A New Current Mode SIMO-Type Universal Biquad Employing Multi-Output Current Conveyors (MOCCIIs)

Chunhua WANG, Yan ZHAO, Qiujing ZHANG, Sichun DU

School of Computer and Communication, Hunan University, Changsha, 410082, Hunan, P.R.China

wch1227164@sina.com, zhaoy1983@foxmail.com, clare014201@hotmail.com, d_sc@sina.com

Abstract. *This study presents a new current-mode single-input and multi-output (SIMO) type universal biquad circuit using second generation multi-output current conveyors (MOCCII) as the active components. The proposed circuit employs three MOCCIIs, two grounded capacitors and four grounded resistors, therefore offers electroning tuning possibilities. It can simultaneously realize second order low-pass, band-pass, high-pass, notch and all-pass filters. The circuit is cascadable and has low sensitivities. It provides independent control of* ω_0 *(natural angular frequency) and Q (quality factor). The influences of MOCCII parasitic elements have been analyzed and simulated using PSPICE. Experimental results including frequency responses of low-pass, high-pass, band-pass and band-stop filters, as well as frequency responses of filters with different* ω_0 *(keeping Q invariable) and different Q (keeping* ω_0 *invariable) are shown to be in agreement with theory.*

Keywords

Current conveyor, current-mode circuit, filter.

1. Introduction

Second generation current conveyor (CCII) element which has a single current output terminal is one of the versatile active building blocks to construct continuous-time universal and multipurpose filters, and many of these filters have been reported in literature [1-5]. However, there are two basic shortcomings of such filters: (1) They can not provide feedforward and feedback currents at the same time; (2) The circuits are rather complex. In order to overcome such problems, some authors attempt to design multipurpose and universal filters using other types of active components [6-20]. On the other hand, a modified CCII, so called multi-output current conveyor (MOCCII) circuit was presented by Pal K [21]. It should be noted here that, a MOCCII element can be realized by copying the output current of an ordinary CCII using current mirroring transistors for its positive output terminals, while its negative terminals can be designed by inverted current mirrors which provide negative copies of the output current of the basic CCII element. Various filters based on MOCCII have already been presented in electronics literature [22-29].

In general, multi-purpose and universal filters can be classified either as multi-input and single-output (MISO) filter [23], [28], [30-33] or single-input and multi-output (SIMO) filter [24-29]. The MISO current-mode filters have rather simple structures. However, by the virtue of their construction, they can not realize multiple outputs at the same time, while MOCCII -SIMO type current-mode filters can realize low-pass (LP), band-pass (BP), high-pass (HP), band-stop (BS) and all-pass (AP) filters simultaneously. Current-mode MOCCII-based SIMO filters in references [24-25], [27] do not provide independent control of natural angular frequency and the Q-factor.

In this paper, a novel current-mode SIMO second-order filter based on MOCCII is proposed. It has only three MOCCIIs and six RC elements, and it can realize LP, BP, HP, BS and AP filters at the same time. The natural frequency and quality factor can be tuned independently, and all of the passive elements are grounded.

2. The Proposed Circuit

The circuit symbol of MOCCII is shown in Fig.1 where terminal Y behaves as a voltage signal input, terminal X behaves as voltage track, z_1~z_n are non-inverting outputs, and z_{1-} ~ z_{m-} are inverting outputs. Its ideal port characteristics can be expressed as:

$$i_y = 0, \quad v_x = v_y,$$
$$i_{z1+} = i_{z2+} = \ldots = i_{zn+} = -i_{z1-} = -i_{z2-} = \ldots = -i_{zm-}\,. \quad (1)$$

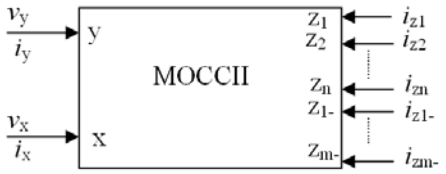

Fig. 1. Circuit symbol of MOCCII.

The proposed SIMO current-mode second-order filter is shown in Fig. 2. I_{in} is input current and I_{o1}~I_{o5} are the output currents. The filter is configured by three MOCCII and two grounded capacitors and four grounded resistors.

