İSTANBUL UNIVERSITY CERRAHPAŞA

ORIGINAL ARTICLE
Electrica 2024; 24(3): 799-811

Single Commercially Available Integrated Circuit-based Sinusoidal Oscillators with Amplitude Adjustability and Electronic Control of Condition

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Cite this article as: S. Duangkaew, P. Supavarasuwat, M. Siripruchyanun, R. Sotner, W. Jaikla and W. Sunthonkanokpong, "Single commercially available integrated circuit-based sinusoidal oscillators with amplitude adjustability and electronic control of condition," *Electrica*, 24(3), 799-811, 2024.

ABSTRACT

This paper presents four new sinusoidal oscillators using a commercially available integrated circuit (IC). The proposed circuits are simple topologies that employ a single commercial IC, LT1228. It is connected to passive element, consisting of four resistors and two capacitors. All derived oscillator circuits have low output impedance, allowing them to connect to other circuits without requiring an additional buffer. Using an active LT1228 device enables electronic adjustment of parameters in the proposed circuits. A feedback resistor can be used to change the output signal's amplitude without affecting the oscillation's frequency or condition. We performed both simulations using the PSPICE program and experiments to confirm the accuracy of all proposed oscillator circuits. The best total harmonic distortion was 0.13% for the proposed oscillator circuit 3. Adjusting the maximum amplitude using a resistor provides a gain of roughly 1.5–16.5 dB for the proposed oscillator circuit no. 1.
Index Terms—Active building block, analog circuit, electronic Tune, LT1228, sinusoidal oscillator

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Received: July 14, 2024

Revision Requested: July 29, 2024

Last Revision Received: September 25, 2024

Accepted: October 11, 2024

Publication Date: November 8, 2024

DOI: 10.5152/electrica.2024.24082

I. INTRODUCTION

Sinusoidal oscillators are electronic circuits specifically designed to produce continuous-time sinusoidal waveforms. They are significant circuits in various applications, such as instrumentation, measurement, communication, control, and other electronic systems [1-4]. These circuits can generate a sinusoidal waveform with only a DC power voltage supply and no additional input voltage or current signal. In telecommunication systems, sinusoidal signals serve as carrier signals for modulation and demodulation in both the transmitter and receiver. For use in various applications, most sinusoidal oscillators are designed to obtain the capacity to tune the frequency and condition of oscillation independently. However, creating the oscillator with the simplest structure is imperative to minimize size, expenses, and power consumption for applications requiring a sine wave of a specific or single frequency. Furthermore, the oscillators should be able to adjust the amplitude of the sinusoidal output waveform, thereby avoiding the need for an additional amplifier to reduce the cost, power, and complexity of the system.

The active building block (ABB) is widely used to design various analog and mixed-mode circuits. Utilizing ABB to realize high-performance circuits can minimize external complexity by interconnecting only a few passive components. Several ABB structures have been implemented using a high number of CMOS or BJT transistors. The advantages of transistor-based ABB architectures include a low power supply, low power consumption, compact size, high speed, minimizing the impact of temperature variations and fabrication mismatches, and so on [5]. Nevertheless, ABB circuits based on CMOS technology exhibit optimal efficiency when fabricated as monolithic chips. Monolithic chips are also expensive to manufacture. For this reason, using the commercially available integrated circuit (IC)-based ABB to realize new active circuits in specific applications is more convenient and cheaper. The well-known commercially available ABBs include LF351, uA741 for operational amplifiers (opamps), AD844, OPA860, EL2082 for current conveyors (CC), and LM13700, LT1228 for operational transconductance amplifiers (OTAs), AD835 for analog multiplier, etc. The LT1228 is an intriguing off-the-shelf active device. It is a modular commercial IC comprising two subparts, the OTA and the current feedback amplifier (CFA), in the same IC package. The OTA in the LT1228 IC converts the voltage difference at the input into an output current using electronically adjustable transconductance (g_m). The CFA with low-impedance outputs can serve as an exceptional amplifier or buffer for the OTA's output in voltage-mode operation [6].

Table I compares and displays the review of commercially available IC-based sinusoidal oscillators [7-26], which includes the circuits we proposed in this paper. These sinusoidal oscillators use various ICs, including AD844, AD835, AD830, EL2082, OPA860, OPA633, VCA810, and LT1228. The proposed sinusoidal oscillators in refs. [7, 9-14, 16, 18, 21-23, and 25] are quadrature oscillators, which give two output signals with a 90-degree phase difference. Although several oscillators have been designed to enable independent adjustment of frequency and condition, some circuits use an extensive number of active devices [7-18, 20-23, 25] and several different kinds of commercially available ICs [10, 14, 20-23]. In practical applications of sinusoidal oscillators, electronic tunability is a crucial automatic feature. The works presented in refs. [10, 14, 18-21, 23, and 26] achieve the electronically controlled feature, whereas the oscillators proposed in refs. [7, 8, 9, 11-13, 15, 16, 17, 22, 24, and 25] do not. Since the voltage or current nodes of the sinusoidal oscillators proposed in refs. [10, 14, and 23] lack low or high impedance, a buffer is required to connect them to the load or next circuits. The amplitude of the sinusoidal output waveform cannot be adjusted without affecting the frequency or condition of oscillation [7-20, 22-25]. Although the proposed oscillator in ref. [21] can adjust the amplitudes of the generated sinusoidal signals, it requires an enormous number of

