Voltage-Mode Multifunction Biquad Filter and Its Application as Fully-Uncoupled Quadrature Oscillator Based on Current-Feedback Operational Amplifiers

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Abstract: This research introduces a new multifunction biquad filter based on voltage mode (VM) current-feedback operational amplifier (CFOA) and a fully uncoupled quadrature oscillator (QO) based on the proposed VM multifunction biquad filter. The proposed VM multifunction biquad filter has high impedance to the input voltage signal, and uses three CFOAs as active components, while using four resistors and two grounded capacitors as passive components. The VM CFOA-based multifunction biquad filter realizes band-reject, band-pass, and low-pass transfer functions at high-input impedance node simultaneously, which has the feature of easy cascading in VM operation without the need for additional voltage buffers. Additionally, the filter control factor parameter pole frequency (\( \omega_0 \)) and quality factor (Q) of the proposed VM multifunction biquad filter can be independently set by varying different resistors. By slightly modifying the VM multifunction biquad filter topology, a VM fully-uncoupled QO is easily obtained. The difference from the previous VM CFOA-based multifunction biquad filter is that the proposed VM CFOA-based multifunction biquad filter can be independently controlled by the filter control factor parameters, \( \omega_0 \) and Q. The proposed VM CFOA-based multifunction biquad filter can be transformed into a VM QO with fully-uncoupled adjustable of the oscillation condition and the oscillation frequency. The oscillation condition and the oscillation frequency can be fully-uncoupled and controlled by varying two sets of completely different resistors. The proposed VM fully-uncoupled QO solves the amplitude instability. The constant amplitude ratio of two quadrature sinusoidal waveforms can be realized when tuning FO. PSpice simulation and experimental results prove the performances of the proposed VM multifunction filter and VM fully-uncoupled QO. Simulation and experimental results confirm the theoretical analysis of the proposed circuits.

Keywords: active filter; current-feedback operational amplifiers (CFOAs); oscillators; circuit design

1. Introduction

Voltage-mode (VM) analog active filters and oscillators using different active components have received extensive attention. Some innovative approaches to realize VM biquad filters [1–4] and oscillators [5–9] can be found in the open study. Single-input three-output VM multifunction biquad filters, such as band-pass filter (BPF), low-pass filter (LPF), high-pass filter (HPF) or band-reject filter
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(BRF), are applied to the phase-locked loop, the high fidelity 3-way speaker, the touch-tone telephone tone decoder, and the phase sensitive detection (PSD) [8–11]. PSD is suitable for detecting and measuring low frequency electrical signal from the sensor [8,9]. The conceptual scheme of a dual PSD including a VM quadrature oscillator (QO), an auto-balancing bridge circuit, two multiplier circuits and two LPF circuits module is shown in Figure 1 [8–10]. VM QO can generate two sinusoidal wave output with a 90° phase difference and is the great significant part of a PSD [8,9]. Based on the dual PSD system, low-frequency QOs and filters research are required. The potential applications and advantages of using current-feedback operational amplifiers (CFOAs) to design VM biquads have attracted considerable attention in [12–27]. CFOA can be obtained by the cascade of a positive second-generation current conveyor and a voltage follower, so it can be implemented by the commercially available circuit (IC) namely Analog Device AD844AN [28,29]. The voltage on the non-inverting input port +IN of AD844AN is transferred to the inverting input port -IN, and the current flowing to the inverting port -IN is replicated to the port Tz. The voltage output port O follows the port Tz voltage. Compared with conventional operational amplifier (OP-AMP), AD844AN has the advantages of wider bandwidth and higher slew rate [28,29]. Therefore, for a specific purpose design, a dual PSD system, or a small number of circuits, using a commercially available ICs to design a VM biquad filters and QOs is better choice. According to the AD844AN datasheet [29], the rated temperature range of AD844AN is −40 °C to +85 °C, which is industrial temperature range, and the power supply range of AD844AN is ±4.5 V to ±18 V. Hence, when the circuits operate at different temperatures, the performances of the circuits will not have obvious fluctuations. Based on the above advantages, AD844AN has been widely used in the open literature [12–32].

As mentioned above, it is beneficial to use CFOA as an active component to implement a variety of high-input impedance VM multifunction biquads. The VM biquads, which has a high impedance for the input voltage signal, has aroused great interest because this biquads can be easily cascaded without any voltage buffer [21–27]. Singh and Senani [23] proposed a VM multifunction biquad HPF, LPF, and BPF transfer functions, but it employed four CFOAs and eight passive components. Horng and Lee [24] proposed a VM multifunction biquad HPF, LPF, and BPF transfer functions using three CFOAs and seven passive components, but it had the disadvantage of using three capacitors. Shan and Malik [25] proposed another VM multifunction biquad BRF, BPF, LPF, and HPF transfer functions using four CFOAs and six passive components, but it had the disadvantage of using four CFOAs. CFOA-based VM multifunction biquad HPF, LPF, and BPF has been proposed [26]. The transfer functions of the proposed filter use three CFOAs and four passive components, where one of the X terminals of the CFOA is connected to a grounded capacitor, which will lead to an improper transfer.
function and poor performance at high frequency. In 2019, a CFOA-based high-input impedance VM multifunction biquad has been proposed [27]. This circuit has important advantages, such as using only three CFOAs and realizing the transfer functions of BRF, BPF and LPF at the same time. In addition, the circuit also has the advantages of single input and three outputs, high-input impedance, and quadrature adjustable pole frequency ($\omega_o$) and quality factor ($Q$), and easily converted to VM QO. However, a further advantage cannot be achieved in [27], that is, the independent tunability of the filter control factor parameters $\omega_o$ and $Q$. Although the topology of VM multifunction biquad [27] can be converted to VM QO, it cannot achieve a fully-uncoupled tuning methods, and cannot obtain the condition of oscillation (CO) and the frequency of oscillation (FO). Note that only when CO and FO are determined by two completely different sets of components, CO and FO are called completely decoupled [30].

