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Implementation of Low-output-impedance Sinusoidal Oscillator and Its Modification for use in Filters

***Abstract**. In this paper, we propose a voltage-mode sinusoidal oscillator and its modification for use in filters. The circuit comprises two commercially available ICs: LT1228, a single resistor, and only two grounded capacitors. The sinusoidal signals of the proposed circuit are generated with a 90° shift at low-output-impedance ports. The condition and frequency of the oscillation can be freely controlled by setting the transconductance gains. Furthermore, the frequency and amplitude of the signals can be directly controlled by adding external resistors to adjust the voltage amplifier. In addition, our proposed sinusoidal oscillator can be slightly modified for operation with low-pass, band-pass, and high-pass filters. The quality factor can be easily and independently set by adjusting the resistor values. The implementation is used to improve the theoretical analysis. All results are in accordance with the theoretical analysis.*

Streszczenie.** W pracy proponujemy napięciowy generator sinusoidalny i jego modyfikację do zastosowania w filtrach. Obwód składa się z dwóch dostępnych na rynku układów scalonych: LT1228, pojedynczego rezystora i tylko dwóch uziemionych kondensatorów. Sygnały sinusoidalne proponowanego układu są generowane z przesunięciem o 90° na portach o niskiej impedancji wyjściowej. Stan i częstotliwość oscylacji można dowolnie kontrolować, ustawiając wzmocnienia transkonduktancji. Ponadto częstotliwość i amplitudę sygnałów można bezpośrednio kontrolować poprzez dodanie zewnętrznych rezystorów do regulacji wzmacniacza napięcia. Proponowany przez nas generator sinusoidalny można nieznacznie zmodyfikować do pracy z filtrami dolnoprzepustowymi, pasmowoprzepustowymi i górnoprzepustowymi. Współczynnik jakości można łatwo i niezależnie ustawić, dostosowując wartości rezystorów. Implementacja służy do usprawnienia analizy teoretycznej. Wszystkie wyniki są zgodne z analizą teoretyczną.* (Projekt niskoimpedancyjnego generatora sinusoidalnego i jego modyfikacja do zastosowania w filtrach***).

Keywords: low-output-impedance, voltage-mode, sinusoidal oscillator, low-pass filter, band-pass filter, high-pass filter, LT1228 IC.
Słowa kluczowe: generator sinusoidalny, wzmacniacz transkonduktancyjkny, filtr.

Introduction

Sinusoidal signals are famous for use in analog signal processing circuits and systems [1-16]. Especially, the 90° phase-shifted sinusoidal signals, well known as quadrature signals, have been advantageous in communication systems [1-7]. It is mainly used in quadrature mixers, single sideband modulation, and demodulation circuits in communication systems [9, 11-13]. In addition, sinusoidal signals are used in invertor and convertor circuits in power electronic systems [14-16]. Moreover, instrument and measurement systems must be provided with sinusoidal signals [4, 15-16]. Besides, sinusoidal signals are important to use for teaching or learning in laboratory of electronics and telecommunication engineering [14]. As mentioned above, sinusoidal oscillators are widely researched as well as reported in literature [1-16]. Their details will be remarked as follows. The sinusoidal oscillators in [1, 3, 8-9] are easily controlled in terms of their oscillation frequency by adjusting a single resistor. The electronic controlling of frequency and condition of oscillation are presented in [2, 4-6, 12-16] that are suitable for application control with microcontrollers or microprocessors [4]. The voltage-mode sinusoidal oscillators in [8-9, 14] used only single active element, which is compact and can be easily constructed. The frequency and condition of oscillation of circuits in [1-6, 12-13, 15] can be independently adjusted. The experiments on sinusoidal oscillators based on commercially available ICs in [4-6, 12, 14-16] can be directly controlled by external bias currents or voltages. Subsequently, the experiment on circuits in [4] can be adjusted in terms of its frequency, condition, and amplitude.

However, the sinusoidal oscillators mentioned above have some disadvantages that are detailed as follows:

(i) The output voltages are high-output-impedance ports [5-7, 9, 12, 15-16], requiring a voltage buffer for connection to the next stages or other circuits.

(ii) The circuits must be used for floating capacitors [10-11, 13], which is unsuitable for integrated circuit configuration.

(iii) Some circuits [8, 10, 14] cannot generate quadrature sinusoidal signals.

(iv) The proposed circuits are used with many active elements [5-6, 15];

(v) The results do not verify the performance of the experiment [2-3, 7-9].

A comparison of the proposed sinusoidal oscillator and the previous publication is presented in Table I.

Simultaneously, various universal filters are used for analog signal processing. The implementation and experiments of universal filters have been published the most [17-26]. The output responses of the filter circuit in [17] are denoted as low-pass, high-pass, and band-pass, and can be electronically controlled. Moreover, the output signals must be used as current mirror circuits to connect to other stages. The voltage-mode universal filters in [18-19] are compacted because they use a single LT1228 IC; however, they are required to use a floating capacitor. The filters proposed in [20-21] realize five standard filter functions and can be controlled using an electronic method. Nevertheless, they have some disadvantages, such as the voltage outputs of [20], which are high-impedance ones, similar to the pole frequency, and the quality factor in [21] must be simultaneously adjusted. The high-input-impedance filter in [22] was introduced to electronic adjustability and realized all filter functions, but it necessitates the use of three active elements. The pole frequency and quality factor of the filters in [23-24] are presented via an independent adjustment. The filters proposed in [25-26] are essential for IC fabrication because they use only grounded elements and their sensitivities are low. However, the filter in [23, 26] cannot be electronically controlled, which is unsuitable for use in automatic systems.