TABLE I. COMPARISON OF SINUSOIDAL OSCILLATORS BASED ON COMMERCIAL IC

Ref.	No. of Commercial IC	(1)	(2)	(3)	(4)	(5)
[7]	3 (AD844)	No	Yes	No	No	sim
[8]	2 (LT1364)	No	Yes	No	No	both
[9]	3 (AD844)	No	Yes	No	No	both
[10]	5 (3 EL2082, 1 OPA860 and 1 buffer OPA633)	Yes	No	No	No	exp
[11]	3 (AD844)	No	Yes	No	No	exp
[12]	2 (OPA860)	No	Yes	No	No	both
[13]	3 (AD844)	No	Yes	No	No	exp
[14]	4 (1 AD830, 1 AD835, 2 EL2082)	Yes	No	No	No	exp
[15]	2 (AD844)	No	Yes	No	No	exp
[16]	4 (AD844)	No	Yes	No	No	both
[17]	3 (AD844)	No	Yes	No	No	both
[18]	5 (LT1228)	Yes	Yes	No	No	both
[19]	1 (LT1228)	Yes	Yes	No	No	both
[20]	4 (OPA860)	Yes	Yes	No	No	both
[21]	3 (LT1228)	Yes	Yes	Yes	Yes	exp
[22]	3 (AD844)	No	Yes	No	No	both
[23]	2 (1 AD844,1 LM13700)	Yes	No	No	No	both
[24]	1 (AD844)	No	Yes	No	No	exp
[25]	8 (OPA860)	No	Yes	No	No	exp
[26]	1 (LT1228)	Yes	Yes	Yes	No	both
Proposed No. 1	1 (LT1228)	Yes	Yes	Yes	No	both
Proposed No. 2	1 (LT1228)	Yes	Yes	Yes	No	both
Proposed No. 3	1 (LT1228)	Yes	Yes	Yes	No	both
Proposed No. 4	1 (LT1228)	Yes	Yes	Yes	Yes	both

(1) Electronic tune. (2) Cascadeability. (3) Gain controllability without affecting the FO and CO. (4) Gain controllability without affecting the operational frequency. (5) Testing; exp: Experiment, both: Simulation and Experiment.

commercial ICs (three LT1228s). Reference [26] reported the successful realization of a simple oscillator using a single LT1228 IC based on the negative resistance–capacitance simulator. The amplitude of the generated sinusoidal waveform in this oscillator can be adjusted without impacting the frequency or condition of the oscillation by adjusting the feedback resistor. However, changing the feedback resistor's value will impact the circuit's bandwidth.

This study proposes an extended oscillator design inspired by ref. [26] to realize simple sinusoidal oscillators using a single LT1228 IC as an active device. This paper's structure is as follows: Section II provides an overview of the commercially available LT1228 IC, the proposed sinusoidal oscillators, and the study of the parasitic impedance effect. Section III presents the simulation results of the proposed sinusoidal oscillators, as well as the experimental results of the designed circuits. Section IV presents a concise overview of the findings.

II. PROPOSED CIRCUIT

A. Overview of LT1228

The LT1228 combines a fast OTA and CFA [6]. Linear Technology manufactures this commercial IC within an eight-lead plastic dual-in-line package (PDIP). The circuit symbol used for the explanation in this paper, labeled with pin numbers, is shown in Fig. 1a, encompassing two voltage input terminals (Pin 2 marked as V_+ and Pin 3 marked as $V\_$) that have high impedances, one current output terminal marked as the y terminal (Pin 1), which has high impedance, and two output voltage terminals marked as the *x* terminal (Pin 8) and *w* terminal (Pin 6) that have low impedance. Additionally, the OTA's transconductance is electronically controlled by the DC bias current (I_B) entering Pin 5. The two terminals, Pin 7 labeled as $+V_{CC}$ and Pin 4 labeled as $-V_{EE}$, accommodate a wide range of power supply voltages from approximately ±2 V to approximately ±15 V. Fig. 1b depicts the equivalent circuit of the LT1228. The matrix equation serves as (1), a crucial tool for determining the ideal voltage–current terminal characteristics of the LT1228 [6, 21].