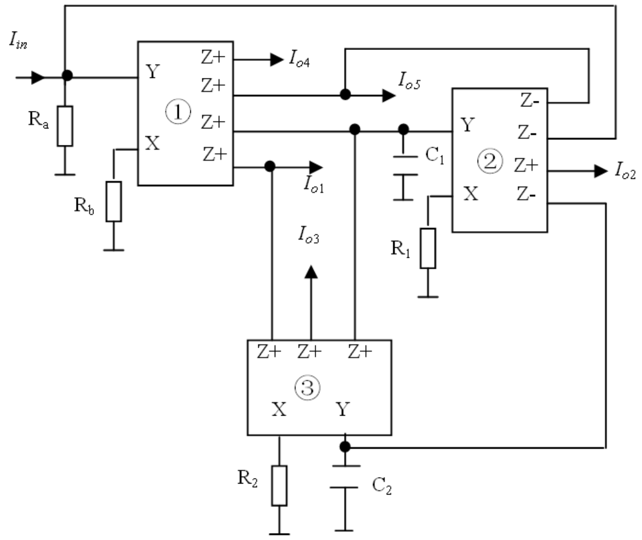

Fig. 2. Proposed current mode filtering circuits with single input and three outputs

Analysis of Fig. 2 yields the following current transfer functions:

$$T_{HP}(s)=\frac{I_{o1}}{I_{in}}=\frac{R_a}{R_b}\frac{s^2R_1R_2C_1C_2}{s^2R_1R_2C_1C_2+sR_2C_2(R_a/R_b)+1}, \quad (2)$$

$$T_{BP}(s)=\frac{I_{o2}}{I_{in}}=\frac{R_a}{R_b}\frac{sR_2C_2}{s^2R_1R_2C_1C_2+sR_2C_2(R_a/R_b)+1}, \quad (3)$$

$$T_{LP}(s)=\frac{I_{o3}}{I_{in}}=\frac{R_a}{R_b}\frac{-1}{s^2R_1R_2C_1C_2+sR_2C_2(R_a/R_b)+1}, \quad (4)$$

$$T_{BS}(s)=\frac{I_{o4}}{I_{in}}=\frac{R_a}{R_b}\frac{s^2R_1R_2C_1C_2+1}{s^2R_1R_2C_1C_2+sR_2C_2(R_a/R_b)+1}, \quad (5)$$

$$T_{AP}(s)=\frac{I_{o5}}{I_{in}}=\frac{R_a}{R_b}\frac{s^2R_1R_2C_1C_2-sR_2C_2+1}{s^2R_1R_2C_1C_2+sR_2C_2(R_a/R_b)+1}. \quad (6)$$

From these equations it is clear that I_{o1} is High Pass output current, I_{o2} is Band Pass output current, I_{o3} is Low Pass output current, I_{o4} is Band Stop output current and I_{o5} is All Pass output current (R_a=R_b). Natural angular frequency (ω_0) and quality factor (Q) are related as:

$$\omega_0=\sqrt{\frac{1}{R_1R_2C_1C_2}}, Q=\frac{R_b}{R_a}\sqrt{\frac{R_1C_1}{R_2C_2}}. \quad (7a, 7b)$$

In equation (7), R_a and R_b are not included in the expression of ω_0. Thus, ω_0 is not influenced when R_a and R_b are adjusted to vary Q. While keeping ratio R_1C_1/R_2C_2 equal, changing R_1 and R_2 simultaneously can produce Q-independent tuning of ω_0. Therefore, ω_0 and Q are tuned independently.

The component sensitivities are computed according to $S_x^y=(x/y)\cdot(\partial y/\partial x)$ as $S_{G_{m1},G_{m2}}^{\omega_0}=-S_{C_1,C_2}^{\omega_0}=1/2$, $S_{G_{m2},C_1}^{Q}=-S_{G_{m1},C_2}^{Q}=1/2$

$S_{G_a}^{Q}=-S_{G_b}^{Q}=1$.

It can be noted here that the passive sensitivities of the proposed circuit are small.

