RF Pure Current-Mode Filters using Current Mirrors and Inverters

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Abstract. In this paper the design method leading to the radio-frequency (RF) filters working in the pure current mode is shown. New active elements called current mirrors and inverters (CMI) are presented, a generalized variant (GCMI) is used for the design purposes, and a universal version (UCMI) is fitted to the filtering-circuit final solution. Initial autonomous circuits are derived from the full admittance network, which is defined. In this paper, a few autonomous circuits with five passive elements are presented. An illustration of the filter design with independent quality factor adjustment with respect to the characteristic frequency is given. Results obtained from the measurement of samples are shown.

Keywords: pure current mode, frequency filter, current mirror, current inverter, CMI, GCMI

1 Introduction

Frequency filters and all other common electrical circuits traditionally work in the voltage mode, which means that circuit input and output values are expressed in the voltages. Of course, there is also a current flowing in the circuit, but its value does not carry any useful information. The operational amplifier (OPA) is often used as an active element, when the voltage mode is mentioned. Despite the sundry innovations effected, this circuit cannot today meet all the filter-design requirements.

The continual progress in the integrated-circuit manufacturing technologies is, among others, accompanied by decreasing the values of supply voltage and power consumption, and thus naturally also by decreasing the voltage being processed (at the same time). It causes an undesirable decrease of signal-to-noise ratio. This ratio is a little more advantageous when we use a current as a carrier of information. Also, a better bandwidth can be obtained when the circuit operates in the current mode. These are some of the reasons leading to the present increase in frequency filters working in the current mode [1] to [6].

There are sometimes mixed-working elements in place of active elements (e.g. OTA amplifiers or Current Conveyors), but the aim of this paper is to deal with the pure current-mode filter design, which means that both the active element and the filter itself are working in the current mode.

We have a number of ways how to design a current-mode frequency filter. The adjoint network method can be regarded as the simplest one, but with the least applications in practice. This method is based on the transformation of the voltage-mode filtering circuit into the current-mode circuit [7]. A method that has been developed in great detail is the method employing synthetic elements and impedance converters forming high-order immittances [8]. From other methods we should mention the signal flow graph method [9] and, last but not least, the autonomous circuit method [10], which is used for the design procedure starting from the full admittance network and which is shown in this paper.

2 Current Mirrors and Inverters

The filtering circuit works in the pure current mode when all of its input and output values are currents and, at the same time, the active element also works only with current values. This means that current inputs and current outputs are the only acceptable terminals of proposed active elements. For the generalization of design procedures, an active element GCMI (Generalized Current Mirrors and Inverters) [11] was defined in our department. This element is suitable for the new filtering circuit design according to all the design methods mentioned in the introduction. The circuit symbol of the GCMI is shown in Fig. 1.

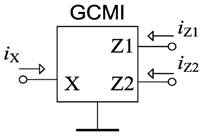


Fig. 1. Symbol of the GCMI circuit used in the schematics

This active element is described by two equations, $i_{Z1} = a.\, i_X$, $i_{Z2} = b.\, i_X$, where a, b are the current transfer coefficients taking the values -1 or 1 only. From these equations it is evident that we can define CMI circuits with four possible combinations of output current orientation when we use both outputs of the GCMI and generally also four other variants if we use just one of the outputs. All these variants are summarized in Table 1.

Such a generalized circuit (GCMI) is used in the design procedure of new filtering circuits, and when we come to the realization we use a particular CMI variant, made by universal CMI, see below.

Table 1. All possible variants resulting from the GCMI definition

Circuit labelling	CMI+/+	CMI-/-	CMI+/-	CMI-/+	CM_1	CI_1	CM_2	CI_2
Value of coefficient *a*	+1	-1	+1	-1	+1	-1	-	-
Value of coefficient *b*	+1	-1	-1	+1	-	-	+1	-1

From the application point of view it is advantageous to have both outputs of the CMI having the same current-flow orientation, so that both inner paths in the CMI circuit mentioned will have approximately the same phase shift. After the basic research was done, it turned out that for the filter realization it was advantageous to have all CMI variants available. Thus the idea of developing a universal current unit came into being that would be capable of realizing these four CMI variants. This circuit (the UCMI) is indicated in Fig. 2.

