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Versatile Voltage-Mode Biquadratic Filter and Quadrature Oscillator Using Four OTAs and Two Grounded Capacitors

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Abstract: This article presents a versatile voltage-mode (VM) biquad filter with independently electronic tunability. The proposed structure using one dual-output operational transconductance amplifier, three single-output operational transconductance amplifiers (OTAs) and two grounded capacitors was explored to derive a new VM quadrature oscillator with the independent control of the oscillation frequency and the oscillation condition. The proposed versatile VM biquad filter achieves nearly all of the main advantages: (i) simultaneous realizations of band-reject, band-pass, and low-pass from the same architecture, (ii) multiple-input and multiple-output functions, (iii) independent electronic adjustability of quality factor and resonant angular frequency, (iv) no resistor needed, (v) all input terminals with cascade functions, (vi) no additional inverting amplifier for input signals, (vii) using only grounded capacitors, and (viii) easy to implement a VM quadrature oscillator with independent electronically controlled oscillation frequency and oscillation condition. The proposed versatile VM biquad filter employs only four OTAs and two grounded capacitors. The active components of the proposed VM biquad filter are one less than that of recent reports. The proposed circuit also brings versatility and simplicity to the design of VM biquad filters and VM quadrature oscillators. Filters and oscillators with less active and passive components have the advantages of low cost, low power dissipation, low circuit complexity, and low noise. Commercially available integrated circuit LT1228 and discrete components can be used to implement the proposed OTA-based circuits. The simulation and experiment results validated the theoretical analysis.

Keywords: voltage-mode circuit; operational transconductance amplifier; quadrature oscillator; analog filter

1. Introduction

In various electronic and communication systems, analog filters and oscillators are basic components. Their applications have been presented in the open literature [1–5]. For example, Figure 1 shows the triple-section crossover network for high-fidelity loudspeakers [4], and the principle of the dual phase sensitive detection (PSD) system [5]. When designing voltage-mode (VM) active biquads and oscillators, many circuits have been proposed that have good applications and advantages by using different active components [1–49]. The applications and advantages in designing electronically tunable operational transconductance amplifier-capacitor (OTA-C) filters also received considerable attention [16,34–40,42–49]. In analog integrated circuit (IC) designs, electronically adjustable circuits

have become the focus of attention, because in the practice of ICs, the tolerances of electronic components in implementation are too high, so fine-tuning must be performed after manufacturing. Therefore, the single-output operational transconductance amplifier (OTA) is very suitable for the design of electronic adjustable circuits, because the transconductance gain (g_m) of OTA can be regulated by an outside direct current (DC) bias current, I_B . The high-input impedance VM biquads have also been extensively investigated, because it can be easily connected in series to form a high-order filter. Hence, many VM biquads with high-input impedances have been studied [6,7,10,38–49].

Figure 1. Basic block diagram of the three-way high-fidelity loudspeaker crossover network and phase sensitive detection (PSD) system. (a) Triple-section crossover network for high-fidelity loudspeakers [4]; and (b) the PSD system [5].

On the basis of the input signals, the VM universal biquads with different filtering functions are obtained, which provide the low-pass (LP), high-pass (HP), band-pass (BP), band-reject (BR), and all-pass (AP) filtering functions in one circuit architecture. The advantage of the VM multifunction biquad filter is that it can simultaneously form BP, LP, HP and/or BR outputs in the same architecture, which can improve the flexibility and versatility of practical applications. Although three electronically tunable VM biquads based on OTAs have been recently proposed [45–47], these proposed circuits cannot realize BR, BP and LP filtering responses simultaneously. In [48,49], two circuit topologies were proposed in 2019 that operated in a versatile VM biquad filter with five OTAs and two grounded capacitors. Both circuits in [48,49] can achieve five standard filter responses, and can independently control the parameters quality factor (Q) and resonance angular frequency (ω_0). The circuits have two more important advantages, that is, they can simultaneously realize BR, BP and LP biquad filters in the same architecture, and they can implement a VM quadrature oscillator with independently electronically controlled condition of oscillation (CO) and frequency of oscillation (FO).

