Electronically Tunable Multiple-Input Single-Output Voltage-Mode Multifunction Filter Using OTA and DURC

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Abstract: This paper presents the design method for multifunction filter circuit. The characteristics of filter (low-pass, high-pass, band-pass, band reject filter, and all-pass) can be obtained without changing circuit topology. Its scheme is principally composed of passive element using double capacitive layers uniform distributed RC (DURC) and active element using operational transconductance amplifier (OTA). The frequency response of filter circuit can be adjusted by the transconductance gains of OTA without affecting the circuit's quality factor (Q). The performance of the proposed filter circuit was simulated by PSpice. Its simulation results were performed for the low-voltage power supply with only plus/minus 2VDC. In addition, the circuit is advantage that there are good magnitude response and low sensitivities of less than one unit. The simulation results of circuit are in good agreement with the theoretical calculations. The proposed filter circuit is very suitable to further develop into a VLSI circuit for communication and signal processing system.

Keywords-- **voltage-mode, universal filter, OTA, DURC, magnitude response**

1. Introduction

Many researches of universal biquadratic filter circuits using active-RC elements base on op-amp device and uniform distributed RC device have been reported in the literature [1]–[4]. Although, the op-amp active device have been used to construct numerous electronic circuits, they exhibit various disadvantages of circuits, including complex circuitry, excessive passive device components for realizing the op-amp based application circuits and the lack of an electronic tuning function. In addition, they are unsuitable for use in high-speed applications because the op-amp device is characterized by constant gain bandwidth production and low slew-rate [5] operation.

This paper presents the design method for universal biquadratic filter circuit using active and passive elements base on operational transconductance amplifier (OTA) and double capacitive layers uniform distributed RC (DURC). The OTA have exhibited some advantages in the filter circuit design for example, provides an electronic tunability, a wide tunable range, and powerful ability to generate various circuits [6]. A uniform distributed RC (URC) passive device has several inherent advantages over passive lumped RC element network. First, from a network theory viewpoint, a distributed network is more general and versatile than a lumped RC element one. A network composed of the URC structures can realize either an infinite number of poles and zeros, or a finite number of poles and zeros exactly as a lumped RC network. Second, the URC implementations consist of structures that contain both the resistance and capacitance needed for active filters. Since the distributed resistance and capacitance are physically co-located, the area needed to realize RC products is in many circumstances reduced, saving fabrication costs. Third, many passive lumped RC implementations have distributed parasitic capacitances and resistances that are not always negligible. Whether a parallel plate capacitor is implemented in thin-film or metal-oxide semiconductor (MOS) device technology, the resistance of the plates is nonzero and may degrade circuit performance in some instances. Such a distributed resistance makes the capacitor appear as a URC structure. Similarly, a resistance structure in many technologies will have a distributed capacitance to another circuit node. Rather than considering distributed effects as no idealities in the various implementations, they can be incorporated into the synthesis process and used to advantage [7]-[8]. Now the URC passive element has many form structure in capacitive layer for example, single capacitive layer [9]-[10], double capacitive layers [11]-[12], and multi-capacitive layers [13]-[14].

This paper introduces the universal biquadratic filter circuit uses only two DURCs and five OTAs, which are suitable for integrated circuit implementation. . The circuit needs neither an inverting type voltage input signal nor any critical component matching conditions, using low-voltage power supply (±2V), allowing adjustments of frequency response filter by the OTA transconductance gains without affecting the circuit's quality factor, and the circuit has low active and passive sensitivities. In addition, the filter circuit can achieve five transfer functions including low-pass filter (LPF), high-pass filter (HPF), band-pass filter (BPF), band reject filter (BRF), and all-pass filter (APF). The circuit simulated results using PSPice.

2. Circuit Implementation and Analysis

2. 1 Double Capacitive Layers Uniform Distributed RC Lines (DURCs)

The double capacitive layers uniform distributed RC lines is circuit symbol illustrated in Fig.1 [15].The admittance parameter [Y_{ij}] equation of DURC with has double capacitive layers in Fig.1 is related by

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} XY & -X & -\alpha X(Y-1) \\ -X & XY & -\alpha X(Y-1) \\ -\alpha X(Y-1) & -\alpha X(Y-1) & \gamma \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{1}$$

when

$$\gamma = \frac{-\alpha X(Y-\alpha)P^2}{XR + 2\alpha^2(Y-1)} \quad X = \frac{P}{R\sinh P}, \quad Y = \cosh P;\ P = \sqrt{sRC}$$

$$C = C_1 + C_2; \quad C_1 = (1-\alpha)C; \quad C_2 = \alpha C$$

where R and C parameters are the value of the total resistance and total capacitance of the DURC, and s parameter is the complex frequency variable.