This research proposes a new topology for the realization of an independently tunable VM multifunction biquad filter. The proposed topology uses three CFOAs as active components, while using four resistors and two grounded capacitors as passive components. The advantages of the proposed CFOA-based VM multifunction biquad filter are follows: (i) use only three CFOAs, (ii) use only two grounded capacitors, (iii) realize three standard filter transfer functions with one input and three outputs at the same time, (iv) high-input impedance, (v) the input parasitic resistances of the X ports of the CFOAs can be easily accommodated in an external resistors, (vi) independent control of the filter control factor parameters $\omega_o$ and $Q$, and (vii) transformed into a VM QO with fully-uncoupled adjustable of CO and FO. Table 1 compares the proposed VM multifunction biquad filter with previously published researches [12–27]. It can be seen that the proposed VM multifunction biquad filter can simultaneously achieve all the above imported properties. Unlike the recently reported in [27], the attractive feature of the proposed VM multifunction biquad filter can be controlled independently of the control factor parameters $\omega_o$ and $Q$, and transformed into a VM QO with fully-uncoupled adjustable of CO and FO. Furthermore, the proposed VM QO with fully-uncoupled is advantageous to achieve amplitude stability. Table 2 summarizes the performance of the filter and oscillator, and compares the specific characteristics of the study [27].

### Table 1. Comparison of the previous reported CFOA-based VM biquad filters.

| Parameter | (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | Simul./Meas. | Supply (V) | Technology |
|-----------|-----|------|-------|------|-----|------|-------|-------------|-------------|------------|
| Ref. [12] | yes | no   | no    | no   | yes | no   | no    | Meas.       | N/A         | AD844 ICs  |
| Ref. [13] | yes | no   | no    | no   | yes | no   | no    | Meas.       | N/A         | AD844 ICs  |
| Ref. [14] | yes | no   | no    | no   | yes | no   | no    | Simul.      | ±12         | AD844 model|
| Ref. [15] | yes | no   | no    | no   | yes | no   | no    | Simul.      | N/A         | AD844 model|
| Ref. [16] | yes | no   | no    | no   | yes | no   | no    | Simul.      | N/A         | AD844 model|
| Ref. [17] | no  | yes  | yes   | no   | no  | no   | no    | Both        | ±12         | AD844 ICs  |
| Ref. [18] | yes | no   | no    | no   | no  | no   | no    | Meas.       | N/A         | AD844 ICs  |
| Ref. [19] | yes | yes  | yes   | no   | no  | no   | no    | Meas.       | N/A         | AD844 ICs  |
| Ref. [20] | yes | no   | no    | no   | no  | no   | no    | Simul.      | N/A         | AD844 model|
| Ref. [21] | no  | yes  | no    | yes  | no  | no   | no    | Meas.       | ±5          | AD844 ICs  |
| Ref. [22] | yes | no   | yes   | no   | yes | no   | no    | Simul.      | ±5          | AD844 model|
| Ref. [23] | no  | yes  | yes   | no   | yes | no   | no    | Simul.      | N/A         | AD844 model|
| Ref. [24] | yes | no   | yes   | no   | no  | no   | no    | Simul.      | N/A         | AD844 model|
| Ref. [25] | no  | yes  | yes   | no   | no  | no   | no    | Both        | N/A         | AD844 ICs  |
| Ref. [26] | yes | yes  | yes   | no   | no  | no   | no    | Simul.      | ±12         | AD844 model|
| Ref. [27] | yes | yes  | yes   | no   | no  | no   | no    | Both        | ±6          | AD844 ICs  |
| Proposed  | yes | yes  | yes   | yes  | yes | yes | yes   | Both        | ±6          | AD844 ICs  |

Note: (i) Use up to three CFOAs; (ii) use only two grounded capacitors; (iii) realize three standard filter transfer functions simultaneously; (iv) high-input impedance; (v) CFOA’s X ports input parasitic resistances can be easily accommodated in an external resistors; (vi) independent control of the filter control factor parameters pole frequency and quality factor; (vii) transformed into a voltage-mode QO with fully-uncoupled adjustable of the condition of oscillation and the frequency of oscillation; Simul.: simulation result; Meas.: measurement result; ICs: integrated circuits; N/A—not available or not tested.
Table 2. Characteristic comparisons with recent previous study.

| Parameter                                      | Ref. [27]          | Proposed          |
|------------------------------------------------|--------------------|-------------------|
| Number of active and passive components of the biquad filter | 3 CFOAs, 3 R, 2 C | 3 CFOAs, 4 R, 2 C |
| Number of active and passive components of the quadrature oscillator | 3 CFOAs, 4 R, 2 C | 3 CFOAs, 4 R, 2 C |
| Center frequency of the biquad filter (kHz)     | 39.79              | 102               |
| Independent tuning of the filter control factor parameters $\omega_o$ and Q | no                 | yes               |
| Fully-uncoupled tuning of the oscillator parameters CO and FO | no                 | yes               |
| Constant amplitude ratio of quadrature waveforms | no                 | yes               |
| Measured the oscillation frequency range (kHz)   | N/A                | 8.16–628          |
| Measured the total harmonic distortion of the quadrature oscillator (%) | N/A                | <0.7              |
| Measured the power dissipation (mW)              | 180                | 168               |
| Measured the input one-dB power gain compression point (dBm) | 12                 | 22                |
| Measured the third-order intermodulation distortion point (dBm) | 21.59              | 33.84             |