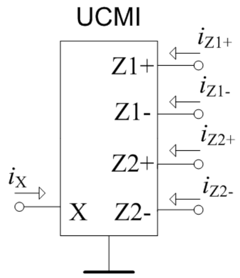


Fig. 2. Circuit symbol of the UCMI used in the schematics

The X terminal represents current input while terminals Z_{1+} and Z_{2+}, or Z_{1-} and Z_{2-} are current outputs with positive or negative current transfer from terminal X. It is clearly evident from the following equations describing the circuit behavior:

$$i_{Z1+} = i_{Z2+} = i_X \, , \, i_{Z1-} = i_{Z2-} = -i_X \, . \qquad (1)$$

Proposing the internal structure of this pure-current element was the subject of completed research, the first fabricated samples produced in cooperation with AMI Semiconductor will be ready later this year (2007). To be able to experimentally verify the CMI-application functionality sooner, a universal current conveyor UCC-N1B [12] made also in AMI Semiconductor was employed. It contains all terminals necessary for the UCMI realization but it also has voltage inputs, which have to be grounded for proper UCMI implementation. Although the UCC circuit was originally not designed for this kind of usage and its bandwidth is only about 30 MHz, it did not show in any markedly negative way in the verification of the newly designed filters. Of course, we can expect that the commencement of production of the UCMI, which will be internally simpler than the UCC, will bring us the widening of frequency bandwidth up to 100 MHz.

3 Autonomous Circuit Design Method

The autonomous circuit filter design method [10] seems to be really advantageous. This method consists of a few steps:

- An autonomous circuit containing only general active elements (GCMI) and general passive elements (admittances) is proposed. We usually proceed intuitively or follow some analogies. A systematic method of autonomous circuit design is introduced in chapter 4 of this paper.

- The characteristic equation (CE) of autonomous circuit is calculated [10].
- CE is simplified by choosing suitable transfer coefficients. We also have to ensure that all the terms are positive in view of the condition of filter stability.
- Passive elements are concretized (admittances are replaced by capacitors or resistors) in such a way that appropriate order of the CE is obtained.
- Input and output positions are appointed, while respecting that current sources can only excite the nodes of a circuit and that current response can be monitored in the branches.
- The transfer functions found are determined.

4 Design of Autonomous Circuits

The first point of the procedure described above is the most sophisticated task and that is why we tried to algorithmize it [11]. As already mentioned, we usually also proceed intuitively, but it is much more favorable to start from a general full admittance network (Fig. 3) connected between two GCMI elements, in case we want to obtain second-order filters. Four passive elements are often enough for a particular solution and it is further possible to realize more than one filter type within one circuit (referred to as the multifunction filter) [11]. In this paper, autonomous circuits with five passive elements are discussed. The main advantage of such circuits is the potential independence of the quality factor on the characteristic frequency and hence these filters are suitable for tuning.

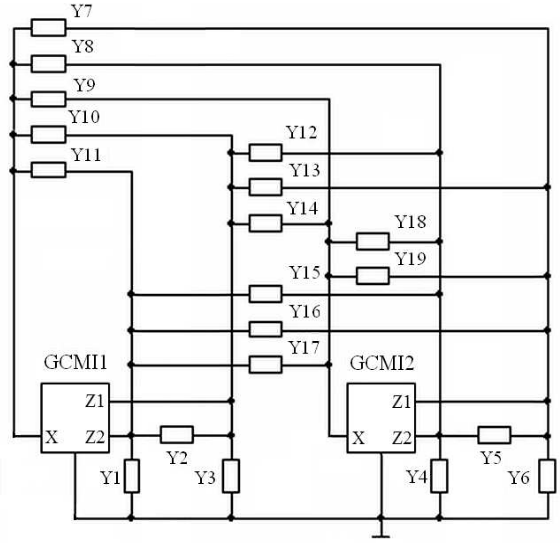


Fig. 3. Improved full admittance network connected to two GCMI

As can be seen from Fig. 3, the improved full admittance network is made up of 19 admittances, so the number of admittances is the same as in [11], but same changes have been made. Based on later findings, the admittance connected between the X terminal of the GCMI and the ground has been removed while an admittance has been added between two outputs (Z1 and Z2) of the GCMI, which holds for both GCMI placed in the network. Like in [11], it should be noted that each of the admittances should theoretically be replaced by a resistor, capacitor, their parallel combination, short-circuit or disconnected, which will be applied below.