This article proposes a new versatile high-input impedance electronic controllable VM biquad filter. The circuit consists of one dual-output operational transconductance amplifier (DO-OTA), three OTAs and two grounded capacitors. The proposed circuit can independently and electronically

control the parameters of ω_o and Q . The proposed versatile VM biquad filter simultaneously has the following eight performance characteristics without trade-offs: (i) employing one DO-OTA, three OTAs and two grounded capacitors without any resistors, (ii) multiple-input and multiple-output functions, (iii) implementing BR, BP and LP biquadratic filtering functions simultaneously with three output terminals, (iv) providing all five standard biquadratic filtering functions with a single-output terminal, (v) tuning ω_o and Q independently and electronically, (vi) having high-input impedance terminals, (vii) no extra inverting amplifiers for special input signals, and (viii) easily a realizing VM quadrature oscillator with the electronic and independent control of CO and FO. Table 1 lists the property comparisons between the proposed circuit and the previous VM biquads. From Table 1, the proposed circuit satisfies all the important properties mentioned above. To the best knowledge of authors, all these properties cannot be achieved simultaneously by any of the earlier known VM biquads [6–11,24–26,34–38,41–49]. With respect to the VM six-OTA biquads in [45,46], the proposed circuit uses two less active components and obtains simultaneous BR, BP and LP biquadratic filtering functions in the same architecture. With respect to the VM five-OTA biquads in [47–49], the proposed circuit uses one less active component and the filter parameters ω_o and Q can still be independent and electronically adjusted. Filters and oscillators using less active and passive components have the advantages of low cost, low power dissipation, low circuit complexity, and low noise.

This article is organized as follows: Section 2 presents the proposed versatile VM biquad filter with independently electronic tunability and the proposed VM quadrature oscillator with the independent and electronic control of CO and FO. Section 3 performs the parasitic and non-ideality analysis for the proposed filter. Section 4 emphasizes and evaluates the respective simulation and measured results obtained employing Cadence OrCAD PSpice software and the LT1228 ICs with discrete components. The experimental test bench is also described in Section 4. Finally, Section 5 is the conclusions.

Table 1. Comparisons of the proposed versatile voltage-mode (VM) biquad filter with previous report circuits.

Features	Reference [41]	Reference [42]	Reference [43]	Reference [44]	Reference [45]	Reference [46]	Reference [48]	Proposed
Active and passive elements	3 DDCC, 2R and 2C	4 OTAs and 2 OA	2 OTAs, 2 TO-OTAs, 2C and 3S	6 OTAs and 2C	6 OTAs, 2Rmos and 2C	6 OTAs and 2C	5 OTAs and 2C	1 DO-OTA, 3 OTAs and 2C
Resistorless topology	no	yes	yes	yes	no	yes	yes	yes
All grounded passive components	yes	yes	yes	no	yes	yes	yes	yes
Absent from using inverting-type input	yes	yes	yes	yes	yes	yes	yes	yes
High impedance at the inputs	yes	yes	yes	yes	yes	yes	yes	yes
Independent and electronic adjustment of filter parameters ω_o and Q	no	no	no	no	yes	no	yes	yes
Multiple-input and multiple-output functions	no	yes	no	no	no	no	yes	yes
Simultaneous realization of three biquad filter functions	no	yes	no	no	no	no	yes	yes
Offer five standard biquad filter functions	yes	yes	yes	yes	yes	yes	yes	yes
Easily transformed into a VM quadrature oscillator	N/A	N/A	N/A	N/A	N/A	N/A	yes	yes
Power supply voltages (V)	± 1.65	N/A	± 1.65	± 3	± 5	± 15	± 15	± 15
Simulated power dissipation (W)	N/A	N/A	N/A	N/A	N/A	N/A	0.861	0.92
Measured power dissipation (W)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.23
Output P1dB (dBm)	N/A	N/A	N/A	N/A	N/A	N/A	−9.2	−5.9
Third-order IMD point	N/A	N/A	N/A	N/A	−37 dBc @ 35 mVp	N/A	−42.86 dBc @ 30 mVp	−48.67 dBc @ 63 mVp
Verification of simulation/experiment	yes/no	yes/no	yes/no	yes/no	yes/yes	yes/yes	yes/yes	yes/yes

OA: operational amplifier; DDCC: differential difference current conveyor; OTA: operational transconductance amplifier; DO-OTA: dual-output OTA; TO-OTA: triple-output OTA; C: capacitor; S: switch; R: resistor; Rmos: metal oxide semiconductor resistor; IMD: intermodulation distortion; P1dB: 1-dB power gain compression point; ω_o : resonance angular frequency; Q: quality factor; N/A—not available or not tested.