In this research, a new VM multifunction biquad filter with high-input impedance and a VM fully-uncoupled QO using the proposed VM multifunction biquad filter are presented. Compared with the previous research [27], the proposed VM multifunction biquad filter can overcome the independent control of the filter control factor parameters $\omega_o$ and Q, and the proposed VM CFOA-based QO can also overcome the fully-uncoupled adjustability of CO and FO. The CFOA-based biquad filter and QO are suitable for PSD system based on the use of commercially available ICs. The filter control factor parameters $\omega_o$ and Q are independently tuned and controlled. The QO control factor parameters CO and FO are fully-uncoupled tuning controlled. The effective frequency ranges of the biquad filter circuit is around 1 MHz, and the QO oscillation frequency varies from 8.16 to 628 kHz. Moreover, the proposed QO with fully-uncoupled is advantageous to achieve amplitude stabilization. The remaining sections of the research is structured as follows. Section 2 will introduce the characteristics and non-ideality of the VM CFOA-based multifunction biquadratic filter. Subsequently, based on the proposed VM CFOA-based multifunction filter, the VM fully-uncoupled QO is introduced. Section 3 verifies the proposed VM CFOA-based circuits and the theoretical comparison between experimental data and simulation data. Finally, Section 4 will summarize the research.

2. Proposed VM CFOA-Based Circuits

2.1. Proposed VM CFOA-Based Multifunction Biquad Filter

CFOA is a four-port versatile active component and its commercially available IC is AD844-type CFOA. The four-port characteristic of CFOA can be described by $V_X = V_Y$, $V_O = V_Z$, $I_Y = 0$ and $I_X = I_Z$ [31,32]. Figure 2 shows the proposed CFOA-based VM multifunction biquad filter with high-input impedance, including three CFOAs as active components, four resistors, and two grounded capacitors. Using only two grounded capacitors is particularly attractive for IC implementation. Routine analysis of the proposed filter yields the following BPF, LPF, and BRF voltage transfer functions.
without disturbing \( Q \). Thus, the CFOA-based VM multifunction biquad filter has independent tuning capability for the filter control factor parameters \( Q \) and \( \omega \). By changing \( R_3 \) and/or \( R_4 \), the control factor parameter \( Q \) can be independently controlled while \( \omega \) remains constant, the control factor parameter \( \omega_{\text{o}} \) can be independently controlled without disturbing \( Q \). For fixed-value capacitors, by simultaneously changing \( R_1 \) and \( R_2 \) while keeping the ratio of \( R_1 \) and \( R_2 \) constant, the control factor parameter \( \omega_{\text{o}} \) can be independently controlled without disturbing \( Q \). Thus, the CFOA-based VM multifunction biquad filter has independent tuning capability for the filter control factor parameters \( \omega_{\text{o}} \) and \( Q \). Assuming that \( C_1 = C_2 = C \) and \( R_1 = R_2 = R \), the filter control factor parameters of \( Q \) and \( \omega_{\text{o}} \) in Equation (5) become

\[
\omega_{\text{o}} = \frac{1}{CR}, \quad Q = \frac{R_4}{R_3}
\]
Equation (6) describes that the control factor parameter \( \omega_o \) can be independently controlled by changing \( R_3 \) and the control factor parameter \( Q \) can be independently controlled by changing \( R_3 \) and/or \( R_4 \). Hence, the filter control factor parameters of \( Q \) and \( \omega_o \) of the CFOA-based VM multifunction biquad filter can be independently controlled.

Next, the parasitic impedances of non-ideal CFOA is studied. The non-ideal CFOA model has parasitic resistances and capacitances from the \( Y \) port and \( Z \) port to the ground, and a series parasitic resistance \( R_X \) at the port \( X \). The parasitic impedances of non-ideal CFOA are \( R_{Xj}/C_{Yj} \) of port \( Y_j \), \( R_{Zj}/C_{Zj} \) of port \( Z_j \), and \( R_{Xj} \) of port \( X_j \) where \( j = 1, 2, 3 \) and represents the \( j \)th non-ideal CFOA [22]. Taking into account the parasitic impedances of non-ideal CFOA, the biquad filter presented in Figure 2 is modified to Figure 3. The proposed VM multifunction biquad filter employs external capacitors \( C_1 \) and \( C_2 \) connected in parallel at the first and second CFOA \( Z \) ports, respectively. This method has the characteristic that the parasitic capacitance, \( C_Z \), is directly incorporated into \( Z \) terminal of CFOA as part of the main capacitance. Hence, \( C_1 \) and \( C_2 \) can be selected to increase the parasitic capacitances at the \( Z \) ports of CFOAs. Each \( X \) port of the CFOA is directly connected to a resistor. This method has the feature of incorporating parasitic resistance, \( R_X \), directly into the \( X \) port of CFOA as a part of the main resistance. However, the parasitic resistances at the \( Z \) port of CFOA will change the type of the impedances. If the following conditions can be satisfied, the influence of the non-ideal CFOA parasitic impedances in Figure 3 can be ignored.

\[
\frac{1}{s(C_1 + C_{Z1})} \ll R_{Z1} \quad (7)
\]
\[
\frac{1}{s(C_2 + C_{Z2})} \ll R_{Z2} \quad (8)
\]
\[
R_3 \ll \frac{R_{Z3}}{1 + sR_{Z3}C_{Z3}} \quad (9)
\]

![Figure 3. Proposed VM multifunction biquad filter including the CFOA parasitic impedances.](image)

### 2.2. Proposed Fully-Uncoupled VM QO

Based on the VM multifunction biquad filter structure in Figure 2, the input signal \( V_{in} \) is grounded, the grounding resistor \( R_3 \) is floating, and the floating terminal of the resistor \( R_3 \) is connected to the output voltage signal \( V_{o1} \). Thus, the CFOA-based VM multifunction biquad filter can be transferred to the VM fully-uncoupled QO as shown in Figure 4. Routine analysis of the proposed VM fully-uncoupled QO results in the following characteristic equation.
where the phase difference $\phi = 90^\circ$ to ensure that the output voltages, $V_{o1}$ and $V_{o2}$ are in quadrature phase shifted.