In order to calculate active sensitivities of the filter, we must calculate out transfer function using non-ideal characteristic of MOCCII. In non-ideal characteristic condition, the port characteristics of MOCCII are

$$\begin{aligned} &i_y=0, \quad v_x=v_y, \\ &i_{z1+}=i_{z2+}=\ldots=i_{zn+}=+\beta_p i_x, \\ &i_{z1-}=i_{z2-}=\ldots=i_{zm-}=-\beta_n i_x \end{aligned} \quad (8)$$

where $\alpha=1-\varepsilon_v$, ε_v ($|\varepsilon_v|$«1) is voltage tracking error of the voltage tracking terminal; $\beta_p=1-\varepsilon_p$, ε_p ($|\varepsilon_p|$«1) is current tracking error of non-inverting output terminals, $\beta_n=1-\varepsilon_n$, ε_n ($|\varepsilon_n|$«1) is current tracking error of inverting output terminals.

Analysis of the circuit in Fig. 2 under these conditions yields the non-ideal natural frequency and quality factor as (9):

$$\omega_{0n}=\sqrt{\frac{\alpha_2\alpha_3\beta_{p2}\beta_{p3}\beta_{n2}}{R_1R_2C_1C_2}}, \quad (9a)$$

$$Q_n=\frac{R_b}{\alpha_1\beta_{p1}R_a}\sqrt{\frac{\alpha_3\beta_{p3}}{\alpha_2\beta_{p2}\beta_{n2}}\frac{R_1C_1}{R_2C_2}}. \quad (9b)$$

where α_i, β_{pi}, β_{ni} are the α, β_p, β_n of the *i*th MOCCII.

The active sensitivities of ω_{0n} and Q_n can be calculated as below:

$$S_{\alpha_2,\alpha_3,\beta_{p2},\beta_{p3},\beta_{n2}}^{\omega_{0n}}=\frac{1}{2}, S_{\alpha_1,\beta_{p1},\beta_{n1},\beta_{n3}}^{\omega_{0n}}=0. \quad (10)$$

$$S_{\alpha_1,\beta_{p1}}^{Q_n}=-1, S_{\alpha_3,\beta_{p3}}^{Q_n}=-S_{\alpha_2,\beta_{p2},\beta_{n2}}^{Q_n}=\frac{1}{2}, S_{\beta_{n1},\beta_{n3}}^{Q_n}=0. \quad (11)$$

From equations (10), (11) we can see that the proposed circuit has small active sensitivities.

3. Influence of MOCCII Parasitic Elements

The nonideal CCII model [34] is shown in Fig. 3.

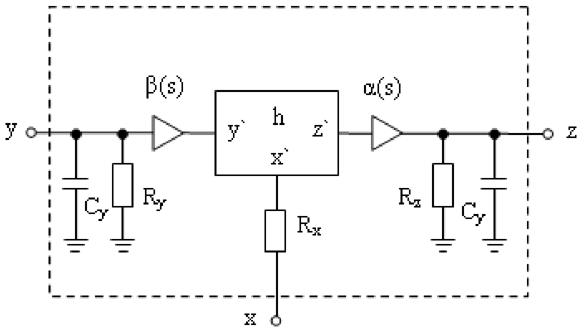

Fig. 3. Nonideal CCII with its parasitic resistors and capacitors.

The real CCII has parasitic resistors and capacitors from the y and z terminals to the ground, and a serial resistor at the input terminal x. $\alpha(s)$ and $\beta(s)$ are used to represent the frequency transfers of the internal current and voltage followers of the CCII, respectively, and they are considered as 1 here.

As in a nonideal MOCCII, parasitic resistors and capacitors of all the z+, z- terminals have almost the same values respectively, so assuming that they all equal to R_z and C_z.

To study the influence of parasitic elements in MOCCII, the proposed filter shown in Fig. 2 can be transformed to Fig. 4.

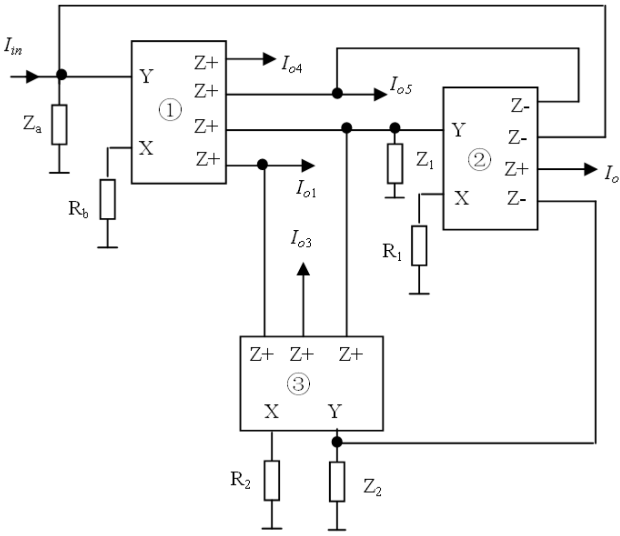

Fig. 4. The proposed filter including the parasitic elements of the MOCCIIs.

