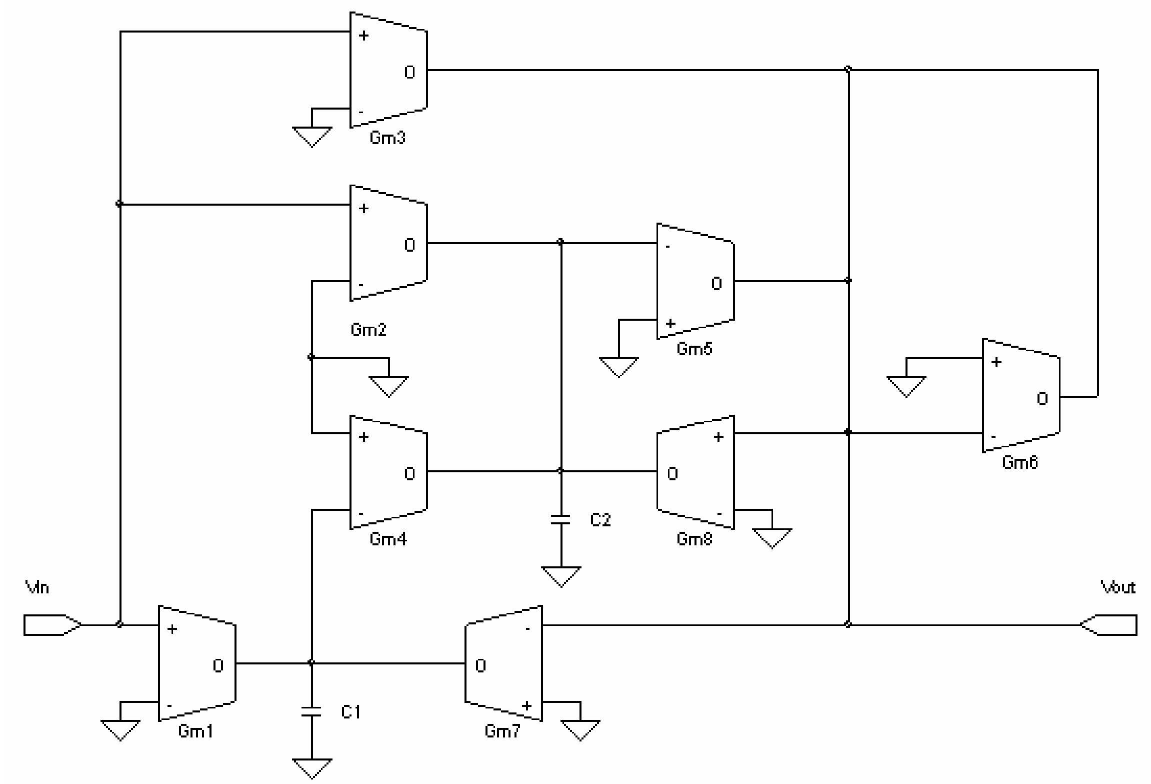

Figure 2. Circuit that implements a biquadratic transfer function with complex zeroes

This sizing strategy is very simple and convenient for silicon implementation, as the placed capacitances have equal values that can be chosen. Also, it allows orthogonal control over the ω_p / $\mathbf{Q_p}$ ratio through the tunable value of $\mathbf{g_{m8}}$ and over the ω_Z / $\mathbf{Q_Z}$ ratio through the tunable value of $\mathbf{g_{m2}}$.

The resulting biquads are, in general, low-sensitivity: by analyzing the equations (5) it is easy to show that all parameters have sub-unitary sensitivities

DESIGN EXAMPLE

A.Filter specifications and schematic

In order to illustrate the potential of the circuit structure proposed here let us consider the design of a low-pass filter, with the following specifications:

- passband edge frequency, $\mathbf{F_c}$ of 10.7MHz;
- passband gain of 0dB;
- max ripple in the passband of 1dB;
- 60dB attenuation above **3*** $\mathbf{F_c}$;
- group delay variation less than 150ns up to **2*** $\mathbf{F_c}$

A classical elliptic approximation indicated that these specs can be met by a fourth order transfer function, implemented by two biquads with purely imaginary zeroes. Figure 3 presents the schematic of such a biquad, derived from the general structure shown in Figure 1 – see second row in Table 1.

A sizing strategy similar to the one described in Section III – see equations (6) - yields the values for each circuit component, summarized in Table 2. It is worth noting the relative low spread of the transconductance values, Gmax/Gmim = 42.76, while all the placed capacitances have the same value, conveniently set to 1pF. The value of the parasitic capacitance at the output node was estimated to 0.5pF; it results that the corresponding parasitic pole was pushed up to a value almost ten times higher than $\mathbf{F_c}$.