From Equation (14), the magnitude ratio of the quadrature output voltages $V_{o1}$ and $V_{o2}$ is given by

$$\left| \frac{V_{o1}}{V_{o2}} \right| = \omega_0 C_2 R_2 = \frac{C_2 R_2}{\sqrt{C_1 R_1}}$$

Assuming that $C_1 = C_2$ and $R_1 = R_2$, the magnitude ratio of the QO output voltages $V_{o1}$ and $V_{o2}$ in Equation (15) becomes

$$\left| \frac{V_{o1}}{V_{o2}} \right|_{C_1=C_2, R_1=R_2} = 1$$

Equation (16) describes that the phase shift of the two quadrature output voltages is $90^\circ$, and the magnitude ratio of two quadrature output voltages is also equal. Thus, the proposed VM fully-uncoupled QO solves the amplitude instability and improves the unbalance of the generated quadrature output amplitudes $V_{o1}$ and $V_{o2}$. When tuning FO, the constant amplitude ratio of two

![Figure 4. The proposed VM QO with fully-uncoupled controlled of CO and FO.](image)
The phase noise figure-of-merit (FoM) for oscillators summarizes the important performance parameters. The conventional phase noise FoM of the oscillators is defined as follows [33].

\[
\text{FoM}(\Delta \omega) = -L(\Delta \omega) + 20 \log\left(\frac{\omega_o}{\Delta \omega}\right) - 10 \log\left(\frac{P_{DC}}{1mW}\right)
\]

(17)

where \(\Delta \omega\) is the offset frequency relative to the carrier, \(\omega_o\) is the oscillation frequency, and \(L(\Delta \omega)\) is the phase noise at the offset frequency to the carrier. \(P_{DC}\) is the power (in mW) consumed by the oscillator. In order to estimate FoM of the proposed VM fully-uncoupled QO, the phase noise FoM will be discussed in the next Section.

3. Simulation and Experimental Results

3.1. Test Setup

In order to use the commercial AD844AN IC to prove the real behavior of the proposed VM multifunction biquad filter and fully-uncoupled QO, an experimental test bench was developed, as shown in Figure 5. In Figure 5, the experimental setup uses a printed circuit board (PCB), DC power supply voltage, signal generator, oscilloscope, network analyzer, and signal analyzer. Keithley 2231A-30-3 power supply provides DC power supply voltage to PCB. The time domain of the filter and the output voltage swing of the oscillator are measured by the Tektronix DPO 2048B oscilloscope, and a Tektronix AFG1022 signal generator is used to generate the input signal of the filter. The frequency domain of biquad filter responses is measured by Keysight E5061B-3L5 network analyzer. One dB power gain compression point (P1dB), intermodulation distortion (IMD), phase noise, and output frequency spectrum are measured by the Keysight-Agilent N9000A CXA signal analyzer.

![Figure 5](image-url)
Figure 5. Cont.
Figure 5. Experimental setup. (a) Test setup block diagram; (b) the top and bottom of the measured prototype; (c) Tektronix DPO 2048B oscilloscope for measuring time domain voltage output, Tektronix AFG1022 signal generator for generating input signal, and Keithley 2231A-30-3 for power supply; (d) Keysight E5061B-3L5 network analyzer for measuring frequency domain filter responses; and (e) Keysight-Agilent N9000A CXA signal analyzer for measuring filter and oscillator output spectrum.

3.2. Effective Frequency Ranges of AD844AN-Based Circuit

The proposed VM multifunction biquad filter and fully-uncoupled QO circuits are simulated by Cadence OrCAD PSpice version 16.6 software. The model parameters of CFOA come from the built-in library AD844/AD. Programming using Intel Core i5-8400 CPU and MATLAB version 2019a has confirmed the effectiveness of simulation and theoretical analysis. For the experiments, the proposed CFOA-based VM multifunction biquad filter and fully-uncoupled QO circuits use AD844AN ICs. The supply voltages for simulation and experiment are ±6 V. In general, the applicability of such filters and oscillators based on CFOA circuits and using AD844AN ICs is usually limited to a few hundred kilohertz [31,32]. To test the frequency ranges of AD844AN, the test circuit based on AD844AN is shown in Figure 6. The supply voltages are ±6 V. In Figure 6a, the selected resistance values are $R_1 = R_2 = R = 2 \, \text{k} \Omega$ (4 kΩ, 6 kΩ, 10 kΩ). Figure 6b shows the measured gain responses of the AD844AN characteristics. Figure 6c shows the measured phase responses of the AD844AN characteristics. As shown in Figure 6, the frequency range of the AD844AN-based circuit is limited to 1 MHz.
Figure 6. Experimental evidence of the frequency ranges of AD844AN with two equivalent resistances (R = 2 kΩ—blue line; R = 4 kΩ—red line; R = 6 kΩ—green line; and R = 10 kΩ—purple line). (a) Circuit diagram for testing gain and phase response frequency ranges of AD844AN; (b) measured gain responses of AD844AN; and (c) measured gain responses of AD844AN.
3.3. Proposed CFOA-Based VM Multifunction Biquad Filter