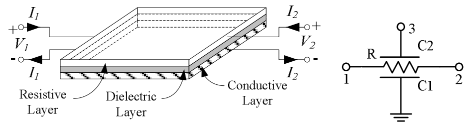

Figure 1. Proposed Circuit

3. Proposed Circuit

Fig.3 shows the proposed circuit of universal biquadratic filter using OTAs and DURCs. It consists of two DURCs and five OTAs. The output of circuit V_{out} is high output impedance which can be interconnecting directly to load. Where V_{in1}, V_{in2}, V_{in3}, and V_{in4} variables are four input voltage, respectively, that setting determine the five filter response function (high-pass, low-pass, band-pass, band reject filter, and all-pass), and V_{out} is the output variable.

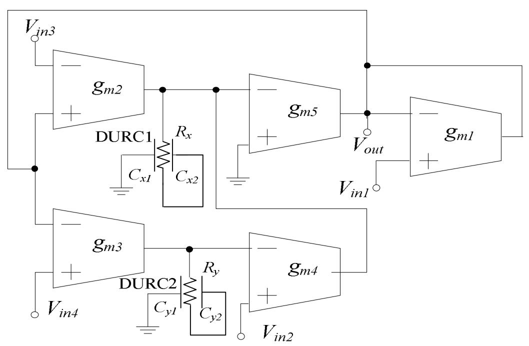

Figure 2. Filter proposed circuit.

From Fig.2 the transfer function of voltage-mode universal biquadratic filter circuit using OTAs and DURCs is given by

$$\frac{V_o}{V_{in}} = -g_{m2}g_{m3}g_{m4}\delta\frac{V_{in1}}{\beta V_{in}} + g_{m2}g_{m4}P_yR_y\sinh P_y(1-\alpha\eta_x)\frac{V_{in2}}{\beta V_{in}} + g_{m3}g_{m5}P_xR_x\frac{V_{in3}}{\beta V_{in}} + g_{m1}g_{m2}g_{m3}P_x[R_x\cosh P_x - \sinh P_x]\frac{V_{in4}}{\beta V_{in}} \tag{2}$$

From Eq. (2) the proposed filter circuit can realize the low-pass filter (LPF), high-pass filter (HPF), band-pass filter (BPF), band reject filter (BRF), and all-pass filter (APF) at the node voltage V_{out}. Where V_{in1}, V_{in2}, V_{in3}, and V_{in4} are four inputs voltage, respectively, that setting determine the filter function as follow:

Case I: Low-pass (LPF) as $V_{in4}=V_{in}$ and $V_{in1}=V_{in2}=V_{in3}=0$. The transfer function $T_{LP}(p)$ of the circuit is given by

$$T_{LP}(p) = \frac{g_{m1}g_{m2}g_{m3}(R_x\cosh P_x - \sinh P_x)}{R_x\cosh P_x\sinh P_x - \delta - 1} \tag{3}$$

Case II: High-pass filter (HPF) as $V_{in1}=V_{in}$ and $V_{in2}=V_{in3}=V_{in4}=0$. The transfer function $T_{HP}(p)$ of the filter circuit is given by

$$T_{HP}(p) = -\frac{g_{m2}g_{m3}g_{m4}(R_x\cosh P_x - \sinh P_x)}{P_xR_x\cosh P_x\sinh P_x - \delta - 1} \tag{4}$$

Case III: Band-pass (BPF) as $V_{in3}=V_{in}$ and $V_{in1}=V_{in2}=V_{in4}=0$. The transfer function $T_{BP}(p)$ of the circuit is given by

$$T_{BP}(p) = \frac{g_{m3}g_{m5}R_x}{R_x\cosh P_x\sinh P_x - \delta - 1} \tag{5}$$