A large number of autonomous circuits can be derived from this full admittance network, which is beyond the scope of this paper and that is why only a few autonomous circuits with five passive elements will be shown, see Table 2. The left side of the characteristic equation is presented on the right side of every autonomous circuit depiction. As is well known, the left side of the CE will appear in the denominator of the transfer function of every filter derived from the autonomous circuit.

Table 2. Autonomous circuits with five passive elements

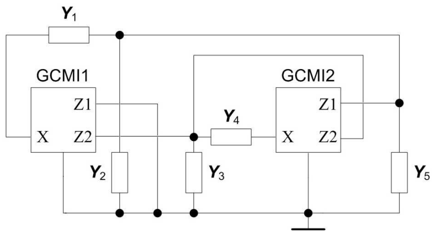
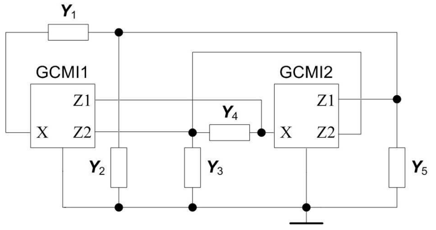
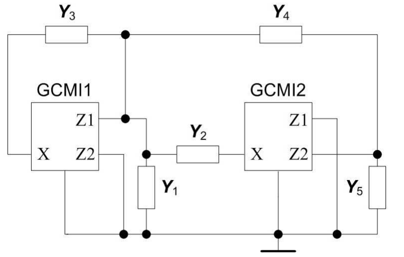
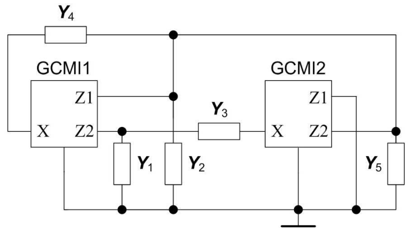
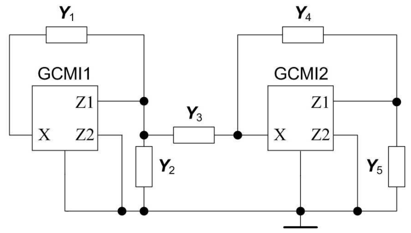
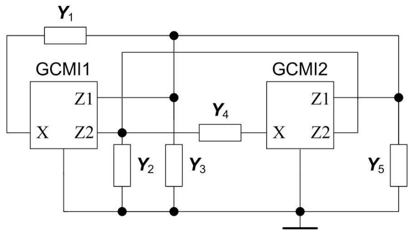
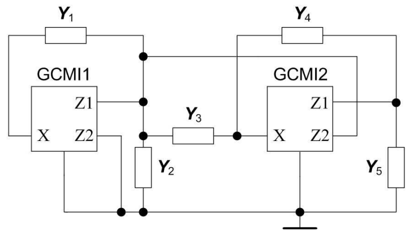
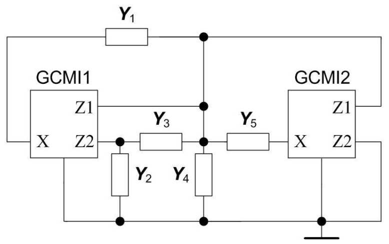
No.	Autonomous circuit	Left side of the characteristic equation
1.		$Y_1Y_3 + Y_1Y_4 + b_2Y_1Y_4 - a_2b_1Y_1Y_4 +$ $+ Y_3Y_5 + Y_2Y_3 + Y_4Y_5 + b_2Y_4Y_5 +$ $+ Y_2Y_4 + b_2Y_2Y_4$
2.		$Y_2Y_3 + Y_3Y_5 + Y_1Y_3 - a_1a_2Y_1Y_3 +$ $+ Y_2Y_4 + b_2Y_2Y_4 + Y_4Y_5 +$ $+ b_2Y_4Y_5 + Y_1Y_4 + b_2Y_1Y_4 -$ $- a_1a_2Y_1Y_4 - a_2b_1Y_1Y_4$
3.		$Y_1Y_5 + Y_2Y_5 + Y_3Y_5 + Y_4Y_5 +$ $+ a_1Y_3Y_5 + Y_1Y_4 + Y_2Y_4 + Y_3Y_4 +$ $+ a_1Y_3Y_4 + b_2Y_2Y_4$