To validate the theoretical study of Figure 2, Figure 7a–c show the simulation and experimental results of the BPF, LPF and BRF with the theory responses, respectively. In Figure 7, the values of passive elements are selected as $C_1 = C_2 = 390 \, \text{pF}$ and $R_1 = R_2 = R_3 = R_4 = 4 \, \text{k} \Omega$. The selection of these values is to obtain a VM multifunction biquad filter with a center frequency of $f_0 = 102 \, \text{kHz}$ and a quality factor of $Q = 1$. The total power consumption of the simulation and experimental results is about 255 mW and 168 mW, respectively. By keeping the values of $C_1 = C_2 = 390 \, \text{pF}$, $R_1 = R_2 = R_3 = R_4 = 4 \, \text{k} \Omega$, the control factor parameter $Q$ of the characteristic filter can be tuned without disturbing $f_0$. When the value of $R_4$ changes between $16 \, \text{k} \Omega$, $8 \, \text{k} \Omega$, and $4 \, \text{k} \Omega$, this resulted in BPF responses are shown in Figure 8a. Similarly, by keeping the values of $C_1 = C_2 = 390 \, \text{pF}$, $R_3 = R_4 = 4 \, \text{k} \Omega$, the control factor parameter $f_0$ of the characteristic filter can be tuned without disturbing $Q$. When $Q = 1$, and $R_1$ and $R_2$ are varied between $8 \, \text{k} \Omega$, $4 \, \text{k} \Omega$, and $2 \, \text{k} \Omega$, this resulted in BPF responses are shown in Figure 8b. This range is dependent on the bandwidth of AD844AN. Figure 8a,b show the CFOA-based multifunction biquad filter, whose filter control factor parameters $Q$ and $f_0$ have independent tuning capabilities. Figures 9–11 show the measured BPF, LPF and BRF responses obtained by a network analyzer, respectively. Figures 12 and 13 show the measured gain responses of $Q$ and $f_0$, respectively, as explained in Equation (5). In order to compare the theoretical analysis, the authors derived the measurement data of Figures 9–13 and added them as additional traces to Figures 7a–c and 8a,b, respectively. As can be seen, the simulation and experimental results are consistent with the theoretical values. However, the real active components have non-ideal characteristics, such as the parasitic impedance effect of AD844AN, the non-ideal characteristics caused by the frequency dependence of the internal voltage and current transmission of the AD844AN, and the parasitic impedance effect of PCB layout issue. These additional parasitic resistances and capacitances of the AD844AN, the PCB layout issue, and the tolerances of the working resistors and capacitors will have main effects on circuit accuracy.

![Figure 7. Cont.](image-url)
Figure 7. Simulated and experimental filter gain and phase responses with the theory responses. (a) The band-pass filter response; (b) the low-pass filter response; and (c) the band-reject filter response.

Figure 8. Cont.
Figure 8. Theoretical, simulated, and experimental gain response of the band-pass filter responses. (a) Variation in Q while keeping $f_0$; and (b) variation in $f_0$ while keeping Q.

Figure 9. The experimental results of gain and phase responses of the BPF in Figure 2.

Figure 10. The experimental results of gain and phase responses of the LPF in Figure 2.
**Figure 10.** The experimental results of gain and phase responses of the LPF in Figure 2.

**Figure 11.** The experimental results of gain and phase responses of the BRF in Figure 2.

**Figure 12.** The experimental results of gain responses by varying Q while keeping $f_o$ ($Q = 1.12$—blue line; $Q = 2.04$—red line; and $Q = 3.91$—green line).

**Figure 13.** The experimental results of gain responses by varying $f_o$ while keeping $Q$ ($f_o = 52.4$ kHz—blue line; $f_o = 104.4$ kHz—red line; and $f_o = 203.8$ kHz—green line).

**Figure 14.** Histogram of the Monte-Carlo analysis.

| Frequency, kHz | Percent samples |
|---------------|-----------------|
| 86.579.7      | 0               |
| 92.786        | 4               |
| 99.267.8      | 8               |
| 108.104       | 12              |
| 113.831       | 20              |

- mean = 99,732.2
- sigma = 5797.5
- minimum = 86,579.7
- 10th %  = 92,786
- median = 99,267.8
- 90th %  = 108,104
- maximum = 113,831
The Monte Carlo analysis method is used to study the VM CFOA-based multifunction biquad filter. Statistical analysis of Monte Carlo 100 simulation can be performed. Figure 14 shows the histogram of center frequency obtained from the Monte-Carlo analysis of the BPF response in Figure 2. The resistor and capacitor values in Figure 2 are chosen as 4 kΩ and 390 pF, respectively, and the Gaussian variation of the resistance and capacitance is 5%. According to Monte-Carlo simulation, the center frequency varies between 86.6 and 113.8 kHz and the $f_0$ value of the BPF response is affected in the range of $-15.1\%$ to $11.6\%$.

![Figure 14. Histogram of the Monte-Carlo analysis.](image)

To obtain the input dynamic range of the proposed CFOA-based VM multifunction biquad filter in Figure 2, the experiment was repeated for a sinusoidal input signal of 102 kHz to show the filter operation in time-domain. Figure 15 shows the input and output voltage waveforms of the experimental BPF. The waveform shows that the amplitude is 6.96 V$_{pp}$ without significiation distortion. The measured center frequency is about 101.8 kHz, which is close to theoretical value of 102 kHz with $-0.2\%$ error rate. To illustrate the linear range of the circuit, P1dB is an important parameter for evaluating linear range of the circuit, when the output is saturated in the circuit. This is defined as the input power that results in the circuit gain to decrease by 1 dB. Input and output power gain is the relationship of output power = input power + gain. To evaluate the linear range of the VM biquad filter, consider the BPF, LPF and BRB in Equations (1) to (3). Figure 16 shows the measured P1dB of the BPF at an input power with a center frequency of 102 kHz. The P1dB of the BPF measured at $V_{oi}$ is about 22 dBm with respect to input power. The measured linearity performance of P1dB and total power consumption with different input signal voltages are summarized in Table 3. It should be noted that Table 3 is the measurement results of spectrum analysis, whose input impedance is 50 Ω, so the measurement result of output power has slightly attenuated. The parasitic resistances and capacitances of the AD844AN, the PCB layout issue, and the tolerances of the working resistors and capacitors will also have effects on circuit accuracy.
To obtain the input dynamic range of the proposed CFOA-based VM multifunction biquad filter in Figure 2, the experiment was repeated for a sinusoidal input signal of 102 kHz to show the filter operation in time-domain. Figure 15 shows the input and output voltage waveforms of the experimental BPF. The waveform shows that the amplitude is 6.96 V pp without significant distortion. The measured center frequency is about 101.8 kHz, which is close to theoretical value of 102 kHz with −0.2% error rate. To illustrate the linear range of the circuit, P1dB is an important parameter for evaluating linear range of the circuit, when the output is saturated in the circuit. This is defined as the input power that results in the circuit gain to decrease by 1 dB. Input and output power gain is the relationship of output power = input power + gain. To evaluate the linear range of the VM biquad filter, consider the BPF, LPF and BPF in Equations (1) to (3). Figure 16 shows the measured P1dB of the BPF at an input power with a center frequency of 102 kHz. The P1dB of the BPF measured at V_o1 is about 22 dBm with respect to input power. The measured linearity performance of P1dB and total power consumption with different input signal voltages are summarized in Table 3. It should be noted that Table 3 is the measurement results of spectrum analysis, whose input impedance is 50 Ω, so the measurement result of output power has slightly attenuated. The parasitic resistances and capacitances of the AD844AN, the PCB layout issue, and the tolerances of the working resistors and capacitors will also have effects on circuit accuracy.

