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Current conveyors–based circuits using novel transformation method

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Abstract: In the paper, a transformation method of frequency filters using Balanced Output Transconductance Amplifiers (BOTA) into equivalent filtering structures with Universal Current Conveyors (UCC) is shown. A newly designed multifunction filter using two BOTAs was derived from the general autonomous circuit and transformed into a UCC–based frequency filter. The properties of the proposed second–order multifunction filter were subjected to an AC analysis in the OrCAD software and the BOTA–based circuit to experimental measurement.

Keywords: multifunction frequency filter, transformation method, current–mode, voltage–mode, BOTA, UCC

Classification: Integrated circuits

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1 Introduction

In the last years a number of new active elements for designing tunable frequency filters working in the current or the voltage–mode have been developed. Primarily these are CFA (Current Feedback Amplifier) [3], OTA (Operational Transconductance Amplifier) [1, 4], BOTA (Balanced Output Transconductance Amplifier) [5, 14], CC (Current Conveyors) [3, 7, 8], COA (Current Operational Amplifier) [13] or pure–current element CMI (Current Mirror and Inverter) [12]. Numerous scientific papers and publications dealing with filters using these active elements have been presented [6, 9, 10]. In this paper we are concerned with the application of transconductance amplifiers BOTA, because in integrated structures these circuits have excellent frequency properties. For experiments a commercially available amplifier, BOTA MAX435 by Maxim Integrated Products [16], was used.

This paper is focused on the design of multifunction filters with two transconductance amplifiers. These filters are often appropriate for signal processing in the analog sections of data communication systems, in cable modems, in hard–drive communication interfaces or in piezoresistive pressure sensors.

2 Balanced Output Transconductance Amplifier and Universal Current Conveyor

Operational transconductance amplifiers with a single output (OTA) were

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made commercially available for the first time in 1969 by RCA. In 1985 R. L. Geiger and E. Sánchez–Sinencio published an article [4], where they presented to wide community the new CMOS OTA architectures and new frequency filter circuits using the new active element. The endeavour of designers to reduce the number of active elements and thus also the size of the chip led to the development of operational transconductance amplifiers with balanced current outputs – BOTA [5, 14].

For the realization of multifunction filters the current conveyors can be used as well. The first–generation current conveyors were presented by Sedra and Smith in 1968 [3]. Since then more types of current conveyors have successively been designed [8]. In 2000 at our workplace and in collaboration with AMI Semiconductor Design Centre Brno the UCC (Universal Current Conveyor) was designed and developed in the CMOS 0.35 μm technology [3, 7], under the designation UCC–N1B. The UCC helps to realize all existing types of current conveyors of all generations such as CCI+/–, CCII+/–, CCIII+/–, ICCI+/–, ICCII+/–, ICCIII+/– and other types, e.g. DVCC and DDCC.

For experiments, the only commercially available BOTA element is the MAX435 [16] circuit. The BOTA circuit can be replace of with UCC. A possible technique of substituting for BOTA is shown in Fig. 1.

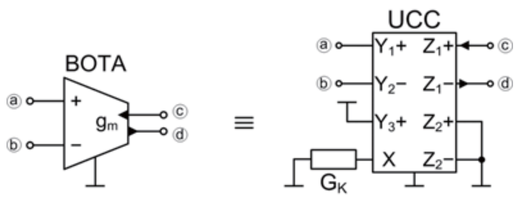

Fig. 1. Equivalent circuits.

For this element it holds:

$$I_a = I_b = 0, \text{ and } I_c = -I_d = g_{\mathrm{m}}(V_{\mathrm{p}} - V_{\mathrm{n}}), \tag{1}$$

where g_{m} is the transconductance. For equivalency it must hold $g_{\mathrm{m}} = G_{\mathrm{K}}$. The method for the transformation of a multifunction filter using BOTA into the equivalent UCC–based multifunction filter is shown in Chapt. 3.

3 Current– and Voltage–Mode Multifunction Frequency Filter Using BOTA and UCC

In the realization of filters, emphasis is on their maximum simplicity. Advantageous filters are those which have as many grounded passive elements as possible, because of the integration of circuits. The proposed current– and voltage–mode multifunction frequency filter shown in Table I matches these requirements. The complex voltage and current transfer functions of the proposed filter with driving voltages V_{IN1}, V_{IN2}, V_{IN3} and current I_{IN} are also shown in Table I.