Table 2. Autonomous circuits with five passive elements - continued

No.	Autonomous circuit	Left side of the characteristic equation
4.		$Y_2Y_3 + Y_3Y_4 + a_1Y_3Y_4 -$ $- b_1b_2Y_3Y_4 + Y_3Y_5 + Y_1Y_2 +$ $+ Y_1Y_4 + a_1Y_1Y_4 + Y_1Y_5$
5.		$Y_3Y_4 + a_2Y_3Y_4 + Y_1Y_4 + a_1Y_1Y_4 +$ $+ a_2Y_1Y_4 + a_1a_2Y_1Y_4 + Y_2Y_4 +$ $+ a_2Y_2Y_4 + Y_1Y_5 + a_1Y_1Y_5 +$ $+ Y_2Y_5 + Y_3Y_5$
6.		$Y_2Y_5 + Y_4Y_5 + b_2Y_4Y_5 + Y_1Y_2 +$ $+ a_1Y_1Y_2 + Y_1Y_4 + b_2Y_1Y_4 +$ $+ a_1Y_1Y_4 + a_1b_2Y_1Y_4 - a_2b_1Y_1Y_4 +$ $+ Y_2Y_3 + Y_3Y_4 + b_2Y_3Y_4$
7.		$Y_3Y_4 + a_2Y_3Y_4 + b_2Y_3Y_4 + Y_2Y_4 +$ $+ a_2Y_2Y_4 + Y_1Y_4 + a_1Y_1Y_4 +$ $+ a_2Y_1Y_4 + a_1a_2Y_1Y_4 + Y_3Y_5 +$ $+ b_2Y_3Y_5 + Y_2Y_5 + Y_1Y_5 + a_1Y_1Y_5$
8.		$Y_2Y_3 + Y_2Y_5 + a_2Y_2Y_5 + Y_2Y_4 +$ $+ Y_1Y_2 + a_1Y_1Y_2 + Y_3Y_5 + a_2Y_3Y_5 +$ $+ Y_3Y_4 + Y_1Y_3 + a_1Y_1Y_3 + b_1Y_1Y_3$

5 Example of the Frequency Filter Design

The frequency filter design will be shown on autonomous circuit No. 1 from Table 2. Its characteristic equation is

$$\boldsymbol{D} = \boldsymbol{Y}_1\boldsymbol{Y}_3 + \boldsymbol{Y}_1\boldsymbol{Y}_4 + b_2\boldsymbol{Y}_1\boldsymbol{Y}_4 - a_2b_1\boldsymbol{Y}_1\boldsymbol{Y}_4 + \boldsymbol{Y}_3\boldsymbol{Y}_5 + \boldsymbol{Y}_2\boldsymbol{Y}_3 + \boldsymbol{Y}_4\boldsymbol{Y}_5 + \\ + b_2\boldsymbol{Y}_4\boldsymbol{Y}_5 + \boldsymbol{Y}_2\boldsymbol{Y}_4 + b_2\boldsymbol{Y}_2\boldsymbol{Y}_4 = 0 \quad . \qquad (2)$$

Choosing the products of coefficients a_2b_1 = -1 and the value of coefficient b_2 = -1 we obtain a simplification of CE (2) and ensure that all admittance products in the CE will be positive, which is one of the conditions required for filter stability. Equation (2) will change to

$$\boldsymbol{D} = \boldsymbol{Y}_1\boldsymbol{Y}_3 + \boldsymbol{Y}_1\boldsymbol{Y}_4 + \boldsymbol{Y}_3\boldsymbol{Y}_5 + \boldsymbol{Y}_2\boldsymbol{Y}_3 \quad . \qquad (3)$$

Following the steps mentioned in chapter 3 we now come to the passive elements choice. We always have more than one option of selecting which of the admittances will be replaced by capacitor and which of them will be replaced by resistor. When we want to obtain a second-order filter, Table 3 lists all suitable variants.