We herein propose a low-output-impedance of a voltage-mode sinusoidal oscillator and its modification for use in filters. The proposed circuit uses commercially available ICs LT1228, one resistor, and two grounded capacitors. The frequency and condition of the oscillation can be easily controlled via external bias currents. In addition, the frequency and amplitude are directly adjusted by adding external resistors to tune the voltage gain. Moreover, the proposed sinusoidal oscillator can be slightly modified for filters that are low-pass, band-pass, and high-pass responses. As well, the quality factor can be controlled by a single resistor without affecting the pole frequency, and the pole frequency can be adjusted using the electronic method. The explanation of the proposed circuit and its results is detailed as follows:

Table I Comparison of the proposed sinusoidal oscillator and the previous publication

Ref.	Active element	No. of Active elements	No. C + R	Only Grounded Capacitor	Electronic tuning	Low-impedances ports	Quadrature signal	Results
[1]	CDBA	2	2+3	Yes	No	Yes	Yes	Experiment
[2]	VDBA	2	2+1	Yes	Yes	Yes	Yes	Simulation
[3]	CDBA	2	2+4	Yes	No	Yes	Yes	Simulation
[4]	LT1228	3	2+1	Yes	Yes	Yes	Yes	Experiment
[5]	OTA	5	2+0	Yes	Yes	No	Yes	Experiment
[6]	OTA	5	2+0	Yes	Yes	No	Yes	Experiment
[7]	CCII	2	2+3	Yes	No	No	Yes	Simulation
[8]	FTFNTA	1	2+2	Yes	Yes	Yes	No	Simulation
[9]	DVCC	1	2+2	Yes	No	No	Yes	Simulation
[10]	CFOA	2	2+4	No	No	Yes	No	Experiment
[11]	CDBA	2	7+7	No	No	Yes	Yes	Experiment
[12]	MO-CCCCTA	2	3+0	Yes	Yes	No	Yes	Experiment
[13]	CDBA CDBA CDBA CDBA	2 2 2 2	2+4 2+4 2+5 2+5	No No Yes Yes	No No No No	Yes Yes Yes Yes	Yes Yes Yes Yes	Experiment Experiment Experiment Experiment
[14]	LT1228	1	2+1	Yes	Yes	Yes	No	Experiment
[15]	OTA	4	2+0	Yes	Yes	No	Yes	Experiment
[16]	VDTA	1	2+0	Yes	Yes	No	Yes	Experiment
Proposed circuit	LT1228	2	2+1	Yes	Yes	Yes	Yes	Experiment

Materials and methods

LT1228

The active element of the proposed circuit is a commercially available IC, LT1228. It is a product of the Linear Technology Corporation [27] and is versatile for analog signal processing. The electrical symbol of LT1228 is depicted in Figure 1 (a), and its equivalent circuit is shown in Figure 1 (b). The construction of LT1228 is shown in Figure (c), involving an operational transconductance amplifier (OTA) and a current feedback amplifier (CFA). The OTA has a high-impedance differential input, and the transconductance gain g_m is set by the externally controlled current that flows into Pin 5 (I_{SET}), while $g_m = 10 I_{SET}$. The CFA has very-high-input and low-output impedances; therefore, it is an excellent buffer for the output of the OTA. The ideal electrical properties of the voltage and current of LT1228 are detailed in the following equation:

(1) $$\begin{vmatrix} I_{V+} \\ I_{V-} \\ I_y \\ V_y \\ V_w \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & R_T & 0 \end{vmatrix} \begin{vmatrix} V_+ \\ V_- \\ V_z \\ I_y \\ I_w \end{vmatrix} .$$

Here, g_m denotes the transconductance gain for converting the difference voltages of V+ and V- ports to the current at the y port.

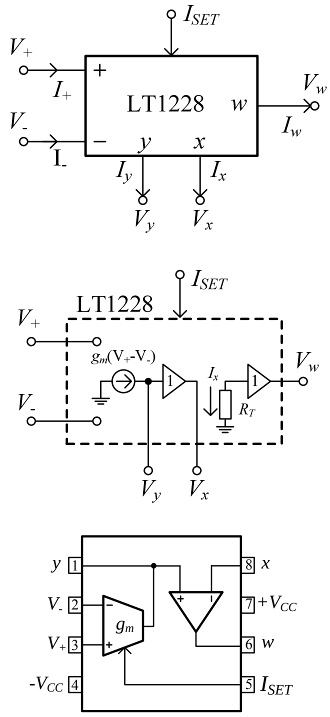
Proposed low-output-impedance sinusoidal oscillator

Figure 2 presents a schematic of the proposed low-output-impedance sinusoidal oscillator. The sinusoidal oscillator utilizes two LT1228, one resistor, and only two capacitors connected to the ground. The sinusoidal signals are generated in the voltage mode, and the outputs are at the low-output-impedance ports. Consequently, output signals can be directly cascaded or connected to other stages or circuits. The characteristic equation of the schematic can be analyzed using the electrical properties of LT1228 in Equation (1):