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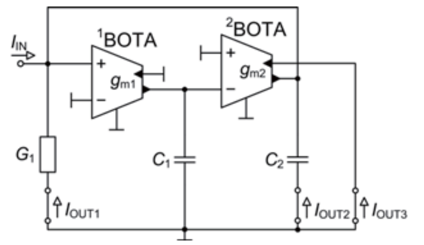
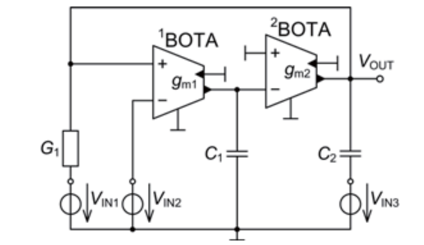
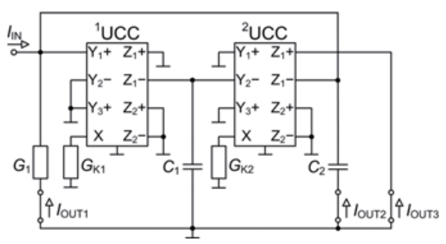
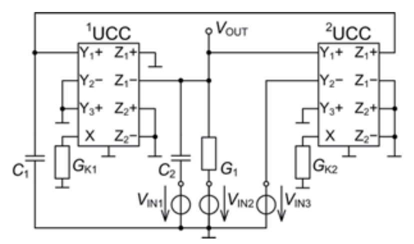
Table I. Current– and Voltage–Mode Multifunction Frequency Filters Using BOTA and its Equivalent Multifunction Frequency Filters Using UCC.

Current–mode multifunction filter using BOTA.	Voltage–mode multifunction filter using BOTA.
	

Filter Type	Low–pass	Band–pass	High–pass
Current–mode	$\frac{I_{OUT3}}{I_{IN}} = -\frac{g_{m1}g_{m2}}{\boldsymbol{D}}$	$\frac{I_{OUT1}}{I_{IN}} = -\frac{sC_1G_1}{\boldsymbol{D}}$	$\frac{I_{OUT2}}{I_{IN}} = -\frac{s^2C_1C_2}{\boldsymbol{D}}$
Voltage–mode	$\frac{V_{OUT}}{V_{IN2}} = \frac{g_{m1}g_{m2}}{\boldsymbol{D}}$	$\frac{V_{OUT}}{V_{IN1}} = \frac{sC_1G_1}{\boldsymbol{D}}$	$\frac{V_{OUT}}{V_{IN3}} = \frac{s^2C_1C_2}{\boldsymbol{D}}$

$$\boldsymbol{D} = s^2C_1C_2 + sC_1G_1 + g_{m1}g_{m2} \tag{2}$$

Equivalent current–mode multifunction filter using UCC.	Equivalent voltage–mode multifunction filter using UCC.
	

Filter Type	Low–pass	Band–pass	High–pass
Current–mode	$\frac{I_{OUT3}}{I_{IN}} = -\frac{G_{K1}G_{K2}}{\boldsymbol{D}}$	$\frac{I_{OUT1}}{I_{IN}} = -\frac{sC_1G_1}{\boldsymbol{D}}$	$\frac{I_{OUT2}}{I_{IN}} = -\frac{s^2C_1C_2}{\boldsymbol{D}}$
Voltage–mode	$\frac{V_{OUT}}{V_{IN3}} = \frac{G_{K1}G_{K2}}{\boldsymbol{D}}$	$\frac{V_{OUT}}{V_{IN2}} = \frac{sC_1G_1}{\boldsymbol{D}}$	$\frac{V_{OUT}}{V_{IN1}} = \frac{s^2C_1C_2}{\boldsymbol{D}}$

$$\boldsymbol{D} = s^2C_1C_2 + sC_1G_1 + G_{K1}G_{K2}$$

$$G_{K1} = G_{K2} = \omega_0\sqrt{C_1C_2}\ ,\ G_1 = \frac{\omega_0 C_2}{Q_0}$$

In both the current and the voltage modes the circuit can be used as a low–pass, band–pass and high–pass filter.