B.Simulation results

PSpice simulations have been run in order to verify the design, using a simple model for the Gm cells: voltage-controlled current sources, with their equivalent input resistances set to 1MΩ and the output resistances set 100kΩ.

As expected, the relatively low value of the Gm cell output resistances caused the degradation of the frequency responses – the dotted-line curves shown in Figure 4. This degradation is mostly equivalent to a higher-than-calculated value of the quality factor associated with the poles, $\mathbf{Q_p}$.

1st biquad	C1=C2=1pF; g_{m1}=406µS; g_{m3}=123µS; g_{m6}= 3mS; g_{m4}=g_{m5}=100µS; g_{m7}=412µS; g_{m8}=1.4mS
2nd biquad	C1=C2=1pF; g_{m1}=1.22mS; g_{m3}=70.1µS; g_{m6}= 3mS; g_{m4}=g_{m5}=100µS;g_{m7}=1.34mS; g_{m8}=516µS
Component spread	Gmax/Gmin=42.76; Cmax/Cmin = 1

Table 2: The calculated component values

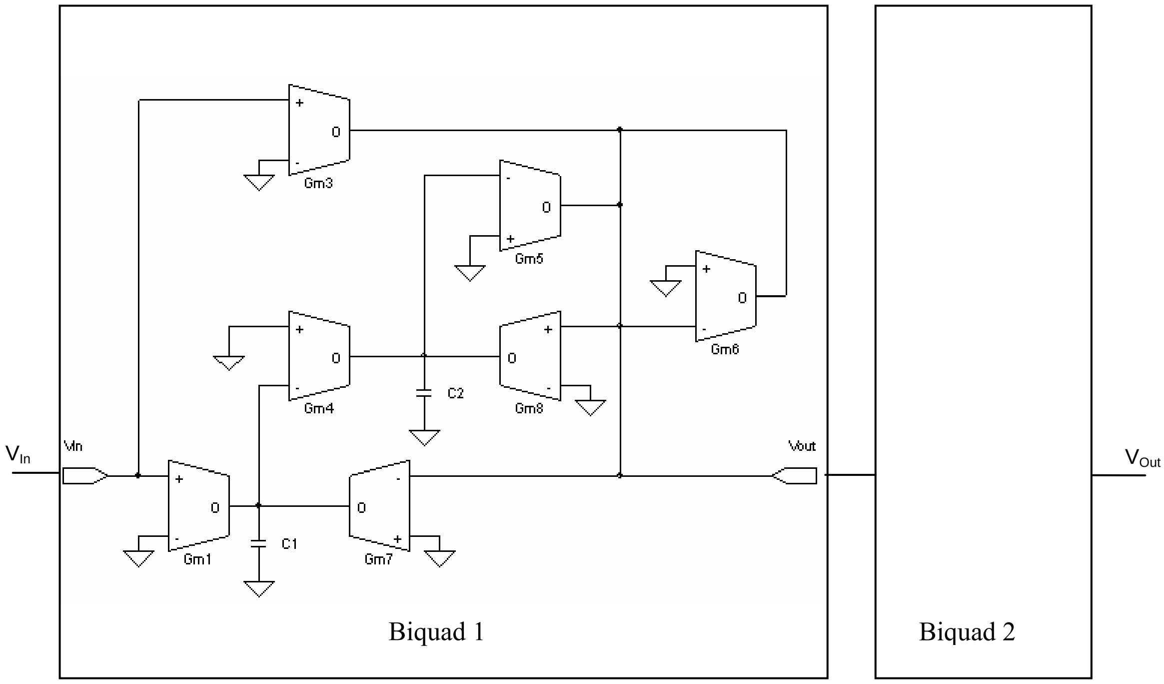

Figure 3. Design example: a 4th order low-pass filter implemented by two biquads with imaginary zeroes. The 2nd biquad schematic is the same as the one presented in detail on the left hand side.

The extended tunability of the biquad proposed here provide a simple solution to this issue: $\mathbf{Q_p}$ can be adjusted independently through $\mathbf{g_{m8}}$ thus compensation for the effect of the Gm cells low output resistance without changing the filter cut-off frequency. The plain-line frequency response shown in Figure 4 demonstrate the effectiveness of this technique. The resulting filter parameters are summarized in Table 3; note that all the design specifications are met.