Case IV: Notch filter (NF) as $V_{in1}=V_{in4}=V_{in}$ and $V_{in2}=V_{in3}=0$. The transfer function $T_{RP}(p)$ of the circuit is given by

$$T_{NF}(p) = \frac{g_{m2}g_{m3}(R_x\cosh P_x - \sinh P_x)(P_xg_{m1} - g_{m4})}{P_xR_x\cosh P_x\sinh P_x - \delta - 1} \tag{6}$$

Case V: All-pass (APF) as $V_{in1}=V_{in2}=V_{in4}=V_{in}$ and $V_{in3}=0$. The transfer function $T_{AP}(p)$ of the circuit is given by

$$T_{AP}(p) = \frac{g_{m1}g_{m2}g_{m3}P_x(R_x\cosh P_x - \sinh P_x)}{P_x(R_x\cosh P_x\sinh P_x - \delta - 1)} - \frac{g_{m3}g_{m4}\delta}{P_x(R_x\cosh P_x\sinh P_x - \delta - 1)} + \frac{g_{m4}P_yR_y\sinh P_y[1-\alpha(\cosh P_x - 1)]}{P_x(R_x\cosh P_x\sinh P_x - \delta - 1)} \tag{7}$$

When

$$\beta = P_x(R_x\cosh P_x\sinh P_x - \delta - 1),$$
$$\delta = R_xR_yg_{m1}g_{m2}\sinh P_1\sinh P_2$$
$$P_x = \sqrt{sR_xC_x},\ C_x = C_{x1} + C_{x2},\ C_{x1} = (1-\alpha)C_x,\ C_{x2} = \alpha C_x$$
$$P_y = \sqrt{sR_yC_y},\ C_y = C_{y1} + C_{y2},\ C_{y1} = (1-\sigma)C_y,\ C_{y2} = \sigma C_y$$

Thus, the proposed filter can realize LPF, HPF, BPF, NF and APF biquadratic filters by appropriately connecting the input and output terminals. It should be noted that no inverting-type input signals and no component-matching conditions are required for realization five types of filter standard biquadratic function. Also the inputs V_{in1}, V_{in2}, V_{in3}, and V_{in4} are connected to the high input impedance, leading to easy cascadability without the need of any supplementary. Inspection of (2) shows that, in all cases, the natural frequency (ω_o) and the quality factor (Q) of the proposed filter are given by

$$\omega_0 = \sqrt{\frac{g_{m3}g_{m5}}{g_{m1}g_{m2}g_{m4}R_xR_yC_xC_y}} \tag{8}$$

$$BW = \frac{R_{x1}R_xC_x}{R_{y2}R_yC_y} \tag{9}$$

$$Q = \sqrt{\frac{R_xC_{x1}C_x}{R_yC_{y1}C_y}} \tag{10}$$

From the Eq. (8), letting $g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_{m5}$ the parameter ω_o can be tuned electronically by changing the value of g_m through the biasing currents of the OTAs while the parameter Q can be given by the capacitance and resistance ratio C_x/C_y and R_x/R_y.

4. Circuit Sensitivities Analysis

The sensitivity $S_{X_i}^{T(p)}$ is defined as the ratio of normalized incremental change of the transfer function T(p), due to the normalized change of circuit parameter X_i as follow [16]:

$$S_{X_i}^{T(p)} = \frac{dT(p)}{dX_i} * \frac{X_i}{T(p)} \tag{11}$$

As form Eq. (11) the active and passive sensitivities of the proposed circuit can be found such as:

$$S_{R_{x,y}}^{\omega} = S_{g_{m1},g_{m2},g_{m4}}^{\omega} = S_{C_{x,y}}^{Q} = S_{g_{m3},g_{m4}}^{Q} = \frac{1}{2} \tag{12}$$

$$S_{C_{x,y}}^{\omega} = S_{g_{m3},g_{m4}}^{\omega} = S_{R_y}^{BW} = S_{C_y}^{BW} = S_{g_{m3},g_{m5}}^{BW} = -\frac{1}{2} \tag{13}$$

$$S_{R_x}^{BW} = S_{C_x}^{BW} = S_{g_{m1},g_{m2},g_{m4}}^{BW} = 0 \tag{14}$$

$$S_{R_{x,y}}^{Q} = S_{g_{m1},g_{m2},g_{m4}}^{Q} = -\frac{1}{2} \tag{15}$$

Values are within unity in magnitude, which represent a low value. Hence, the proposed circuit exhibits good sensitivity performance.