(2) $$s^2 + \left(\frac{1}{R_1} - g_{m2} \right) \frac{s}{C_2} + \frac{g_{m1}}{R_1 C_1 C_2} = 0$$

The proposed circuit can generate sinusoidal signals by setting the oscillation condition. This can be succeeded by configuring as follows:

(3) $$\frac{1}{R_1} \cong g_{m2} \quad .$$



(a)

(b)

(c)

Fig. 1. The LT1228 (a) electrical symbol, (b) equivalent circuit, and (c) pin configuration

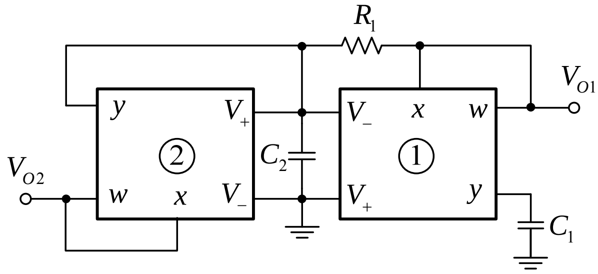


Fig. 2. Proposed sinusoidal oscillator

The frequency of oscillation is successfully determined by the following equation

(4) $$f_{osc} = \frac{1}{2\pi}\sqrt{\frac{g_{m1}}{R_1 C_1 C_2}} .$$

The condition and frequency of oscillation can be substituted for the transconductance gain in Equations (3) and (4), respectively. The condition of oscillation is electronically adjustable by the external DC current I_{SET2}, which is expressed as

(5) $$\frac{1}{R_1} \cong 10 I_{SET2} .$$

In addition, the frequency of oscillation can be electronically adjustable by the external DC current I_{SET1}, which is given by

(6) $$f_{osc} = \frac{1}{2\pi}\sqrt{\frac{10 I_{SET1}}{R_1 C_1 C_2}} ,$$

and the frequency of oscillation is proportional to the externally controlled current. The condition and frequency of oscillation are independently/electronically adjustable with two separate g_m.

Furthermore, the transfer function of sinusoidal signals can be expressed as

(7) $$\frac{V_{O1}(s)}{V_{O2}(s)} = -\frac{g_{m1}}{C_1 s} .$$

The phase relation of sinusoidal signals becomes 90°, i.e.

(8) $$\frac{V_{O1}(j\omega)}{V_{O2}(j\omega)} = \left|\frac{g_{m1}}{C_1 \omega}\right| e^{-j90} .$$

(9) $$S_{g_{m1}}^{\omega_{osc}} = \frac{1}{2} ,\ S_{R_1, C_1, C_2}^{\omega_{osc}} = -\frac{1}{2} .$$

It is clear that the sensitivities are less than unity.

Effect of parasitic elements

LT1228 has a parasitic element at high-impedance ports such as V+, V-, and y ports. These parasitic elements have high-value resistors connected to the ground and low-value capacitors connected to the ground. The output ports x and w are in series with low-parasitic-values of resistors. The details are presented in Figure 3.

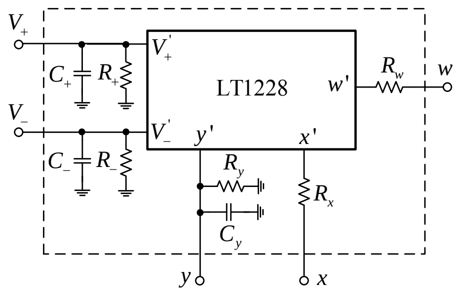


Fig. 3. LT1228 with the parasitic elements

The characteristic equation of the proposed sinusoidal oscillator is reanalyzed by including the parasitic elements of LT1228, where $R_1 >> R_x$ and R_W, that is,

(10) $$s^2 + \left(\frac{G_{y1}}{C_{T1}} + \frac{G_{T2}}{C_{T2}} + \frac{G_1}{C_{T2}} - \frac{g_{m2}}{C_{T2}}\right)s + \frac{G_{y1}G_{T2} + G_{y1}G_1 - g_{m2}G_{y1} + g_{m1}G_1}{C_{T1}C_{T2}} = 0 .$$

Subsequently, the frequency and condition of oscillation are modified in Equations (11) and (12), respectively.

(11) $$\omega_{osc} = \sqrt{\frac{G_{y1}G_{T2} + G_{y1}G_1 - g_{m2}G_{y1} + g_{m1}G_1}{C_{T1}C_{T2}}} ,$$

and

(12) $$\frac{G_{y1}}{C_{T1}} + \frac{G_{T2}}{C_{T2}} + \frac{G_1}{C_{T2}} \approx \frac{g_{m2}}{C_{T2}} ,$$

where $C_{T1} = C_1 + C_{z1}$, $C_{T2} = C_2 + C_{z2} + C_{V_+2} + C_{V\_1}$, $G_1 = 1/R_1$, $G_{y1} = 1/R_{y1}$ and $G_{T2} = G_{y2} + G_{V_+2} + G_{V\_1} = 1/R_{y2} + 1/R_{V_+2} + 1/R_{V\_1}$.