The characteristic frequency and the quality factor of these filters are:

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}, \tag{3}$$

$$Q_0 = \frac{1}{G_1}\sqrt{\frac{g_{m1}g_{m2}C_2}{C_1}}. \tag{4}$$

For the required values Q_0, ω_0, and the chosen values C_1 and C_2 we can

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determine the other parameters necessary for the design:

$$g_{m1} = g_{m2} = \omega_0\sqrt{C_1C_2}, \tag{5}$$

$$G_1 = \frac{\omega_0 C_2}{Q_0}. \tag{6}$$

All filters have in their denominator the same left side of characteristic Eq. (2) of the circuit function and the characteristic frequency, quality factor and relevant relative sensitivities are identical for all types of filters. The relative sensitivities of characteristic frequency and quality factor are the following:

$$-\mathrm{S}^{\omega_0}_{\mathrm{C}_1} = -\mathrm{S}^{\omega_0}_{\mathrm{C}_2} = \mathrm{S}^{\omega_0}_{\mathrm{gm1}} = \mathrm{S}^{\omega_0}_{\mathrm{gm2}} = \frac{1}{2}, \quad \mathrm{S}^{\omega_0}_{\mathrm{G}_1} = 0, \tag{7}$$

$$-\mathrm{S}^{Q_0}_{\mathrm{C}_1} = \mathrm{S}^{Q_0}_{\mathrm{C}_2} = \mathrm{S}^{Q_0}_{\mathrm{gm1}} = \mathrm{S}^{Q_0}_{\mathrm{gm2}} = \frac{1}{2}, \quad \mathrm{S}^{Q_0}_{\mathrm{G}_1} = -1. \tag{8}$$

From the results it is evident that the sensitivities of the circuit are low. Potential deviations, which occur in manufacturing, can be compensated by changing the values of transconductance g_m by the driving current I_{SET}.

For the demonstration of the equivalence of BOTA and UCC the current– and voltage–mode multifunction filter presented in Table I was chosen. The equivalent current– and voltage–mode multifunction filter using UCC is also shown in Table I. For the current–mode multifunction filter its adjoint voltage–mode filter was derived. The adjoint counterpart of the original UCC is again UCC, in which the following changes were made: Y+ ↔ Z− and Y− ↔ Z+. Here the symbol ↔ means that it is necessary to perform the indicated interchanges of gates, i. e. in place of Y+ it is necessary to consider Z− and vice vesa or in place of Y− to consider Z+ and vice vesa. The primary parameters, i. e. characteristic equation, complex voltage and current transfer functions of the proposed filter with driving voltages V_{IN1}, V_{IN2}, V_{IN3} and current I_{IN} are also shown in Table I.

The filter example was designed for the characteristic frequency $f_0 \approx 1\,\mathrm{MHz}$ and the quality factor $Q_0 = 0.707$ based on the Butterworth approximation [2]. Capacitors $C_1 = 1\,\mathrm{nF}$ and $C_2 = 470\,\mathrm{pF}$ were chosen. Other parameters are: $g_{m1} = g_{m2} = G_{K1} = G_{K2} = 4.18\,\mathrm{mA/V}$, and $R_1 = 240\,\Omega$. For computer simulation the MAX435 [16] company models and a 3rd–level model of UCC–N1B [11] were used in the OrCAD software [15]. The comparison of the characteristics of a filter using these elements is shown in Fig. 2 (a) and (b). From the results it is evident that when using MAX435 the results are closer to the ideal curves than when using UCC–N1B.

4 Experimental Results

The current–mode second–order low–pass, band–pass and high–pass filters were chosen for the implementation presented in Table I. The characteristic frequency $f_0 \approx 1\,\mathrm{MHz}$ and quality factor $Q_0 = 0.707$ based on the Butterworth approximation [2] were chosen in the implementation of the filters. Capacitors $C_1 = 1\,\mathrm{nF}$ and $C_2 = 470\,\mathrm{pF}$, resistor $R_1 = 1/G_1 = Q_0/(\omega_0 C_2) =$