Figure 15. The experimental results of input (channel 1, blue line) and output (channel 2, cyan line) time-domain experimental voltage waveforms.

Figure 16. The simulation and measurement P1dB of the BPF with input power at the output voltage V_o1.
Table 3. The linearity performance of P1dB and total power consumption with different input signal voltages.

| Supply (V) | Band-Pass Filter (V₀₁) | Low-Pass Filter (V₀₂) | Band-Reject Filter (V₀₃) |
|-----------|------------------------|-----------------------|-------------------------|
|           | Power (dBm) | P₀ (mW) | P1dB (dBm) | Power (dBm) | P₀ (mW) | P1dB (dBm) | Power (dBm) | P₀ (mW) | P1dB (dBm) |
| Input     | Output         |          |           | Input     | Output         |          |           | Input     | Output         |          |           |
| ±6        |              |          |           |          |              |          |           |          |              |          |           |
| −20       | −21.56       | 264      | −20       | −21.38     | 264          | −20      | −21.19     | 264       |
| −10       | −11.53       | 264      | −10       | −11.32     | 264          | −10      | −11.15     | 264       |
| 0         | −1.49        | 264      | 0         | −1.26      | 264          | 0        | −1.1       | 264       |
| 10        | 8.46         | 300      | 10        | 8.67       | 300          | 10       | 9          | 300       |
| 20        | 18.16        | 396      | 20        | 18.15      | 396          | 20       | 18.72      | 408       |
| 21        | 18.91        | 408      | 21        | 18.79      | 408          | 21       | 19.42      | 432       |
| 22        | 19.46        | 420      | 22        | 19.25      | 408          | 22       | 19.82      | 444       |
| 23        | 19.8         | 432      | 23        | 19.47      | 420          | 23       | 20.11      | 456       |
| 24        | 20.02        | 432      | 24        | 19.58      | 420          | 24       | 20.33      | 456       |
| 25        | 20.24        | 444      | 25        | 19.65      | 420          | 25       | 20.52      | 456       |
| ±9        |              |          |           |          |              |          |           |          |              |          |           |
| −20       | −21.6        | 396      | −20       | −21.3      | 396          | −20      | −21.23     | 396       |
| −10       | −11.56       | 396      | −10       | −11.26     | 396          | −10      | −11.19     | 396       |
| 0         | −1.5         | 396      | 0         | −1.22      | 396          | 0        | −1.12      | 396       |
| 10        | 8.44         | 450      | 10        | 8.68       | 450          | 10       | 8.97       | 450       |
| 20        | 18.35        | 666      | 20        | 18.4       | 666          | 20       | 19.02      | 684       |
| 24        | 22.26        | 846      | 24        | 22.2       | 846          | 24       | 22.92      | 864       |
| 25        | 23.18        | 900      | 25        | 23.09      | 900          | 25       | 23.76      | 918       |
| ±12       |              |          |           |          |              |          |           |          |              |          |           |
| −20       | −21.54       | 528      | −20       | −21.26     | 528          | −20      | −21.15     | 528       |
| −10       | −11.5         | 528      | −10       | −11.23     | 528          | −10      | −11.11     | 528       |
| 0         | −1.46         | 528      | 0         | −1.22      | 528          | 0        | −1.06      | 528       |
| 10        | 8.49         | 600      | 10        | 8.7        | 600          | 10       | 9.04       | 600       |
| 20        | 18.35        | 888      | 20        | 18.46      | 888          | 20       | 19.04      | 912       |
| 25        | 23.3         | 1224     | 25        | 23.2       | 1224         | 25       | 24.08      | 1272      |
| 26        | 24.26        | 1320     | 26        | 24.03      | 1320         | 26       | 24.92      | 1368      |
| 27        | 25.12        | 1416     | 27        | 25.1       | 1416         | 27       | 25.35      | 1440      |
| ±15       |              |          |           |          |              |          |           |          |              |          |           |
| −20       | −21.48       | 660      | −20       | −21.17     | 660          | −20      | −21.8      | 630       |
| −10       | −11.36       | 660      | −10       | −11.14     | 660          | −10      | −11.04     | 630       |
| 0         | −1.41        | 690      | 0         | −1.1       | 690          | 0        | −0.99      | 660       |
| 10        | 8.53         | 750      | 10        | 8.82       | 750          | 10       | 9.1        | 750       |
| 20        | 18.43        | 1110     | 20        | 18.57      | 1110         | 20       | 19.11      | 1110      |
| 25        | 23.35        | 1560     | 25        | 23.34      | 1560         | 25       | 23.98      | 1590      |
| 26        | 24.33        | 1680     | 26        | 24.36      | 1680         | 26       | 24.63      | 1710      |
| 27        | 25.15        | 1920     | 27        | 25.16      | 1830         | 27       | 25.4       | 1800      |
| 28        | 25.9         | 2010     | 28        | 25.8       | 2010         | 28       | 25.7       | 1830      |
| 28.8      | 26.4         | 2160     | 28.2      | 25.9       | 2040         | 28       | 25.8       | 1890      |

Note: P₀: Dynamic power consumption; P1dB: input one-dB power gain compression point.