The parasitic elements depreciate the performance of the proposed oscillator. However, the effect of the frequency and condition of oscillation can be directly solved and corrected by a slight adjustment of the transconductance gain of LT1228.

Frequency and amplitude increments of the proposed sinusoidal oscillator

The frequency of oscillation can be controlled by adding a voltage amplifier, as shown in Figure 4. It can be set up by adding external resistors, R_{F1} and R_{F2}. Then, the oscillation frequency becomes

(13) $$f_{osc} = \frac{1}{2\pi}\sqrt{\frac{10 I_{SET1}}{R_1 C_1 C_2}\left(\frac{R_{F1}}{R_{F2}} + 1\right)} .$$

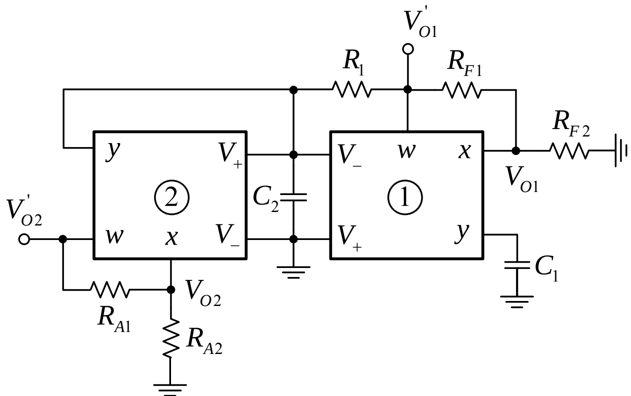


Fig. 4. Proposed sinusoidal oscillator with frequency and amplitude adjustment

However, the external resistors R_{F1} and R_{F2} are directly affected by the amplitude of the output voltage V_{O1}. In addition, the voltage gain of the output voltage, $V_{O1}^{'}$ and V_{O1} can be calculated as

(14) $$A_{V1} = \frac{V_{O1}^{'}}{V_{O1}} = \frac{R_{F1}}{R_{F2}} + 1 .$$

Therefore, the frequency of oscillation can be directly adjusted by g_{m1}, the voltage gain, or both.

In addition, the amplitude of the output voltage V_{O2} can be adjusted by adding a voltage amplifier. It is set up by the external resistors, R_{A1} and R_{A2}, the voltage amplifier is not affected by the frequency and amplitude of $V_{O1}^{'}$. The amplitude of the output voltage $V_{O2}^{'}$ in relation to V_{O2} can be detailed by using the following expression:

(15) $$A_{V2}=\frac{V_{O2}^{'}}{V_{O2}}=\frac{R_{A1}}{R_{A2}}+1\,.$$

The frequency and amplitude can be adjusted by adding a voltage amplifier as well as the output voltages $V_{o1}^{'}$ and $V_{O2}^{'}$ are low-output impedances that do not require a buffer devices.

Experimental results

The experimentation of the proposed sinusoidal oscillator in Figure 4 can be achieved by configuring the external passive elements as, $R_1=1k\Omega$, $R_{F1}=R_{F2}=R_{A1}=R_{A2}=10k\Omega$ and $C_1=C_2=1nF$. The Siglent SPD3303C power supply was used to power the voltage bias of the circuit by setting it to $\pm 5V$. The condition of oscillation is electronically set by configuring the transconductance gain at $g_{m2}=1000\mu A/V$, and the external bias current $I_{SET2}=100\mu A$. Simultaneously, the frequency of oscillation is electronically set by defining the external bias current $I_{SET1}=100\mu A$ for the transconductance gain $g_{m1}=1000\mu A/V$. These external bias currents were tested with a Keysight 34461A multimeter for supplying to the circuit. A Keysight DSOX3024T oscilloscope was used to measure the sinusoidal waveforms and properties of the output signals. The first results of $V_{o1}^{'}$ and $V_{O2}^{'}$ are illustrated in the voltage waveforms in Figure 5. In this result, the resistor R_{A1} must be adjusted to $3.9k\Omega$ for the same amplitude of output signals. The frequency of oscillation is 224.5kHz, while the calculated frequency from Equation (4) is approximately 225kHz. The absolute error of the theoretical and experimental frequencies was approximately 0.22%. This deviation in frequency arises from the tolerance errors of the external passive elements and the parasitic resistances and capacitances of LT1228. However, the effect of tolerance errors can be directly eliminated and decreased by slightly adjusting the transconductance gain g_{m1} and voltage gain by adjusting R_{F1} and R_{F2} or both.