Table 3. All possible variants of passive elements selection

Variant	$\boldsymbol{Y}_1$	$\boldsymbol{Y}_2$	$\boldsymbol{Y}_3$	$\boldsymbol{Y}_4$	$\boldsymbol{Y}_5$
A	$\boldsymbol{p}C_1$	G_1	G_2	$\boldsymbol{p}C_2$	G_3
B	G_1	G_2	$\boldsymbol{p}C_1$	G_3	$\boldsymbol{p}C_2$
C	G_1	$\boldsymbol{p}C_1$	$\boldsymbol{p}C_2$	G_2	G_3

If we choose, for example, variant B, CE (3) will change to

$$\boldsymbol{D} = \boldsymbol{p}^2C_1C_2 + \boldsymbol{p}C_1(G_1 + G_2) + G_1G_3 \quad , \qquad (4)$$

where the complex variable $\boldsymbol{p} = \mathrm{j}\omega$. The current-mode multifunction frequency filter designed according to variant B is shown in Fig. 4. At the same time, the exciting current sources connected to the nodes and all possible current responses are shown.

There are lots of possible transfer functions in this circuit, so it is advantageous to summarize them all for greater lucidity, see Table 4. From this Table, it is much better evident how to choose the remaining transfer coefficients appropriately and how to obtain the required filtering transfer functions (low pass, band pass and high pass frequency filters at least). There are only numerators of transfer functions in Table 4; denominators are equal to the CE (4).

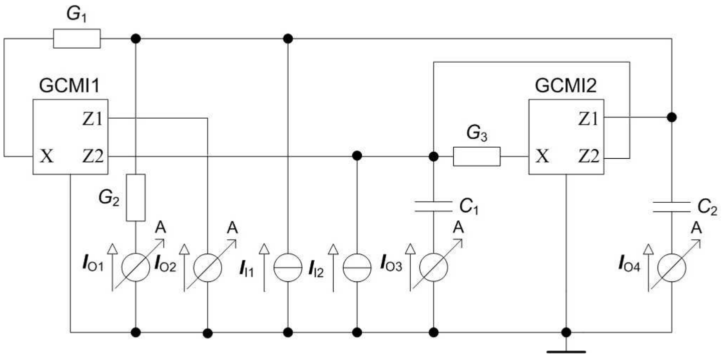


Fig. 4. Frequency filter designed for current mode

Table 4. Numerators of all potential transfer functions

		Current source	
		$\boldsymbol{I}_{I1}$	$\boldsymbol{I}_{I2}$
Current response	$\boldsymbol{I}_{O1}$	$-\boldsymbol{p}G_2C_1$	$a_2G_3G_2$
	$\boldsymbol{I}_{O2}$	$a_1\boldsymbol{p}G_1C_1$	$-a_1a_2G_1G_3$
	$\boldsymbol{I}_{O3}$	$b_1\boldsymbol{p}G_1C_1$	$-\boldsymbol{p}(G_1C_1+G_2C_1)-\boldsymbol{p}^2C_1C_2$
	$\boldsymbol{I}_{O4}$	$-\boldsymbol{p}^2C_1C_2$	$a_2\boldsymbol{p}G_3C_2$

In case of current-mode filter, the filtering functions can also be obtained by adding two or more output current responses. The remaining non-defined transfer coefficients of the GCMI have to be chosen with respect to the two previously mentioned conditions and in such a way that most functions are obtained. Table 5 contains all possible versions of the transfer coefficient selection.

Table 5. All possible versions of transfer coefficient selection

Version	a_1	b_1	$GCMI_1$	a_2	b_2	$GCMI_2$
1.	1	-1	+/-	1	-1	+/-
2.	1	1	+/+	-1	-1	-/-
3.	-1	-1	-/-	1	-1	+/-
4.	-1	1	-/+	-1	-1	-/-

The third version in Table 5 appears to be the best because it enables us to implement two identical inverting band pass filters by adding up two output currents. The first filter by adding up $\boldsymbol{I}_{O1}+\boldsymbol{I}_{O2}$ and second one by adding up $\boldsymbol{I}_{O1}+\boldsymbol{I}_{O3}$, while regarding $\boldsymbol{I}_{I1}$ as the current source. Thus if we choose the third version of coefficient selection, we obtain the following second-order transfer functions:

$$\boldsymbol{K}_{HP} = \frac{\boldsymbol{I}_{O4}}{\boldsymbol{I}_{I1}} = -\frac{\boldsymbol{p}^2 C_1 C_2}{\boldsymbol{D}} \ , \tag{5}$$