2. Circuit Descriptions

2.1. Proposed Versatile VM Biquad Filter

OTA is an active component available on the market, and is frequently utilized in the application and design of electronic controllable circuits. The symbol of OTA is shown in Figure 2a, which is a single current output OTA. Figure 2b shows the symbol for a DO-OTA, which is a dual current output OTA. The dual current outputs of the OTA can be characterized by $I_O = \pm g_m (V_+ - V_-)$ [34]. The symbol $\pm$ shows the polarity of the current output.

Figure 2. Symbols for operational transconductance amplifier (OTA) and dual-output operational transconductance amplifier (DO-OTA). (a) OTA. (b) DO-OTA.

Figure 3 shows the proposed versatile VM OTA-C biquad. It employs one DO-OTA, three OTAs and two grounded capacitors with four input signals and three output signals. The routine analysis of the circuit in Figure 3 can derive the following three output voltage signals:

$$V_{o1} = \frac{sC_2g_{m1}g_{m3}V_{i1} + g_{m1}g_{m2}g_{m3}V_{i2} + g_{m1}g_{m3}g_{m4}(V_{i3} - V_{i4})}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \quad (1)$$

$$V_{o2} = \frac{(sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3})V_{i1} - sC_1g_{m2}g_{m3}V_{i2} - sC_1g_{m3}g_{m4}(V_{i3} - V_{i4})}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \quad (2)$$

$$V_{o3} = \frac{-s^2C_1C_2g_{m1}V_{i1} - sC_1g_{m1}g_{m2}V_{i2} + (s^2C_1C_2g_{m3} + g_{m1}g_{m2}g_{m3})V_{i3} + sC_1g_{m1}g_{m4}V_{i4}}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \quad (3)$$

Figure 3. Proposed versatile VM biquad.

From Equations (1)–(3), there are two different possibilities to realize the VM multifunction biquad according to input and output conditions as follows.

Case I: If $V_{i1} = V_{i2} = V_{i4} = 0$ (grounded) and $V_{i3} =$ input voltage signal (V_{in}), then three biquadratic filtering functions can be obtained as shown in Equations (4)–(6):

$$\frac{V_{o1}}{V_{in}} = \frac{g_{m1}g_{m3}g_{m4}}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \quad (4)$$

$$\frac{V_{o2}}{V_{in}} = \frac{-sC_1g_{m3}g_{m4}}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \quad (5)$$

$$\frac{V_{o3}}{V_{in}} = \frac{s^2C_1C_2g_{m3} + g_{m1}g_{m2}g_{m3}}{s^2C_1C_2g_{m3} + sC_1g_{m1}g_{m4} + g_{m1}g_{m2}g_{m3}} \quad (6)$$

As indicated in Equations (4)–(6), a non-inverting LP filtering function is obtained from V_{o1} , an inverting BP (IBP) filtering function is obtained from V_{o2} , and a non-inverting BR filtering function is obtained from V_{o3} .

With the inspection of Equations (1)–(3), the filter parameters ω_o and Q are obtained as

$$\omega_o = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}, \quad Q = \frac{g_{m3}}{g_{m4}} \sqrt{\frac{C_2g_{m2}}{C_1g_{m1}}} \quad (7)$$

From Equation (7), the filter parameter ω_o can be tuned through the g_{m1} and g_{m2} first and the filter parameter Q can be adjusted independently through g_{m3} and/or g_{m4} without disturbing ω_o . Moreover, by selecting $g_{m1} = g_{m2} = g_m$ and $C_1 = C_2 = C$, the parameters of ω_o and Q in Equation (7) are expressed as

$$\omega_o = \frac{g_m}{C}, \quad Q = \frac{g_{m3}}{g_{m4}} \quad (8)$$

Equation (8) shows that the filter parameters of ω_o and Q can be non-interactively electronically tuned by varying g_m , g_{m3} and/or g_{m4} . This means that the parameters ω_o and Q of the VM biquad filter can be independently controlled.