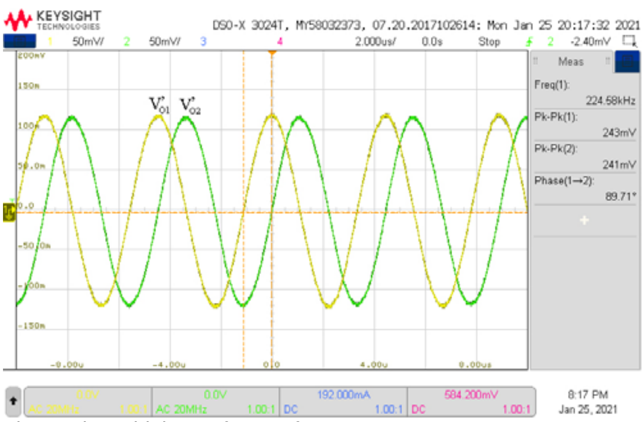


Fig. 5. Sinusoidal waveforms of outputs

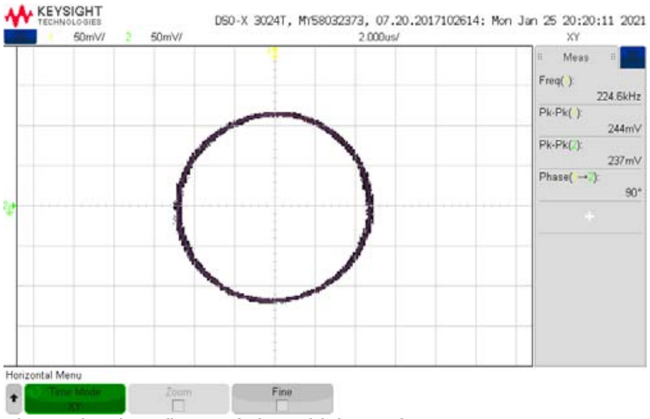
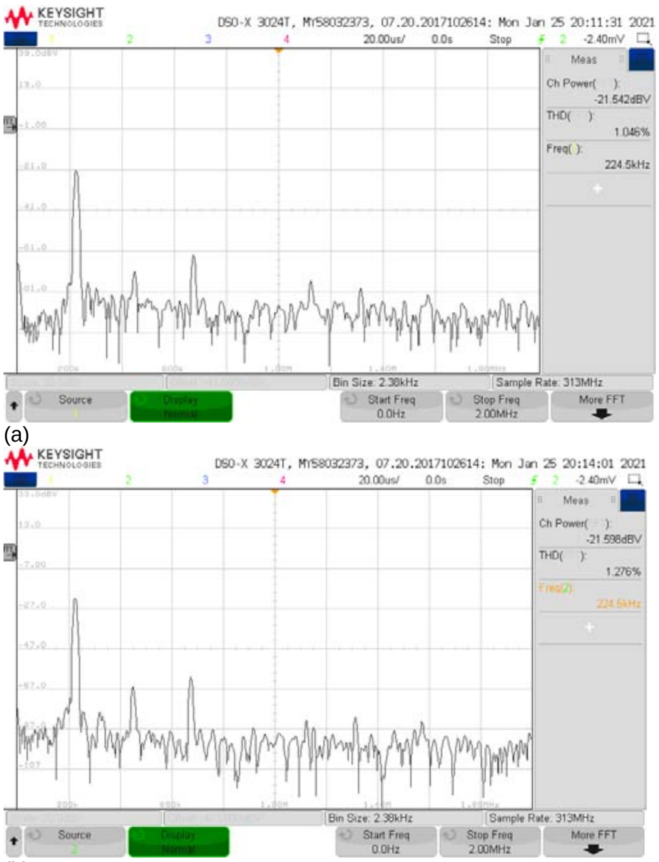


Fig. 6. Lissajous figure of sinusoidal waveforms



(a)

(b)

Fig. 7. Frequency spectrum of output sinusoidal signals (a) $V_{o1}^{'}$ and (b) $V_{O2}^{'}$