We define R_{z1}, R_{z2}, R_{z3}, C_{z1}, C_{z2}, C_{z3} as the parasitic resistors and capacitors of the z terminals of MOCCII①②③ in Fig. 4, and R_{y1}, R_{y2}, R_{y3}, C_{y1}, C_{y2}, C_{y3} as the parasitic resistors and capacitors of the y terminals of MOCCII①②③, respectively.

Assuming that $\min(C_1,C_2) >> (C_{y1}+C_{y2}+C_{y3}+C_{z1}+C_{z2}+C_{z3})$, and $R_a << R_z$, we can get that

$$Z_a = [R_a // R_{Z2}]//[C_{y1} // C_{z2}] \approx \frac{R_a}{1+s(C_{y1}+C_{z2})R_a}, \quad (12)$$

$$Z_1 = [R_{z1} // R_{z3}]//[C_1 // C_{z1} // C_{z3} // C_{y2}] \approx \frac{R_{z13}}{1+sC_1R_{z13}}, \quad (13)$$

$$Z_2 = [C_2 // C_{y3} // C_{z1}]//[R_{z2}] \approx \frac{R_{z2}}{1+sC_2R_{z2}}. \quad (14)$$

where $R_{z13}=R_{z1}//R_{z3}=R_{z1}/2=R_{z2}/2=R_{z3}/2$, $C_{yz}=C_y//C_z$. So from Fig. 4 we can get the following functions:

$$\begin{aligned}\frac{I_{o1}}{I_{in}} &= \frac{Z_aR_1R_2}{Z_aR_2Z_1+Z_2R_bZ_1+R_1R_2R_b}\\ &= \frac{R_aR_1R_2(1+sC_2R_{z2})(1+sC_1R_{z13})}{D(s)},\end{aligned} \quad (15)$$

$$\begin{aligned}\frac{I_{o2}}{I_{in}} &= \frac{Z_aR_2Z_1}{Z_aR_2Z_1+Z_2R_bZ_1+R_1R_2R_b}\\ &= \frac{R_aR_{z13}R_2(1+sC_2R_{z2})}{D(s)},\end{aligned} \quad (16)$$

$$\begin{aligned}\frac{I_{o3}}{I_{in}} &= \frac{-Z_aZ_1Z_2}{Z_aR_2Z_1+Z_2R_bZ_1+R_1R_2R_b}\\ &= \frac{-R_aR_{z13}R_{z2}}{D(s)},\end{aligned} \quad (17)$$

$$\begin{aligned}\frac{I_{o4}}{I_{in}} &= \frac{Z_aR_1R_2+Z_aZ_1Z_2}{Z_aR_2Z_1+Z_2R_bZ_1+R_1R_2R_b}\\ &= \frac{R_aR_1R_2(1+sC_2R_{z2})(1+sC_1R_{z13})+R_aR_{z13}R_{z2}}{D(s)},\end{aligned} \quad (18)$$

$$\begin{aligned}\frac{I_{o5}}{I_{in}} &= \frac{Z_aR_1R_2+Z_aZ_1Z_2-Z_aR_2Z_1}{Z_aR_2Z_1+Z_2R_bZ_1+R_1R_2R_b}\\ &= \frac{R_aR_1R_2(1+sC_2R_{z2})(1+sC_1R_{z13})-sC_2R_{z2}R_aR_{z13}R_{z2}}{D(s)}.\end{aligned} \quad (19)$$

where

$$\begin{aligned}D(s) &= R_aR_2R_{z13}(1+sC_2R_{z2})+R_{z2}R_bR_{z13}(1+sC_{yz}R_a)\\ &\quad +R_1R_2R_b(1+sC_{yz}R_a)(1+sC_1R_{z13})(1+sC_2R_{z2})\end{aligned} \quad (20)$$