5. Discussion to Simulation Results

5. 1 Parameters for Computer Simulation

The proposed circuit of Fig.2 was simulated with PSPice using active component: OTA IC no.LT1228 simplified model, and URC was designed using the following passive component is approximated by the ladder lumped RC elements of 20 sections with the following values:

Capacitance of DURC$_1$; $C_{xDURC1} = C_{xDURC1}$ = 60 nF

Capacitance of DURC$_2$; $C_{yDURC2} = C_{yDURC2}$ = 60 nF

Resistance of DURC$_1$; R_{xDURC1} = 2MΩ

Resistance of DURC$_2$; R_{yDURC1} = 2MΩ

The circuit was biased with ±2V supply voltages, and bias current of OTAs with $I_{B1} = I_{B2} = I_{B3} = I_{B4} = I_{B5}$ = 100 µA.

5. 2 Simulation Result

The proposed of voltage-mode universal filter circuit has been simulated using PSpice simulator. The simulated responses of the LPF, HPF, BPF, NF, and APF of the proposed filter are shown in Fig. 3. This yields frequency of 7.78 MHz, where the calculated value of this parameter from (10) yields 8.201 MHz (deviated by 5.13%). The power consumption of the filter circuit is about 1.24mW. From Fig. 4 shows the simulated the phase responses characteristics of the APF and NF filter. It is evident from Fig. 3 that the proposed filter performs five standard biquadratic filtering functions well.

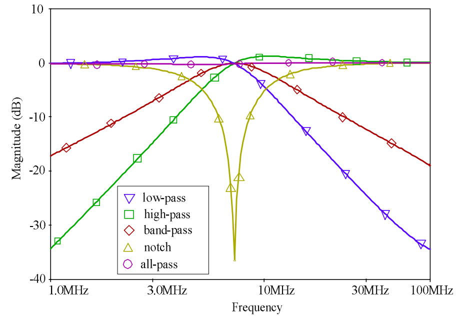

Figure 3. Magnitude responses of proposed circuit.

Fig.5 shows the simulated NF filter response when changed the bias current of OTAs and while keeping the total resistance and capacitance of the DURC element $R_{x,y}$=2 MΩ and $C_{x,y}$=60 nF, respectively. Fig. 6 shows the simulated BPF filter response when adjusted the capacitance of DURC and Fig. 7 shows the calculated using MATLAB when various bias current and capacitances of OTAs and DURCs. This result can confirm that the proposed circuit the frequency response can be adjusted by varying the bias current of OTAs and total capacitance value of the DURC without affecting the quality factor (Q).

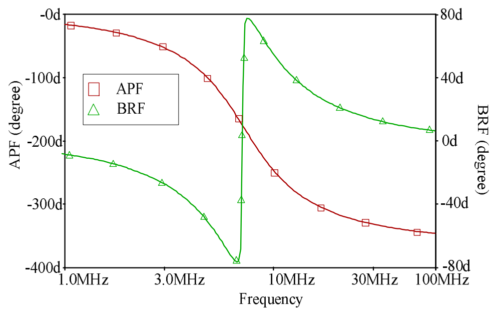

Figure 4. Phase-frequency responses of APF and BRF.

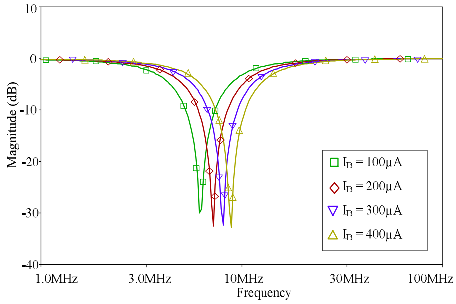

Figure 5. NF magnitude responses for different values of I_B.

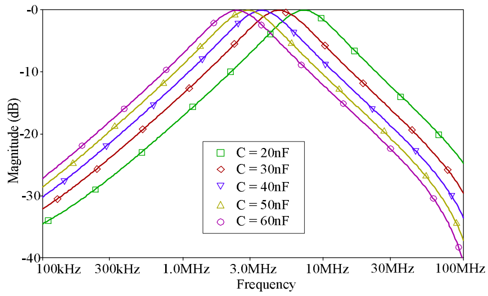

Figure 6. BPF frequency responses for different values of capacitance.