Case II: According to Equation (3), with $g_{m1} = g_{m3}$ and $g_{m2} = g_{m4} = kg_{m1}$, the voltage transfer function is as

$$V_{o3} = \frac{-s^2V_{i1} - s\frac{k}{\tau_2}(V_{i2} - V_{i4}) + (s^2 + \frac{1}{\tau_1\tau_2})V_{i3}}{s^2 + s\frac{k}{\tau_2} + \frac{1}{\tau_1\tau_2}} \quad (9)$$

where k is a scaling factor, $\tau_1 = \frac{C_1}{g_{m2}}$ and $\tau_2 = \frac{C_2}{g_{m1}}$ are the realized time-constants.

The specializations of the numerator in Equation (9) results in the VM universal biquad standard filtering functions:

- (1) LP filter: $V_{i1} = V_{i3} = V_{in}$, and $V_{i2} = V_{i4} = 0$.
- (2) IBP filter: $V_{i2} = V_{in}$, and $V_{i1} = V_{i3} = V_{i4} = 0$.
- (3) BP filter: $V_{i4} = V_{in}$, and $V_{i1} = V_{i2} = V_{i3} = 0$.
- (4) IHP filter: $V_{i1} = V_{in}$, and $V_{i2} = V_{i3} = V_{i4} = 0$.
- (5) BR filter: $V_{i3} = V_{in}$, and $V_{i1} = V_{i2} = V_{i4} = 0$.
- (6) AP filter: $V_{i2} = V_{i3} = V_{in}$, and $V_{i1} = V_{i4} = 0$.

Obviously, the proposed versatile VM biquad can be used as a multifunction filter with single input and three outputs, as well as a universal filter with four inputs and a single output. Therefore, the proposed VM biquad has more versatility than a single-input–three-output multifunction VM biquad or a multiple-input–single-output universal VM biquad.

because they are connected to input voltage source. Taking into account the current tracking errors and parasitic elements shown in Figure 6 and reanalyzing the versatile VM biquadratic filter, the following characteristic equation D(s) is obtained:

Figure 5. The non-ideal DO-OTA model.

Figure 6. Proposed versatile VM biquad filter including the parasitic components of OTAs.

$$D(s) = \alpha_3 s^2 C_1 C_2 g_{m3} \left(1 + \frac{C_1 C_2 G_{3p} + C_1 G_{2p} C_{3p} + C_2 G_{1p} C_{3p}}{\alpha_3 C_1 C_2 g_{m3}} \right) + \beta_1 \alpha_4 s C_1 g_{m1} g_{m4} \left(1 + \frac{C_1 G_{2p} G_{3p} + C_1 G_{2p} \alpha_3 g_{m3} + C_2 G_{1p} G_{3p} + C_2 G_{1p} \alpha_3 g_{m3} + C_{3p} G_{1p} G_{2p} + C_{3p} \alpha_1 \alpha_2 g_{m1} g_{m2} + s^2 C_1 C_2 C_{3p}}{\beta_1 \alpha_4 C_1 g_{m1} g_{m4}} \right) + \alpha_1 \alpha_2 \alpha_3 g_{m1} g_{m2} g_{m3} \left(1 + \frac{G_{1p} G_{2p} G_{3p} + G_{1p} G_{2p} \alpha_3 g_{m3} + \beta_1 \alpha_4 g_{m1} g_{m4} G_{1p} + \alpha_1 \alpha_2 g_{m1} g_{m2} G_{3p}}{\alpha_1 \alpha_2 \alpha_3 g_{m1} g_{m2} g_{m3}} \right) \quad (14)$$