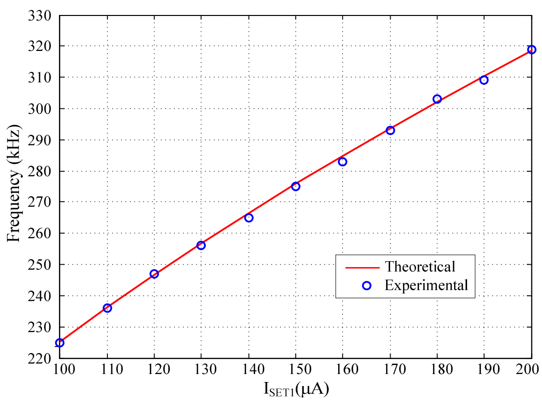


Fig. 8. Frequency of oscillation vs. I_{SET1}

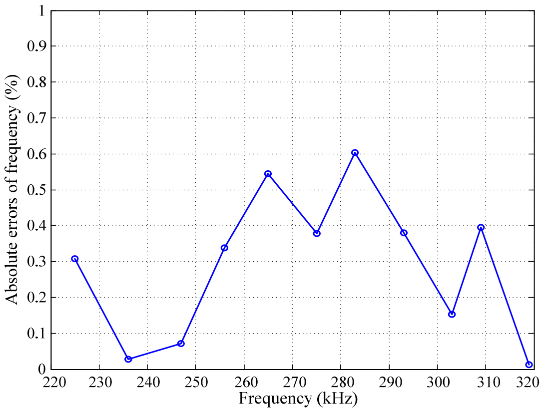


Fig. 9. Absolute errors of frequency

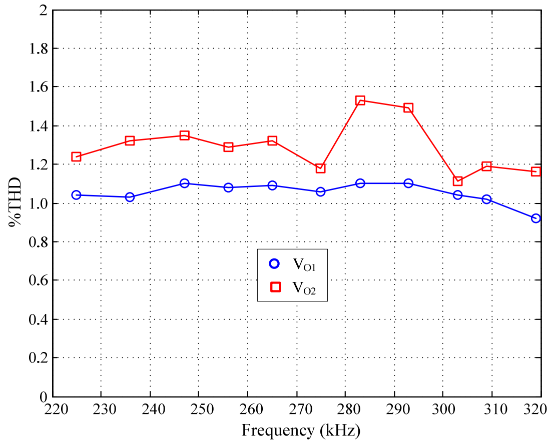


Fig. 10. %THD vs. frequency of oscillation

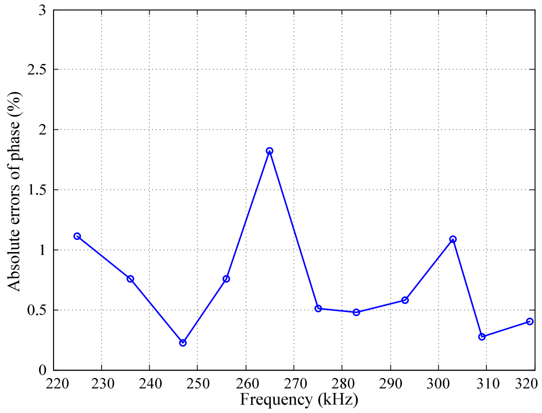


Fig. 11. Phase error of $V_{o1}^{'}$ and $V_{O2}^{'}$

The phase relation of $V_{o1}^{'}$ and $V_{O2}^{'}$ is approximately 89.7°, which deviates from 90° by approximately 0.33%. The relation of the phase of the sinusoidal signals by the XY plot is displayed in Figure 6. The spread spectra of the frequencies of $V_{o1}^{'}$ and $V_{O2}^{'}$ are shown in Figure 7 (a) and (b), respectively. The total harmonic distortions (THD) of the sinusoidal output signals $V_{o1}^{'}$ and $V_{O2}^{'}$ are measured and displayed in Figure 7 (a) and (b), respectively, corresponding to approximately 1.04% and 1.24%. The electronically controllable frequency can be demonstrated in Figure 8, when the external current bias I_{SET1} is varied from $100\mu A$ to $200\mu A$. The results of the electronically controllable frequency are clearly compared to the experimental and theoretical calculations, which are slightly different. The absolute errors of frequency of oscillation can be plotted in Figure 9. The maximum and minimum absolute errors of frequency are approximately 0.60% at 284.84kHz and 0.01% at 318.47kHz, respectively. Figure 10 shows the measurement of %THD versus the frequency of oscillation, which is lower than 2%. The absolute errors of the phase by 90° of $V_{o1}^{'}$ and $V_{O2}^{'}$ can be measured and plotted in Figure 11. Their absolute errors were lower than 2%.

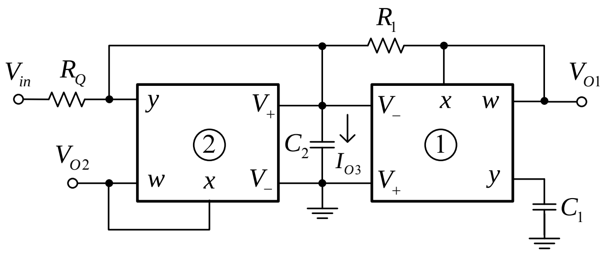


Fig. 12. Proposed filters

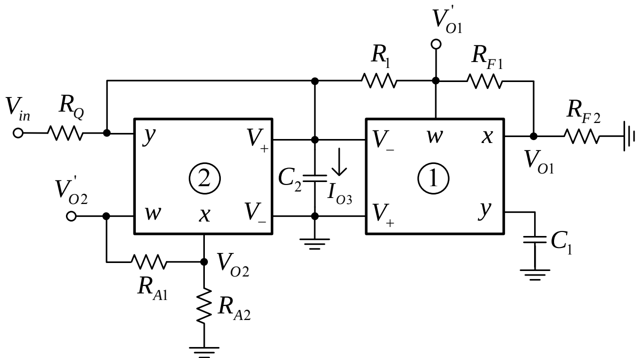


Fig. 13. Proposed filter with the pole frequency, quality factor and amplitude adjustment

Modification for filters

The sinusoidal oscillator can be modified for low-pass, high-pass, and band-pass filters. It is slightly modified by cascading the external passive resistor with the proposed sinusoidal circuit shown in Figure 12. The complete voltage-mode transfer function of V_{O1}, V_{O2}, and I_{O3} can be analyzed and written as

$$\frac{V_{O1}}{V_{in}} = \frac{\dfrac{g_{m1}}{C_1C_2R_1}}{s^2 + \dfrac{1}{C_2R_Q}\left(\dfrac{R_Q}{R_1} + 1 - g_{m2}R_Q\right)s + \dfrac{g_{m1}}{C_1C_2R_1}}, \tag{16}$$

$$\frac{V_{O2}}{V_{in}} = \frac{\dfrac{1}{C_2R_Q}s}{s^2 + \dfrac{1}{C_2R_Q}\left(\dfrac{R_Q}{R_1} + 1 - g_{m2}R_Q\right)s + \dfrac{g_{m1}}{C_1C_2R_1}}, \tag{17}$$

and

$$\frac{I_{O3}}{V_{in}} = \frac{\dfrac{1}{R_Q}s^2}{s^2 + \dfrac{1}{C_2R_Q}\left(\dfrac{R_Q}{R_1} + 1 - g_{m2}R_Q\right)s + \dfrac{g_{m1}}{C_1C_2R_1}}, \tag{18}$$

Equations (16)–(18) denote the low-pass, band-pass, and high-pass transfer function, respectively. However, the high-pass response cannot be directly used but can be applied to a current mirror circuit to copy a current through to other devices.