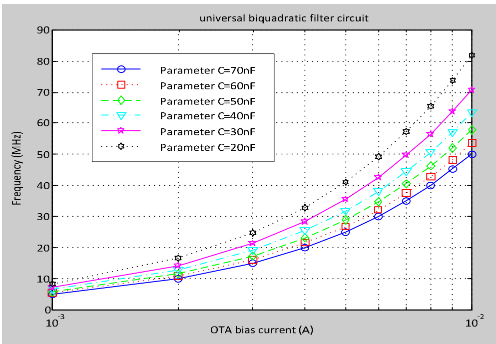

Figure 7. Frequencies various bias current and capacitances.

5. Conclutions

This paper proposed the voltage-mode universal filter using OTA and double capacitance layers uniform distributed RC (DURC). The proposed universal circuit can achieve voltage-mode universal filtering responses (including low-pass, high-pass, band-pass, notch and all-pass) from the same topology. Filters using the simpler structure have the advantages of lower cost, chip area, power dissipation and noise. The frequency response can be tuned electronically via bias currents of OTAs and adjusted by varying the capacitance value of the DURC without affecting the quality factor. The simulation results are in reasonably good agreement with the theoretical calculations. The proposed circuit in this paper is suitable for fabrication of the VLSI circuit, portable circuit such as wireless communication, and signal processing devices.

References

[1] K. Janchitrapongvej et al., "Capacitive Double Layers Uniformly Distributed RC Line and its Applications to Active Filters," Proc. in TENCON-2000, pp.23-25.

[2] R. Phantonglow et al., "The design of an active band pass filter using uniformly distributed RC line," Proc in ICCCAS-2002, pp.1275-1278.

[3] N. Tangthong et al., "Active Notch Uniformly Distributed RC Circuit and Their Application," Proc. in COEX-2008, Seoul, Korea, pp.1548-1552.

[4] V. Pirajnanchai et al., "Active Low Pass Notch Filter Using Multielectrode Distributed RC Circuit," Proc. in CSNDSP-2010, pp.355-358.

[5] S. Franco, Design with Operational Amplifiers and Analog Integrated Circuits, third ed., McGraw-Hall, New York, 2001.

[6] S.H. Tu et al., "OTA-C Arbitrary-Phase-Shift Oscillators," IEEE Trans. Instrum. Meas., vol. 61, pp.2305-219, 2012.

[7] J.M. Khoury and Y.P. Tsividis, "Synthesis of Arbitrary Rational Transfer Functions in S Using Uniform Distributed RC Active Circuits," IEEE Trans. Circuits Syst., vol. 37, pp.464-472, 1990.

[8] P.P. Sotiriadis and Y. Tsividis, "Integrators using a single distributed RC element," Proc. in ISCAS-2002, pp.II-21-II-24.

[9] N. Panyanouvong et al., "Designing active lowpass filter using uniformly distributed RC line," Proc. in ICNNSP-2003, pp.612-615.

[10] S. Klungtong and D. Thanapatay, "Voltage-mode universal biquadratic filter using OTA and Uniform Distributed RC," Proc. in ISCIT-2013, pp. 253-256.

[11] M. Neelakantan, "Design of elliptic function filters using a double-layer RC distributed-active circuit," IEEE Trans. Circuit Theory vol. 19, pp.403-406, 1972.

[12] S. Wachirarattanapornkul, "Active DURC Notch Filter," Proc in JICTEE-2014, pp. 1-4.

[13] S. Wachirarattanapornkul, "On Design of Active Notch Tunable Filter Using Multilayer Uniformly Distributed RC Line," Proc in ISCIT-2009, pp. 605-608.

[14] S. Wachirarattanapornkul, "On The Realization of Active MURC Filter with a Single Pole Amplifier," Proc in APCCAS-2006, pp. 1709-1712.

[15] M.S. Ghausi. T.J. Kelly, Introduction to Distributed Parameter Network with Application to Integrated Circuits, Holt, Rinehardt, and Winston, 1968.

[16] S. Wachirarattanapornkul et al., "The voltage-mode with triple-input single-output universal biquad filter using DURCs and CCCIIs," Proc. in ICCE-2014, pp.323-326.

[17] P. Tangtisanon et al., "Active LPF using uniformly distributed RC line," Proc. in APCCAS-1998, pp.283-286.