where $C_1 = C_1 + C_{1p}$, $C_2 = C_2 + C_{2p}$, $C_{1p} = C_{o1} + C_{p2}$, $C_{2p} = C_{o2} + C_{o4} + C_{n1}$, $C_{3p} = C_{q1} + C_{o3} + C_{n3} + C_{n4}$, $G_{1p} = \frac{1}{R_{1p}}$, $G_{2p} = \frac{1}{R_{2p}}$, $G_{3p} = \frac{1}{R_{3p}}$, $R_{1p} = R_{o1} // R_{p2}$, $R_{2p} = R_{o2} // R_{o4} // R_{n1}$ and $R_{3p} = R_{q1} // R_{o3} // R_{n3} // R_{n4}$.

The following conditions should be satisfied for a biquad filter:

$$\frac{1}{sC_1} \ll R_{1p} \quad (15)$$

$$\frac{1}{sC_2} \ll R_{2p} \quad (16)$$

$$sC_{3p} + G_{3p} \ll g_{m3} \quad (17)$$

Under these conditions in Equations (15)–(17), the modified characteristic equation $D_1(s)$ is determined as

$$D_1(s) = \alpha_3 s^2 C_1 C_2 g_{m3} + \beta_1 \alpha_4 s C_1 g_{m1} g_{m4} + \alpha_1 \alpha_2 \alpha_3 g_{m1} g_{m2} g_{m3} \quad (18)$$

From (18), the modified biquadratic filter parameters of ω_o and Q are obtained by

$$\omega_o = \sqrt{\frac{\alpha_1 \alpha_2 g_{m1} g_{m2}}{C_1 C_2}}, \quad Q = \frac{\alpha_3 g_{m3}}{\beta_1 \alpha_4 g_{m4}} \sqrt{\frac{\alpha_1 \alpha_2 C_2 g_{m2}}{C_1 g_{m1}}} \quad (19)$$

The active and passive sensitivities of the biquadratic filter parameters ω_o and Q in Equation (19) remain less than or equal to one in magnitude. Hence, the proposed filter has a good sensitivity performance.

4. Simulation and Experimental Results

Simulation and measurement are essential to verify the theoretical analysis. The theoretical analysis of the proposed filter in Figure 3 and the oscillator in Figure 4 is verified by using PSpice for simulation and commercial LT1228 OTA for implementation. The experimental power supply voltages were ± 15 V. According to the LT1228 datasheet [50], the transconductance gain is given by $g_m = 10 I_{SET}$, where I_{SET} is the bias current of LT1228. This feature makes it useful for the electronic control of transconductance gain.

4.1. Versatile VM Biquad Filter Simulation and Experimental Results

The proposed filter is verified by simulation and experimental results. The filter was designed to obtain the natural frequency of $f_o = 144.7$ kHz and $Q = 1$. In this case, the passive component values of Figure 3 were chosen as $C_1 = C_2 = 2.2$ nF and $g_{m1} = g_{m2} = g_{m3} = g_{m4} = 2$ mS (i.e., $I_b = 200$ μ A). Figures 7–9 show the gain and phase of simulation and measurement responses of LP (V_{o1}), IBP (V_{o2}), and BR (V_{o3}) filters, respectively, as depicted in Equations (4)–(6). Figures 10–14 show the gain and phase responses of the simulation and measurement of LP, BP, IBP, IHP, and AP filters, respectively. The simulation and measurement results are in accordance with the theoretical value of Equation (9). The power consumption of simulation and measurement are approximately 0.92 W and 1.23 W, respectively. To verify the tunable electronic property of parameter f_o without affecting the parameter Q , the tuning transconductance gains, $g_{m1} = g_{m2}$, were simultaneously changed to 1.5 mS, 2 mS and 3 mS, while keeping $C_1 = C_2 = 2.2$ nF, and $g_{m3} = g_{m4} = 2$ mS for constant $Q = 1$. Figure 15 shows the simulated and measured gain responses of the BP responses on the V_{o3} output terminal when $V_{i4} = V_{in}$ and $V_{i1} = V_{i2} = V_{i3} = 0$. This illustrates the tunable property of parameter f_o without affecting parameter Q . However, to verify the tunable electronic property of parameter Q without affecting parameter f_o , the transconductance gain g_{m4} was given as 2 mS, 1.5 mS and 1 mS, while keeping $C_1 = C_2 = 2.2$ nF and $g_{m1} = g_{m2} = g_{m3} = 2$ mS for constant $f_o = 144.7$ kHz. Figure 16 shows the simulated and measured frequency gain responses of the BP responses on the V_{o3} output terminal when $V_{i4} = V_{in}$ and $V_{i1} = V_{i2} = V_{i3} = 0$. This illustrates the tunable property of parameter Q without affecting the parameter f_o . These results show that by using various values of g_{m4} , the parameter Q can be easily adjusted without affecting the parameter f_o , as explained in Equation (7).