In addition, the parameters of the pole frequency (f_p) and quality factor (Q_p) can be analyzed and expressed as

$$f_p = \frac{1}{2\pi}\sqrt{\frac{g_{m1}}{R_1C_1C_2}}, \tag{19}$$

and

$$Q_p = \frac{R_1R_QC_2}{R_Q + R_1 - g_{m2}R_1R_Q}\sqrt{\frac{g_{m1}}{R_1C_1C_2}}. \tag{20}$$

However, the quality factor can be adjusted by changing the values of the resistor R_Q without distributing the pole frequency.

In addition, the pole frequency and amplitude of the output of the filter can be tuned by adding a voltage amplifier with the same configuration as the proposed sinusoidal oscillator, as shown in Figure 13.

The pole frequency, quality factor, and amplitude of the outputs are modified to Equations (21), (22), (23), and (24), respectively.

$$f_p = \frac{1}{2\pi}\sqrt{\frac{g_{m1}}{R_1C_1C_2}\left(\frac{R_{F1}}{R_{F2}}+1\right)}, \tag{21}$$

$$Q_p = \frac{R_1R_QC_2}{R_Q + R_1 - g_{m2}R_1R_Q}\sqrt{\frac{g_{m1}}{R_1C_1C_2}\left(\frac{R_{F1}}{R_{F2}}+1\right)}, \tag{22}$$

$$V_{O1}^{'} = \left(\frac{R_{F1}}{R_{F2}}+1\right)V_{O1}, \tag{23}$$

and

$$V_{O2}^{'} = \left(\frac{R_{A1}}{R_{A2}}+1\right)V_{O2}. \tag{24}$$

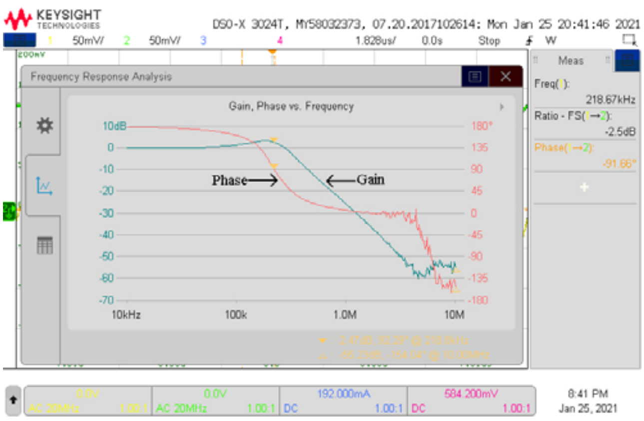


Fig. 14. Low-pass responses

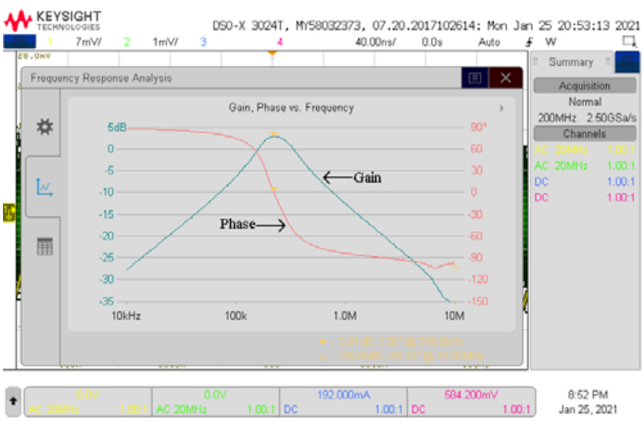
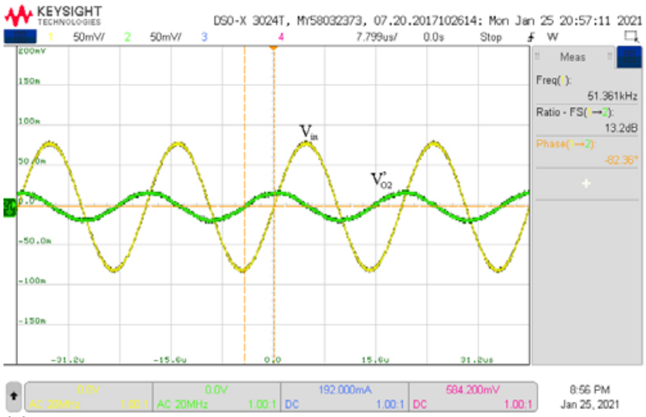
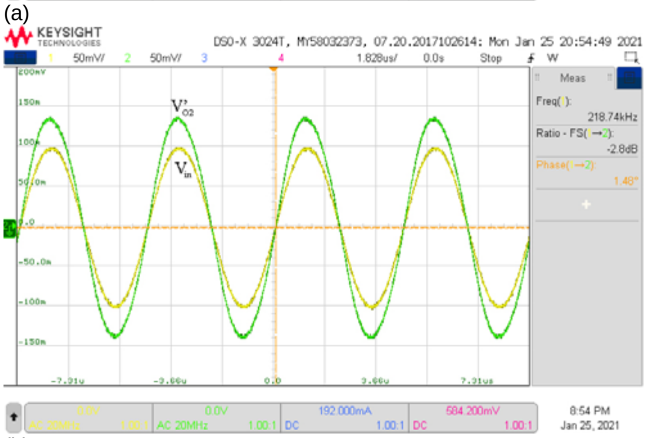