$$\begin{aligned}&= s^2(C_1C_{yz}R_1R_2R_aR_bR_{z13}+2C_1C_2R_1R_2R_bR_{z13}^2\\ &\quad +2C_2C_{yz}R_1R_2R_aR_bR_{z13}+s2C_1C_2C_{yz}R_1R_2R_aR_bR_{z13}^2)\\ &\quad +s(C_1R_1R_2R_bR_{z13}+C_{yz}R_1R_2R_aR_b+2C_2R_1R_2R_bR_{z13}\\ &\quad +2C_2R_2R_aR_{z13}^2+2C_{yz}R_aR_bR_{z13}^2)\\ &\quad +(R_1R_2R_b+R_2R_aR_{z13}+2R_bR_{z13}^2),\end{aligned}$$

so

$$\omega_0' = \sqrt{\frac{1}{C_1C_2R_1R_2}} \bullet \sqrt{\frac{R_1R_2R_b/R_{z13}^2+R_2R_a/R_{z13}+2R_b}{R_aR_bC_{yz}/(C_2R_{z13})+2R_b+2C_{yz}R_aR_b/(C_1R_{z13})+s2C_{yz}R_aR_b}}, \quad (21)$$

$$Q' = \frac{R_b}{R_a}\sqrt{\frac{R_1C_1}{R_2C_2}} \bullet \frac{\sqrt{C_{yz}R_a/(C_2R_{z13})+2+2C_{yz}R_a/(C_1R_{z13})+s2C_{yz}R_a}\sqrt{R_1R_2/R_{z13}^2+R_2R_a/(R_bR_{z13})+2}}{C_1R_1R_b/(C_2R_aR_{z13})+C_{yz}R_1R_b/(C_2R_{z13}^2)+2R_1R_b/(R_aR_{z13})+2+2C_{yz}R_b/(R_2C_2)}. \quad (22)$$

For the value of C_{yz} is smaller than 10 pF and that of R_{z13} is larger than 1 MΩ, so C_1, C_2, R_1, R_2 are chosen under the following relations: $C_{yz} << \min(C_1, C_2)$, $R_{z13} >> \max(R_1, R_2)$. Therefore we can get

$$\omega_0' \approx \omega_0 \frac{1}{\sqrt{1+\omega^2 C_{yz}^2 R_a^2 R_b^2}}, \tag{23}$$

$$Q' \approx Q\sqrt{1+\omega^2 C_{yz}^2 R_a^2}\,. \tag{24}$$

From (23) and (24), it is clear that when considering influence of parasitic elements, the natural angle frequency is less than the one in ideal condition, namely $\omega_0`<\omega_0$, and the quality factor is higher than that in the ideal one $(Q`>Q)$.

If $\omega C_{yz} R_a R_b << 1$, so $\omega C_{yz} R_a << 1$, the influence of non-ideal characteristics of MOCCII can be ignored.

The influence of parasitic elements to the proposed filter is simulated by PSPICE. The CMOS MOCCII circuit used in the simulation was reported in [35].

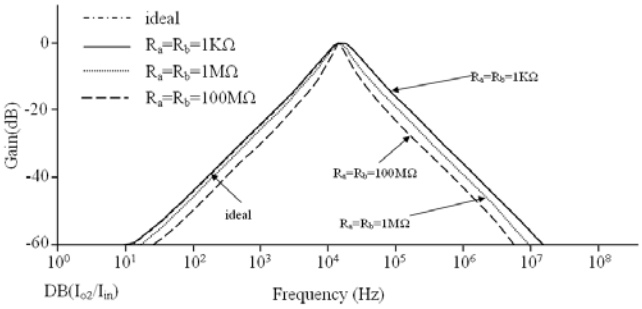

Fig. 5. Simulation results of the influence of parasitic elements to the proposed filter.

It can be seen from Fig. 5 that in the proposed filter, the parasitic elements have some influences on the ω_0 and Q. When R_a and R_b are chosen with very large numerical value (e.g. $R_a=R_b=100$ MΩ), the Q is slightly higher than the one in ideal condition, and the ω_0 is slightly lower than the one in ideal condition. When $\omega C_{yz} R_a R_b << 1$ (e.g. $R_a=R_b=1$ kΩ as shown in Fig. 5), the MOCCII can be seen as an ideal one. The simulation results are well conformed to the theory analysis.