Figure 7. Experimental and simulated low-pass (LP) filters with theoretical responses.

Figure 8. Experimental and simulated inverted band-pass (IBP) filters with theoretical responses.

Figure 9. Experimental and simulated band-reject (BR) filters with theoretical responses.

Figure 10. Experimental and simulated LP filters with theoretical responses in case II.

Figure 11. Experimental and simulated BP filters with theoretical responses in case II.

Figure 12. Experimental and simulated IBP filters with theoretical responses in case II.

Figure 13. Experimental and simulated inverted high-pass (IHP) filters with theoretical responses in case II.

Figure 14. Experimental and simulated all-pass (AP) filters with theoretical responses in case II.

Figure 15. Theoretical, simulated, and measured gain responses of BP filters realized by varying f_0 while keeping Q .

Figure 16. Theoretical, simulated, and measured gain responses of BP filters realized by varying Q while keeping f_0 .

To verify the input dynamic range of the proposed filter, the simulation was repeated for a sinusoidal input signal with $f_0 = 144.69$ kHz. Figure 17 shows the input signal and output signal transient waveforms of the BP response on the V_{o3} output terminal when $V_{i4} = V_{in}$ and $V_{i1} = V_{i2} = V_{i3} = 0$. The expansion amplitude is 120 mV_{pp} (peak to peak) without signification distortion. The dependence of the V_{o3} output harmonic distortion of the BP responses on input voltage amplitude is illustrated in Figure 18. Figure 18 shows that the total harmonic distortion (THD) is about 3.83% when the input signal increases to 170 mV_{pp}. For the experimental testing, Figure 19 shows the measured input and output voltage waveforms for the BP response, which can be extended to an amplitude of 120 mV_{pp} without signification distortion. Figure 20 shows the spectrum of the BP response of Figure 19. The measured angular frequency is about 144 kHz, which is close to the theoretical value of 144.69 kHz and the error rate is 0.48%. The THD, including the first harmonic to the fifth harmonic components of Figure 20, is about 2.13%. To verify the linear performance of the proposed filter, the 1 dB compression point of the circuit characteristics must be evaluated. Figure 21 shows the measured P1dB of the BP filter output voltage V_{o3} by applying input power at an angular frequency of 144.69 kHz, when $V_{i4} = V_{in}$, and $V_{i1} = V_{i2} = V_{i3} = 0$. As shown in Figure 21, relative to the output power, the measured P1dB of BP filter is about −5.9 dBm. Furthermore, to represent the nonlinearity of the filter proposed in Figure 3, a two-tone test of intermodulation distortion (IMD) was used to characterize the nonlinearity of the BP response. Figure 22 shows the frequency spectrum of the BP response at the V_{o3} output terminal, where $V_{i4} = V_{in}$, and $V_{i1} = V_{i2} = V_{i3} = 0$. The BP filter has inter-modulation characteristics by applying two-tone signals around 144.69 kHz. In Figure 22, two closely spaced tones, $f_1 = 143.69$ kHz and $f_2 = 145.69$ kHz, were used with an equal input amplitude of 63 mV_{pp}. The measured value of the third-order IMD is about −48.67 dBc, and the third-order intercept (TOI) point is approximately −2.597 dBm. The component values used in Figures 17–22 were $C_1 = C_2 = 2.2$ nF and $g_{mi} = 2$ mS ($i = 1$ to 4), leading to a center frequency of $f_0 = 144.69$ kHz.