Parameter	Sim value
Passband gain and ripple	0dB; 0.85dB
-3dB corner frequency, Fc	10.7 MHz
Attenuation at 3*Fc	62.5 dB
Group delay deviation (max-min values up to 2*Fc)	145ns

Table 3: Simulated filter parameters

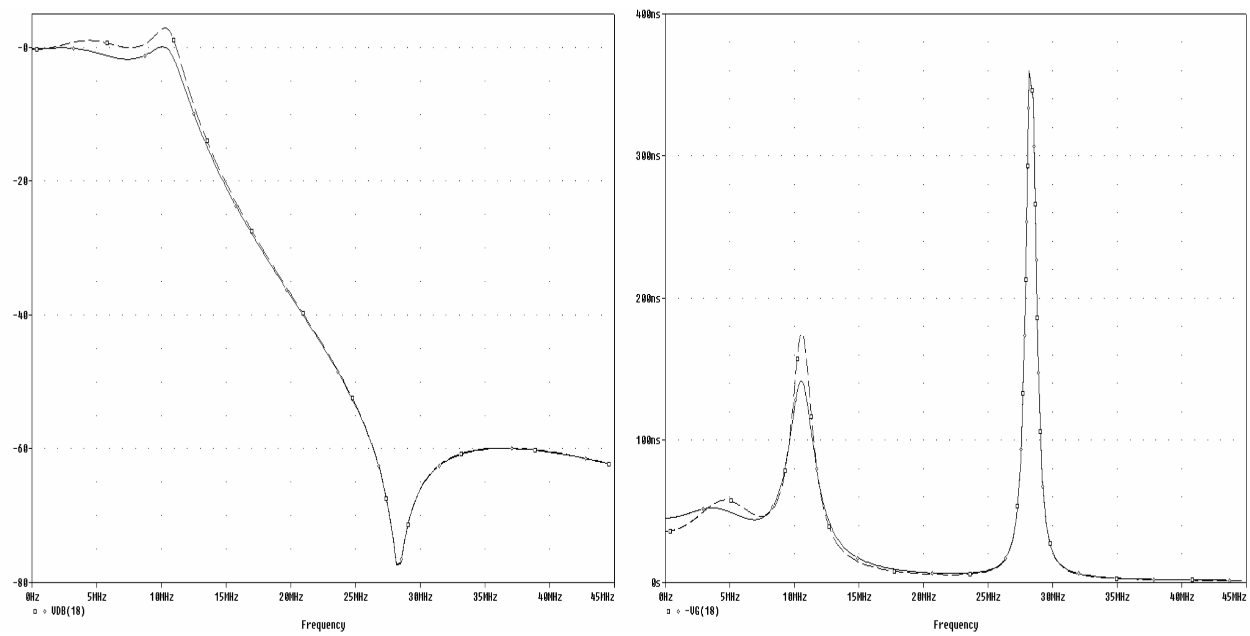

Figure 4. Simulated frequency responses of the designed filter: magnitude on the left hand side and group delay on the right hand side. Dotted line = before $\mathbf{Q_p}$ tuning ; plain line = after adjusting $\mathbf{Q_p}$ (through $\mathbf{g_{m8}}$) to compensate for the Gm cells low output resistance.

CONCLUSIONS

This paper proposes a Gm-C universal biquad, a core structure that provides, with minimum of adjustments, not only the most usual transfer functions –low-pass, band-pass, all-pass- but also transfer functions with imaginary and complex zeroes, which are required in special applications and/or allow multi-criteria optimization of the filter performances. It is worth noting that the circuit provide both voltage and current outputs.

The proposed circuits are well suited for silicon integration: they are based on the Gm-C implementation technique and employ only grounded capacitors and Gm cells with only one hot input. There are several advantages to this arrangement: first, the main parasitic capacitances appear in parallel with the placed ones, therefore the effect of parasitics can be minimized by pre-distorting the value of the placed capacitors; second, fully differential counterparts can be directly derived for all the single-ended circuits presented here, without topological changes. Most importantly, the main parameters of the biquadratic transfer functions can be electronically tuned through the transconductance values.

The relatively large number of Gm cells required – between 6 and 8, depending on the transfer function type - is compensated by the multiple sizing strategies available, some of them providing independent control over the canonical parameters, $\mathbf{H_0}$, $\boldsymbol{\omega_0}$ and **Q.**

The excellent tunability features of the proposed biquads provide an elegant solution to the frequency response degradation caused by the finite (low) output resistance of practical transconductors: the quality factor associated with the poles, $\mathbf{Q_p}$, can be tuned (or pre-distorted) independently, thus compensating for the effect of low R_{out} without disturbing the other parameters. The effectiveness of this is compensation technique is demonstrated in the design example presented in the last Section of the paper.

A similar technique can be use to reduce the effects of the other main non-ideality of real-life Gm cells, that is their limited bandwidth.

The simulation results presented in the paper indicate that the circuits proposed here can implement high-order filters that operate effectively in the MHz-to-tens of MHz frequency range.

The main factors that differentiate the circuits proposed here from other circuits reported in the literature are the possibility to realize transfer functions with imaginary and complex zeroes and the electronic tunability of the main parameters, including those related to the complex zeroes.

Further work will focus on transistor-level implementation and refining the technique of compensating for practical Gm cell limitations by making use of the tuning features provided by this structure.

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