4. Experimental Results

In order to check the validity of the theory described above, laboratory experiments were performed using conventional lab equipment (Oscilloscope: HM1507-3 100MHz Hameg, signal generator, HP3326A). In these experiments, the MOCCII circuit shown in Fig. 6 was adopted from [36]. TEC9014C and TEC9015C bipolar junction transistors (Toshiba Inc., Japan) were used as NPN and PNP transistors, respectively. IC LF351 (National Semiconductor, USA) was used for the op-amp.

When $R_a=R_b=1$ kΩ, $R_1=R_2=1$ kΩ, $C_1=C_2=10$ nF in Fig. 2, we measured the natural frequency as $f_0 \approx 159$ kHz. The measured results are shown in Fig. 7, where "▲", "■", "●", "▼"denote results of LP, HP, BP and BS filters respectively. From Fig. 6, the natural frequency is about 159 kHz.

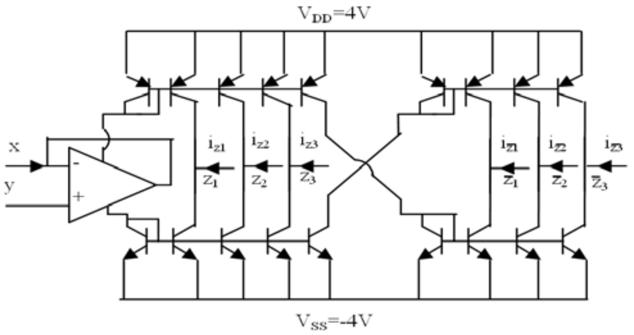

Fig. 6. Realization circuit of MOCCII.

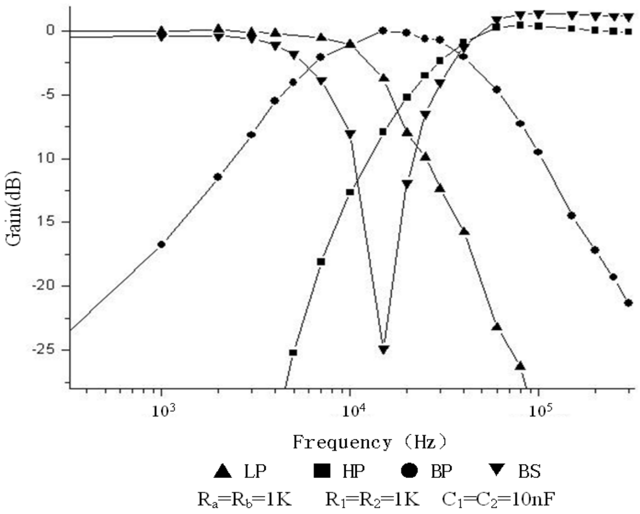

Fig. 7. Measurement results of frequency responses in Fig. 2.

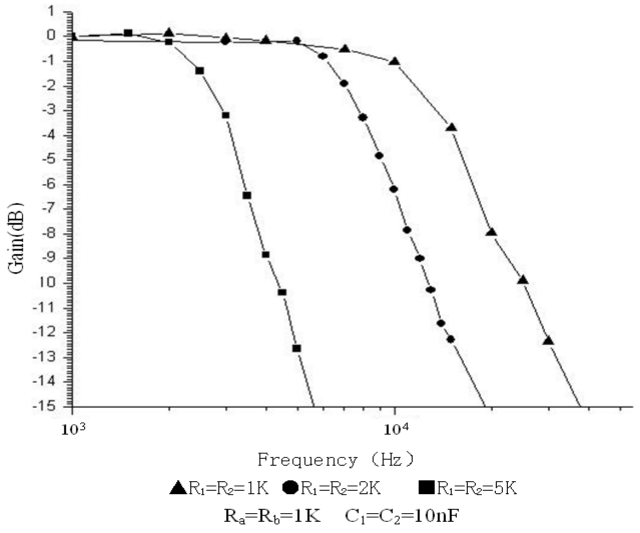

Fig. 8. Measurement results of frequency response of LP filter with different ω_0 (keeping Q invariant).