Figure 17. Simulated time-domain voltage input (blue line) and voltage output (red line) signals of BP filter.

Figure 18. Total harmonic distortion (THD) analysis results of BP response.

Figure 19. The experimental time-domain voltage input (channel 1, blue line) and voltage output (channel 2, cyan line) signals of the BP filter of V_{o3} output terminal.

Figure 20. The experimental BP frequency spectrum analysis of Figure 19.

Figure 21. Measured P1dB of the BP filter with the input power of the voltage output V_{o3} .

Figure 22. Third-order intercept (TOI) measurement of BP filter.

To collect statistics on the effects of mismatch and change in Figure 3, Monte-Carlo simulations were performed by choosing a 5% tolerance for the capacitor values in Figure 3 and running 100 times in each case. The results when the two capacitor values are 5% Gaussian deviation are shown in Figure 23. In Figure 23, the center frequency of the nominal design was $f_0 = 144.7$ kHz by choosing $C_1 = C_2 = 2.2$ nF and $g_{mi} = 2$ mS ($i = 1$ to 4), and the Monte-Carlo analysis shows the median value of 141.8 kHz. The results show that the center frequency achieved by the mismatch of two capacitor values in the proposed circuit has little effect and is completely within the acceptable range. According the Monte-Carlo simulation, as the center frequency varies between 125 and 162.7 kHz, the f_0 -value of the BP response on the V_{o3} output terminal was affected in the range of -13.8 – 12.2% .

Figure 23. Histogram of the Monte-Carlo analysis for the BP filter.

4.2. VM Quadrature Oscillator Simulation and Experimental Results

To confirm the theoretical analysis, the oscillator in Figure 4 is designed as $C_1 = C_2 = 3$ nF and $g_{m1} = g_{m2} = g_{m4} = 1$ mS. In practice, to ensure that the oscillation starts, consider that the value of $g_{m3} = 1.013$ mS is greater than g_{m1} . Figure 24 shows the simulated waveforms of the quadrature voltage outputs V_{o1} and V_{o2} at steady state. The simulated oscillation frequency in Figure 24 is 52.18 kHz, which is close to the theoretical value of 53 kHz. The error percentage between the theoretical and simulated oscillation frequency is -1.5% . In the experimental test, the measured oscillation frequency

is 53.28 kHz, which is close to the theoretical value of 53 kHz and the error rate is 0.53%, as shown in Figure 25. The frequency spectrum of the oscillator output voltage, V_{o2} , is shown in Figure 26. The measured oscillation frequency is 53.56 kHz, which is closed to theoretical value of 53 kHz, and the error rate is 1.06%. The THD in Figure 26 is about 2.8%. Figure 27 shows the simulation and experimental results of the oscillation frequency obtained by varying the values of g_{m2} with $C_1 = C_2 = 1\text{ nF}$ (or 3 nF), $g_{m1} = g_{m4} = 1\text{ mS}$ and $g_{m3} = 1.013\text{ mS}$. When the tuning transconductance gain, g_{m2} is in the range of 0.5–5 mS, to start and maintain the sine wave oscillation under the same oscillation condition, the electronic tuning oscillation frequency range of the oscillator will be between 37.95 kHz and 355.88 kHz. The simulation and experimental results are consistent with the theoretical values. For wideband frequency adjustment and amplitude stabilization, the automatic gain control (AGC) system is required. Therefore, an additional auxiliary AGC circuit and technology are necessary. The AGC circuit can improve the unbalance of the voltage amplitude generated and can reduce the THD to achieve better performance. This technique has been presented in the literature [31]. Figures 28 and 29 show how to calculate phase noise using the Agilent's phase noise measurement solution. In Figures 28 and 29, the phase noise of the proposed oscillator is lower than -75.42 dBc/Hz (at 1 kHz offset) and -96.71 dBc/Hz (at 10 kHz offset), respectively.

Figure 24. Simulated steady state waveform of the VM quadrature V_{o1} (blue) and V_{o2} (red) voltage outputs.