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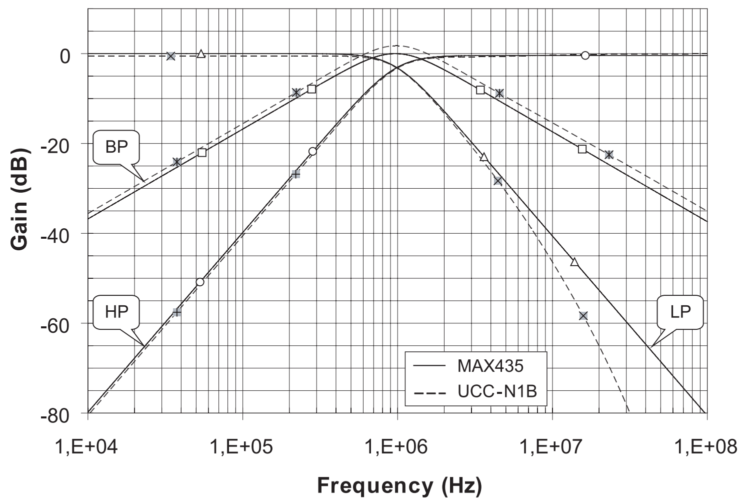
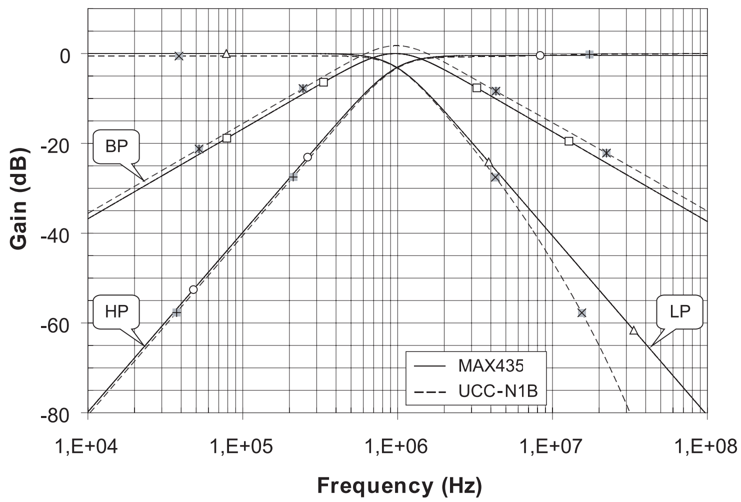
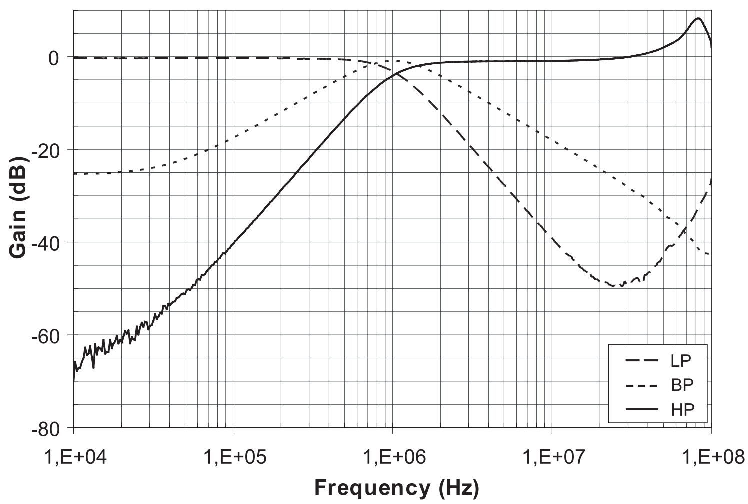


a)



b)



c)

Fig. 2. Frequency characteristics of simulation a) current–, b) voltage-mode multifunction filters shown in Table I using MAX435 and UCC, c) measured frequency responses of current–mode second–order multifunction filter using MAX435.

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$240\,\Omega$ and transconductance $g_{\mathrm{m1}} = g_{\mathrm{m2}} = \omega_0\sqrt{C_1C_2} = 4.18\,\mathrm{mA/V}$ were used in the realization of the filters.

The measurement was carried out with an HP3589A network/spectrum analyzer connected to computer via the GPIB bus system. We used a voltage–to–current and a current–to–voltage converter using OPA860 [11]. These converters have a bandwidth of ca. 100 MHz, that is why the experimental results are presented only up to this frequency region. The frequency responses measured for the second–order low–pass, band–pass and high–pass filters are given in Fig. 2 (c). The results of measurement are in agreement with the simulations.

5 Conclusion

In the paper, a new circuit of multifunction filter with two BOTA elements is presented. The transformation of multifunction filter using BOTA into equivalent UCC–based multifunction filter is shown as well. The UCC was designed at our workplace and developed in the CMOS 0.35 μm technology in the AMI Semiconductor Design Centre Brno. It turned out that the replacement of MAX435 element by UCC–N1B is fully–fledged, which demonstrates the wide usage of this element. For the simulation of a specific filter solution the OrCAD software [15], the MAX435 [16] company models and 3^{rd}–level model of UCC–N1B [11] were used. The designed second–order multifunction filters were measured experimentally.

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