Fig. 15. Band-pass responses

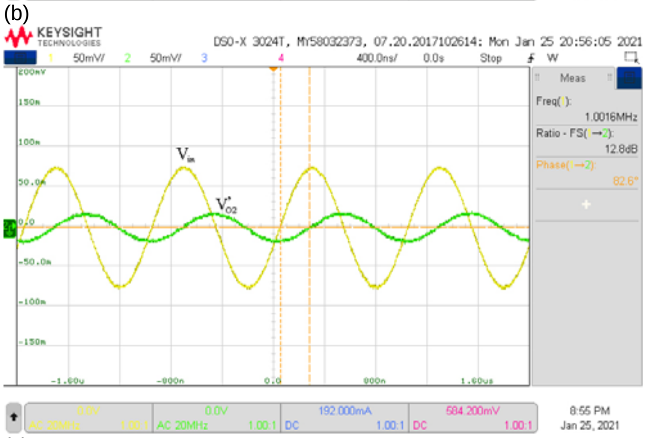
The experiment of the proposed filter in Figure 13 is operated by setting the external passive elements, as in the case of the sinusoidal oscillator and R_Q = 1 kΩ. The voltage and current biases are configured as $\pm 5V$ and $I_{SET1}=I_{SET2}$ = 1000 μA. The frequency responses of the proposed filter were used in the Keysight oscilloscope model DSOX3024T using the frequency response analyzer function. The frequency response analyzer was set by sweeping the frequency from 10kHz to 1MHz with a 100-mVp-p amplitude. The gain and phase responses in Figure 14 are the experimental results of the output, V_{O1} which is a low-pass response. The maximum gain and phase at the pole frequency of the low-pass response are approximately 2.47dB and 92°, respectively. Furthermore, the results of the band-pass response of V_{O2} are depicted in Figure 15, including gain and phase responses that are 2.8dB and 1.02°, respectively. The pole frequency and quality factor of the results are approximately 218.8kHz and 1, respectively.



(a)



(b)



(c)

Fig. 16. Band-pass responses at (a) 51.3kHz (b) 218.7kHz, and (c) 1MHz

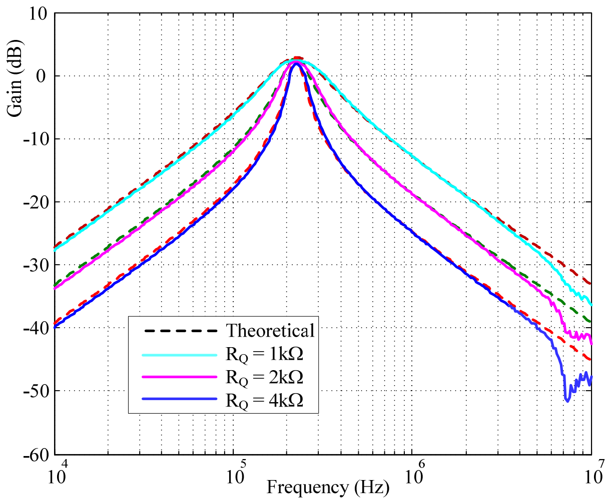


Fig. 17. Band-pass responses with different R_Q (a) $R_Q = 1k\Omega$, (b) $R_Q = 2k\Omega$, and (c) $R_Q = 4k\Omega$

Figure 16 (a), (b), and (c) display the sinusoidal waveforms of the band-pass responses for comparison of the input and output signals, with frequencies of 50.3kHz, 218.7kHz, and 1MHz, respectively. However, the quality factor can be demonstrated to be adjustable by changing $R_Q = 1k\Omega, 2k\Omega$ and $4k\Omega$, while the quality factors are varied to 1, 2, and 4, respectively. These results can be presented by band-pass responses to compare the experimental and theoretical analyses in Figure 17. The experimental results of the filter show that the gain and phase responses agree with the theoretical analysis.

Conclusions

The implementation of a sinusoidal oscillator with low-output-impedances is proposed. The electronically adjustable frequency and condition can be adjusted using the transconductance g_{m1} and g_{m2}, respectively. Furthermore, the external capacitors are only connected to the ground, which is important for the development of integrated circuits. Moreover, the frequency and amplitude of the signals can be directly controlled by adding a voltage amplifier. The proposed sinusoidal oscillator is a slight modification of the filters. The responses of the filter are provided as low-pass, high-pass, and band-pass. The pole frequency can be electronically adjusted by the transconductance. Moreover, the quality factor can be freely adjusted by an external resistor without affecting the pole frequency. The experimental results of the sinusoidal oscillator and filter agree with those of the theoretical analysis.

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