To represent the nonlinearity of the proposed VM multifunction biquad filter proposed in Figure 2, the two-tone test of IMD has been used to characterize the nonlinearity of BPF response. Figure 17 shows the frequency spectrum analysis of BPF through intermodulation characteristics by applying two-tone signals, f₁ and f₂, around the corner frequency of f₀ = 102 kHz. In Figure 17, a low-frequency tone of f₁ = 101 kHz and a high-frequency tone of f₂ = 103 kHz are used with equal input amplitudes of 4.5 Vpp. As shown in Figure 17, the measured value of the third-order IMD is around −48.54 dBc, and the third-order intercept (TOI) point is around 33.84 dBm.
The parallel combination of $R_{Z}$ and $C_{Z}$ was operating in the frequency range of 8.16 to 628 kHz. Obviously, the experimental results are consistent with the theoretical values. However, the real active components have the non-ideal characteristics of AD844AN parasitic impedance effect and PCB layout issue, and the tolerances of the working resistors and capacitors will have main effects on circuit accuracy.

3.4. Proposed CFOA-Based VM QO Experimental Results

In order to get the theoretical oscillation frequency $f_{o} = 102$ kHz of the VM fully-uncoupled QO proposed in Figure 4, the values of the passive components are selected as $R_{1} = R_{2} = R_{3} = 4\, \text{k} \Omega$, and $C_{1} = C_{2} = 390\, \text{pF}$, and $R_{4} = 4.02\, \text{k} \Omega$ is greater than $R_{3}$ to ensure that the oscillations starts. Figure 18a shows the output waveforms of $V_{o1}$ and $V_{o2}$. Figure 18b shows $V_{o1}$ versus $V_{o2}$ in the X-Y plot. Figure 19 shows the frequency spectrum analysis of the oscillator output voltage. From Figures 18 and 19, the measured oscillation frequency is 103.2 kHz, which is closed to theoretical result of 102 kHz. The error percentage between the theoretical oscillation frequency and measured oscillation frequency is 1.08%. Total harmonic distortion (THD) is about 0.63%. Figure 20 shows the measured value of the oscillation frequency of Figure 4, which is measured by simultaneously changing the values of resistors $R_{1}$ and $R_{2}$. According to Figure 20, the experimental oscillation frequency varies from 8.16 to 628 kHz. These measurement results are close to theoretical prediction and confirm the feasibility of the proposed VM QO. Figure 21 shows the measured oscillation frequency relative to the magnitude ratio of the two output voltages, as explained in Equation (16). As can be seen, the constant amplitude ratio of two quadrature sinusoidal waveforms can be realized when tuning FO. The magnitude ratio of the two output voltages fluctuates from $-2.04\%$ to $1.14\%$. Automatic level control can obtain better oscillation amplitude [34]. Figure 22 shows the measured phase error percentage of the quadrature voltage outputs. The VM QO operates at frequencies from 8.16 to 628 kHz, and the maximum deviation from $90^\circ$ is less than $4.12\%$. The THD of the quadrature output voltage waveforms is shown in Figure 23. It was found that the measured THD percentage fluctuated between 0.2% and 0.66% when VM QO was operating in the frequency range of 8.16 to 628 kHz. Obviously, the experimental results are consistent with the theoretical values. However, the real active components have the non-ideal characteristics of AD844AN parasitic impedance effect and PCB layout issue. According to AD844AN datasheet [29], the actual AD844AN exhibits a non-zero input resistance of $R_{IN} = 50\, \text{Ω}$ at the port -IN. The parallel combination of $R_{Z}$ and $C_{Z}$ is the parasitic impedances connected from the current output port $T_{Z}$ of the AD844AN. For AD844AN, the nominal values are $R_{Z} = 3\, \text{M} \Omega$ and $C_{Z} = 4.5\, \text{pF}$. These additional parasitic resistances and capacitances of the AD844AN, the PCB layout issue, and the tolerances of the working resistors and capacitors will have main effects on circuit accuracy.
Figure 18. The experimental results. (a) The quadrature voltage outputs $V_{o1}$ (blue) and $V_{o2}$ (cyan); and (b) X-Y pattern.

Figure 19. The measured output frequency spectrum of $V_{o1}$.

Figure 20. The measured oscillation frequency with simultaneously varying the values of $R_1$ and $R_2$ for the proposed VM quadrature oscillator in Figure 4.
Figure 21. The measured relationship between the oscillation frequency and the magnitude ratio of quadrature output voltages.

Figure 22. The measured phase error of oscillation frequency.

Figure 23. The measured THD of oscillation frequency.
The noise of the oscillator will affect the characteristics of frequency spectrum and timing. Even if a small amount of noise can cause large variations in the oscillator’s spectrum and timing. The Keysight-Agilent N9000A CXA signal analyzer provides a phase noise measurement solution starting at 3 Hz. Figure 24 shows the phase noise performance of the operating frequency from 3 Hz to 100 kHz with different frequency offsets. The phase noise measurement result in Figure 24 shows that the phase noise of the proposed VM QO is less than $-75.23 \text{ dBc/Hz}$ at a 100 Hz offset, which has little impact on the frequency spectrum and timing. Another interesting parameter is the phase noise FoM of the proposed VM fully-uncoupled QO. Table 4 lists the phase noise performance measured at different oscillator supply voltages of ±6 V and a power consumption of 300 mW. According to Equation (17), and using the data in Table 4, the minimum phase noise FoMs of $V_{o1}$ and $V_{o2}$ are 90.3 dBc/Hz and 100.4 dBc/Hz, respectively. The measured phase noise performance under different oscillator supply voltages are summarized in Table 5.