$$\boldsymbol{K}_{BP1} = \frac{\boldsymbol{I}_{O1} + \boldsymbol{I}_{O2}}{\boldsymbol{I}_{I1}} = -\frac{\boldsymbol{p} C_1 (G_1 + G_2)}{\boldsymbol{D}} \ , \tag{6}$$

$$\boldsymbol{K}_{BP2} = \frac{\boldsymbol{I}_{O1} + \boldsymbol{I}_{O3}}{\boldsymbol{I}_{I1}} = -\frac{\boldsymbol{p} C_1 (G_1 + G_2)}{\boldsymbol{D}} \ , \tag{7}$$

$$\boldsymbol{K}_{LP} = \frac{\boldsymbol{I}_{O2}}{\boldsymbol{I}_{I2}} = \frac{G_1 G_3}{\boldsymbol{D}} \ . \tag{8}$$

From (5) to (8) it is evident that going down from the top, we are concerned with an inverting high pass (HP) filter, two identical inverting band pass (BP1 and BP2) filters and a low pass (LP) filter.

The final solution of the multifunction filter working in the pure current mode is presented in Fig. 5. Both types of the GCMI chosen have been implemented by the UCC-N1B circuits to be able to verify the correctness of the whole design process.

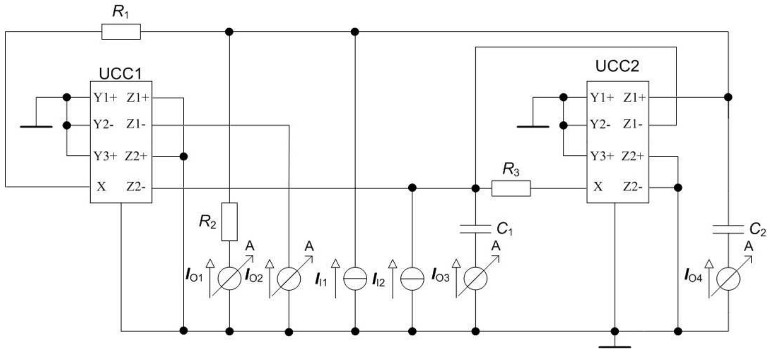


Fig. 5. Multifunction second-order filter working in the current mode with UCC

The characteristic frequency and quality factor formulas can be derived from CE (2) for all filter kinds given and they are

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{1}{C_1 C_2 R_1 R_3}} \ , \tag{9}$$

$$Q = \sqrt{\frac{C_2 R_1}{C_1 R_3}} \frac{R_2}{R_2 + R_1} \ . \tag{10}$$

When comparing eq. (9) and eq. (10), we can notice that the quality factor can be adjusted independently of the characteristic frequency by the value of resistor R_2. The values of capacitors have been chosen as $C_1 = C_2 = 68$ pF, the characteristic frequency equal to $f_0 = 2$ MHz, and resistor $R_1 = 1.8$ kΩ, as an example of a particular solution. From all these selected values, the value of R_3 has been calculated, $R_3 = (C_1C_2R_14\pi^2f_0^2)^{-1} \approx 820$ Ω. We can then tune the quality factor of this multifunction filter by the value of the R_2 resistor. Three suitable values of the R_2 resistor have been chosen (1 kΩ, 2.7 kΩ, 22 kΩ) to obtain three quality factor values (0.53, 1.00, 1.37).

The common circuit analyzer unit, used for measuring the voltage-mode circuits, was complemented with a voltage-current converter to obtain current excitation for the filter input. It was implemented by an operational transconductance amplifier (OTA) integrated in the OPA860 circuit. The reverse current-voltage conversion was also realized in a similar way, in order to transform the output current of the filter into the analyzer (voltage) input [13]. The frequency bandwidth of such converters is approximately 100 MHz, which is absolutely sufficient for design verification. The measured transfer characteristics of such a multifunction filter are depicted in Fig. 6 to Fig. 9.