Figure 25. The experimental quadrature V_{o1} (blue) and V_{o2} (cyan) voltage waveforms.

Figure 26. The measured frequency spectrum of the V_{o2} output terminal.

Figure 27. The frequency of oscillation (FO) theoretical, simulated and experimental results by varying the value of g_{m2} .

Figure 28. The measured phase noise of the VM quadrature oscillator at 1 kHz offset.

Figure 29. The measured phase noise of the VM quadrature oscillator at 10 kHz offset.

Finally, the experimental test bench for the versatile VM biquadratic filter and quadrature oscillator is shown in Figure 30. In Figure 30, the experimental test bench includes a printed circuit board, a power supply, an oscilloscope, a network analyzer, and a signal analyzer. An oscilloscope is used to measure the time-domain of filter and oscillator waveforms. A network analyzer is used to measure the frequency-domain of the filter gain and phase responses. A signal analyzer is used to measure the frequency spectrum and analyze phase noise. Figures 31–40 show the filter measurement results of the network analyzer. In Figures 31–40, the authors have exported measurement data and added them as additional traces to Figures 7–16 in order to compare the theoretical analysis.

(a)

(b)

(c)

Figure 30. Cont.

(d)

Figure 30. Experimental test bench for the versatile VM biquad filter and quadrature oscillator: (a) the measured gain and phase responses of the BP filter; (b) the measured time-domain of the BP filter in the center frequency of 144.69 kHz; (c) the measured frequency spectrum analysis of the BP filter of Figure 30b; and (d) the discrete element prototype board.

Figure 31. Experimentally observed gain and phase responses of the LP filter realized in case I.

Figure 32. Experimentally observed gain and phase responses of the IBP filter realized in case I.

Figure 33. Experimentally observed gain and phase responses of the BR filter realized in case I.

Figure 34. Experimentally observed gain and phase responses of the LP filter realized in case II.

Figure 35. Experimentally observed gain and phase responses of the BP filter realized in case II.

Figure 36. Experimentally observed gain and phase responses of the IBP filter realized in case II.

Figure 37. Experimentally observed gain and phase responses of the IHP filter realized in case II.

Figure 38. Experimentally observed gain and phase responses of the AP filter realized in case II.

Figure 39. Experimentally observed gain responses of the BP filters realized by varying f_0 while keeping Q .

Figure 40. Experimentally observed gain responses of the BP filters realized by varying Q while keeping f_0 .

5. Conclusions

In this paper, a configuration for realizing a versatile VM biquad filter with independent electronic tunability and a VM quadrature oscillator with the independent control of CO and FO using OTAs was presented. The proposed versatile VM biquad filter simultaneously exhibits BR, BP and LP filters by using one DO-OTA, three OTAs and two grounded capacitors. The proposed versatile VM biquad filter enjoys the following advantages: (i) four active components and two grounded capacitors are used, (ii) three basic filter responses with a single input and three outputs can be realized, (iii) LP, BP, IBP, HP, BR and AP filter responses can be realized by selecting different four input voltage signals, (iv) have multiple-input and multiple-output functions, (v) have independently and electronically controllable characteristic parameters ω_0 and Q , (vi) all input terminals have cascade function, and (vii) there is no extra inverting amplifiers for special input signals. The proposed VM quadrature sinusoidal oscillator is based on the proposed VM biquad filter structure. The proposed VM quadrature oscillator provides two sinusoidal output voltages with a phase difference of 90° and only uses grounded capacitors. CO and FO can be independently and electronically controlled. To the best knowledge of the authors,

all these properties cannot be obtained simultaneously by any previously known OTA-based VM biquad filters. It must be emphasized that the proposed versatile VM biquad filter employs only four OTAs and two grounded capacitors, and its active component is one less than that of the recently proposed VM biquad filter in the open literature [47–49]. It also brings versatility and simplicity to the design of the VM biquad filter and VM quadrature oscillator. VM biquad filters and VM quadrature oscillators using less active and passive components have the advantages of low cost, low power dissipation, low circuit complexity, and low noise. The simulation and experimental results also confirm the theoretical analysis.

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