![Figure 24](image-url). Phase noise performance with different frequency offsets measured from 3 Hz offset frequency. (a) $V_{o1}$ output phase noise; and (b) $V_{o2}$ output phase noise.
### Table 4. Phase noise performance measured at different oscillator frequencies.

| f_o (kHz) | Phase Noise (dBc/Hz) | FoM (dBc/Hz) | f_o (kHz) | Phase Noise (dBc/Hz) | FoM (dBc/Hz) |
|-----------|----------------------|--------------|-----------|----------------------|--------------|
| 8.1       | 85.23                | 98.5         | 8.1       | 87.6                | 101.2        |
| 13.3      | 83.36                | 103.9        | 13.3      | 84.35               | 102.2        |
| 20.7      | 84.27                | 105.7        | 20.7      | 80.59               | 102.3        |
| 30.9      | 84.98                | 110.0        | 30.9      | 84.61               | 109.8        |
| 41.6      | 83.56                | 111.2        | 41.6      | 81.87               | 109.7        |
| 46.1      | 84.09                | 112.4        | 46.1      | 84.39               | 113.1        |
| 52.1      | 82.84                | 112.4        | 52.1      | 82.66               | 112.4        |
| 59.6      | 81.95                | 112.7        | 59.6      | 83.29               | 114.2        |
| 69.3      | 80.74                | 112.8        | 69.3      | 81.76               | 114.0        |
| 83.4      | 92.25                | 126.5        | 83.4      | 82.21               | 116.0        |
| 104.1     | 75.23                | 110.8        | 104.1     | 74.24               | 110.0        |
| 138       | 68.28                | 120.8        | 138       | 65.43               | 103.6        |
| 205.8     | 62.26                | 118.4        | 205.8     | 76.57               | 118.2        |
| 256.7     | 47.09                | 90.3         | 256.7     | 76.48               | 120.1        |
| 300.5     | 75.29                | 119.9        | 300.5     | 71.3                | 116.3        |
| 356.9     | 73.92                | 119.9        | 356.9     | 53.93               | 100.4        |
| 402.7     | 73.54                | 120.7        | 402.7     | 72.43               | 119.9        |

Note: f_o: Oscillation frequency; and FoM: Figure-of-Merit.

### Table 5. Phase noise performance measured at different supply voltages.

| V_DC ± | Phase Noise (dBc/Hz) | ∆f (Hz) | P_DC (mW) | f_o (kHz) | FoM (dBc/Hz) | Phase Noise (dBc/Hz) | ∆f (Hz) | P_DC (mW) | f_o (kHz) | FoM (dBc/Hz) |
|--------|----------------------|--------|-----------|-----------|--------------|----------------------|--------|-----------|-----------|--------------|
| ±4.5   | 71.41               | 100    | 216       | 102       | 108.4        | 73.46                | 100    | 225       | 102       | 110.2        |
| ±6     | 72.26               | 100    | 300       | 102       | 107.8        | 74.24                | 100    | 300       | 102       | 109.8        |
| ±9     | 72.67               | 100    | 432       | 102       | 106.7        | 76.91                | 100    | 450       | 102       | 110.7        |
| ±12    | 71.9                | 100    | 576       | 102       | 104.6        | 71.6                 | 100    | 624       | 102       | 103.9        |
| ±15    | 69.88               | 100    | 720       | 102       | 101.7        | 76.28                | 100    | 780       | 102       | 107.7        |

Note: V_DC: Supply voltage; ∆f: Offset frequency; P_DC: Power consumption; f_o: Oscillation frequency; and FoM: Figure-of-Merit.

### 4. Conclusions

The paper proposes an independently tunable VM multifunction biquad filter with high-input impedance and a VM fully-uncoupled QO realized by the proposed VM multifunction biquad filter. Both proposed circuits use three CFOAs as active components, while using four resistors and two grounded capacitors as passive components. The proposed VM multifunction biquad filter offers the following important features: (i) simultaneous realization of BRF, BPF, and LPF voltage transfer functions without component value constraints, (ii) high-input impedance, (iii) using only two grounded capacitors, (iv) the X ports of the CFOAs are connected directly to the resistors, (v) independent controllability of the biquad filter control factor parameters ω_o and Q, and (vi) fully-uncoupled adjustable of CO and FO when transformed to VM QO. Unlike the recently reported VM CFOA-based multifunction biquad filter [27], the attractive feature of the proposed VM multifunction biquad filter is that it can independently control the filter control factor parameters ω_o and Q, and due to the characteristics of fully-uncoupled adjustable of CO and FO, it can be converted into VM QO. The proposed VM fully-uncoupled QO improves unbalance of produced quadrature output voltages V_o1 and V_o2, and solves the amplitude instability. The constant amplitude ratio of two quadrature sinusoidal waveforms can be realized when tuning FO. The QO oscillation frequency could be tuned in the range of 8.16 to 628 kHz and tested with ±6 V voltage power supplies. The minimum phase
noise FoM in the entire tuning range is 90.3 dBc/Hz at 100 Hz offset frequency. The measured THD is less than 0.7%. The measured P1dB and IMD of VM biquad filter are 22 and 33.84 dBm, respectively. PSpice simulations and experimental results based on commercial IC AD844AN are used to verify the theoretical characteristics of the proposed CFOA-based circuits.

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