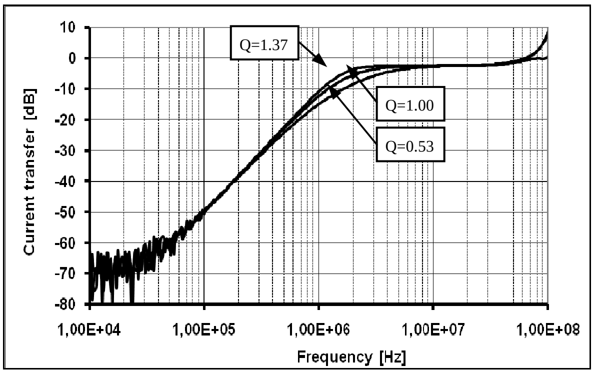


Fig. 6. Measured characteristics of HP filters

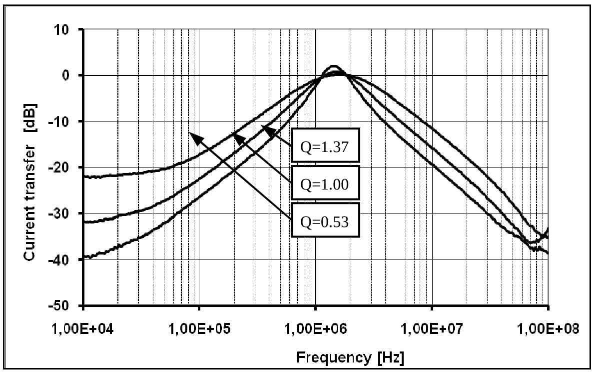


Fig. 7. Measured characteristics of BP1 filters

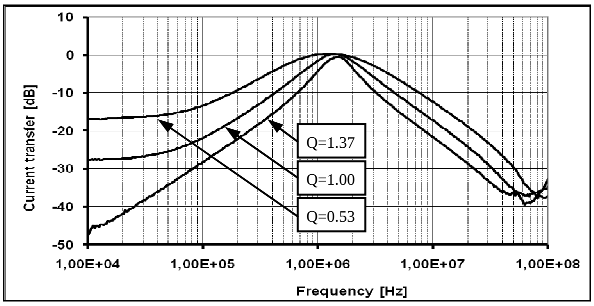


Fig. 8. Measured characteristics of BP2 filters

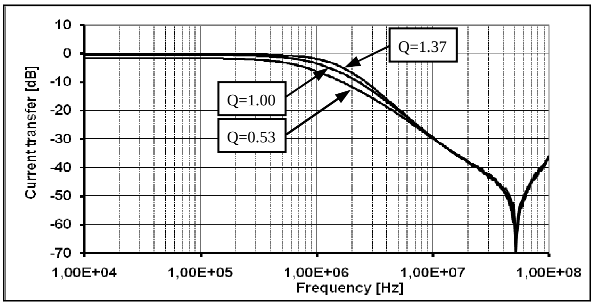


Fig. 9. Measured characteristics of LP filters

The characteristics obtained for all the filters have a lower quality factor than it was expected. The characteristic frequency is also a little bit lower, about 1.5 MHz. The pattern of frequency curves at frequencies of over 30 MHz is damaged by parasitic effects present on the sample boards and by the real features of the UCC circuit. Theoretically similar band passes have different characteristics, which can be attributed to the divergent circuit and also to the board disposition. Measured characteristics performance is absolutely sufficient for design verification, which was the objective of the measurement. Filters based on the GCMI circuit can be assessed overall as good.

6 Conclusion

The paper describes the design process of autonomous circuits with five passive elements starting from a general full admittance network connected between two generalized active elements GCMI. These autonomous circuits are suitable not only for the frequency filter design but also for oscillators working in the current mode, which however was not part of this paper. We limited ourselves to autonomous circuits with five passive elements, but the procedure is similar also when looking for autonomous circuits with another number of passive elements.

The whole design procedure was demonstrated on one of the autonomous circuits, leading to a second-order multifunction frequency filter working in the pure current mode and providing the possibility of the quality factor being independent of the characteristic frequency tuning. The circuit characteristics were subsequently verified experimentally, the evaluation of results can be found in chapter 5.

The active element (UCC) was used only to enable an experimental verification of the CMI-application functionality. As mentioned before, the first fabricated samples of the UCMI circuit produced in cooperation with AMI Semiconductor should be ready by the end of this year (2007). The commencement of production of the UCMI, which will be internally simpler than the UCC, is expected to widen the frequency bandwidth up to the 100 MHz and also to improve other features.

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