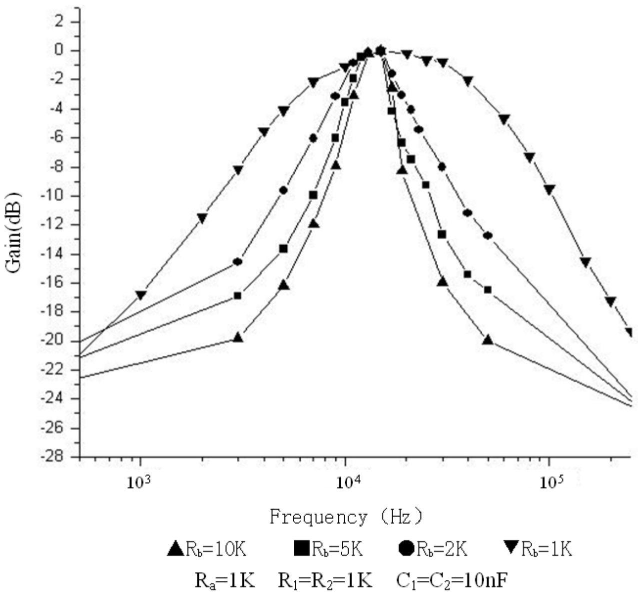

Fig. 9. Measurement results of frequency response of LP filter with different Q (keeping ω_0 invariant).

To verify whether the filter can be independently tuned, we measured the frequency-response under different natural frequencies and quality factors. While keeping R_a, R_b, C_1, C_2 fixed and adjusting R_1 and R_2, we obtained the measurement results of LP filter's frequency response, as shown in Fig. 8. In Fig. 8 quality factor Q is fixed and natural frequency ω_0 is changed. While keeping R_a, R_1, R_2, C_1, C_2 constant and adjusting R_b, we get the measurement results of BP filter's frequency response, as shown in Fig. 9. In Fig. 9 natural frequency ω_0 is kept constant and quality factor Q is changed.

5. Conclusion

In this paper, a new single-input and multi-output current-mode universal second-order filter circuit is proposed and its experimental performance results are given. The influences of MOCCII parasitic elements have been analyzed and simulated using PSPICE. It is noted that experimental observations are in good agreement with theory.

This universal current mode biquad circuit provides the following advantages:

(i) The filter has only three MOCCIIs and six RC elements; (ii) The circuit has universal character; it can simultaneously realize second-order low-pass, band-pass, high-pass, band-stop and all-pass filters; (iii) Natural frequency and quality factor can be tuned independently; (iv) All of the passive elements are grounded (electronic tuning may be possible); (v) The circuit sensitivities are very small, (vi) The circuit is cascadable.

These results indicate that the proposed circuit can particularly be useful in continuous time current mode universal filtering applications.

Acknowledgements

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About Authors...

Chunhua WANG was born in Yongzhou, China, in 1963. He received the B.Sc degree from Hengyang Teacher's College, Hengyang, China, in 1983, the M.Sc degree from Physics Department, Zhengzhou University, Zhengzhou, China, in 1994, the Ph.D. degree from the School of Electronic Information and Control Engineering, Beijing University of Technology, Beijing, China. He is currently a Professor of the School of Computer and Communication, Hunan University, Changsha, China. From 2004 to 2005, he served as a Professor and the associate Dean of Information Engineering School, Xiangtan University, Xiangtan, China. His research interests include current-mode circuit design, filtering, radio frequency circuit and wireless communications

Yan ZHAO was born in Luoyang, Henan, China, in 1983. He received the B.Sc. from the School of Computer and Communication, Hunan University, in 2006. He is studying in Hunan University for master degree now. He is interested in analog IC circuit and filter design.

Qiujing ZHANG was born in Jishou, Hunan, China, in 1982. She received the B.Sc. from the School of Computer and Communication, Changsha University of Science and technology. She is studying in Hunan University for doctor degree now. She is interesting in analog IC circuit and filter design.

Sichun DU (S'02–SM'05) received the M.E. degree in Computer Application Technology from Hunan University, Changsha, China. Since July 2002, he has been with the School of Computer and Communication, Hunan University, where he is currently a lecturer, and the deputy director for computing centre. His current research interests include design and simulation of RF CMOS integrated circuits and mixed analog–digital circuits .