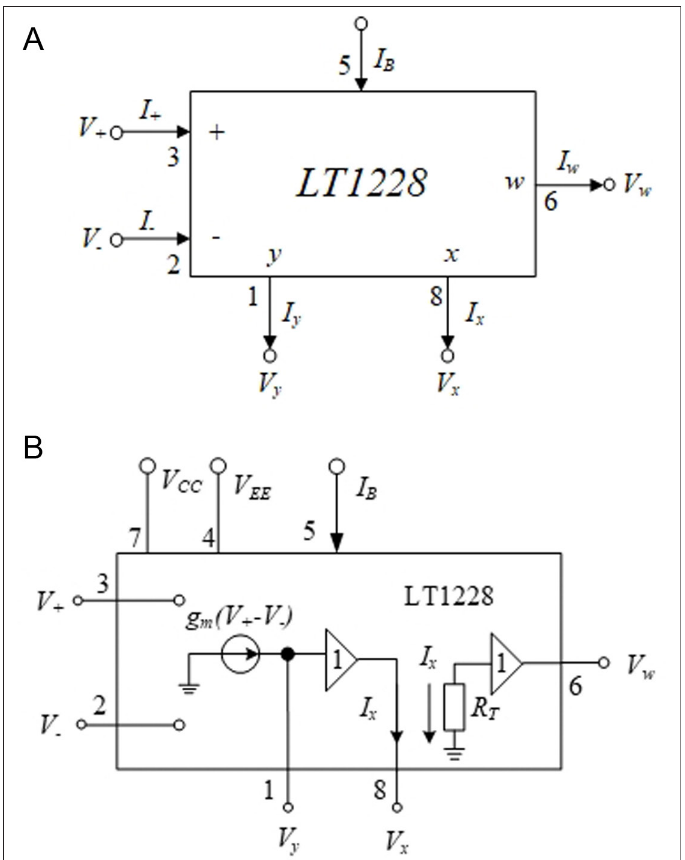


Fig. 1. LT1228. (a) Symbol. (b) Equivalent circuit [21].

$$\begin{pmatrix} I_+ \\ I_- \\ I_y \\ V_x \\ V_w \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & R_T & 0 \end{pmatrix} \begin{pmatrix} V_+ \\ V_- \\ V_y \\ I_x \\ I_w \end{pmatrix} \quad (1)$$

In (1), R_T denotes the trans-resistance gain, which tends towards an infinitely large number under ideal conditions. This feature allows the voltage gain of the CFA to be infinite, which makes it an exceptional amplifier or buffer for the output of the OTA. It is noteworthy that g_m can be controlled through the adjustment of external DC bias current, as follows [6, 21]:

$$g_m = 10 I_B \quad (2)$$

B. Proposed Sinusoidal Oscillators Based on LT1228

The goals for designing the sinusoidal oscillators presented in this study are to achieve electronic and amplitude controllability, as well as simple construction utilizing only one active device and a low-voltage output node. This paper is designed with four sinusoidal oscillators. These are illustrated in the first column of Table I. They consist of a single LT1228 and passive elements, including four resistors and two capacitors. Using a single LT1228 results in low power consumption. The proposed circuits 1 and 3 use grounded capacitors, which can reduce the effect of parasitic capacitances in the active device [27]. The output voltage node, v_o of all proposed oscillators described herein, possesses low output impedance and can be connected in cascade to other circuits without requiring a buffer circuit. The characteristic equation, condition equation (CO), and frequency equation (FO) for each proposed oscillator are shown in the second column of Table II. The third column of Table II provides the voltage gain equation for each oscillator if the voltage gain is defined as the ratio of the voltage at nodes v_o and v_x. The condition of the proposed oscillators can be tuned electronically via I_B. Then, the capacitor value is adjusted to tune the desired frequency of the sinusoidal signal without affecting the generated condition. Moreover,

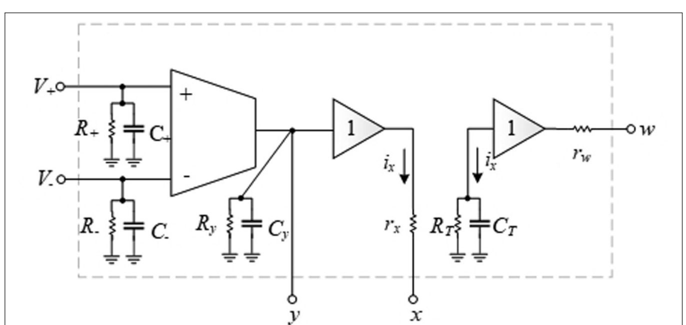


Fig. 2. LT1228 parasitic elements [21].

TABLE II. PROPOSED SIMPLE SINUSOIDAL OSCILLATORS

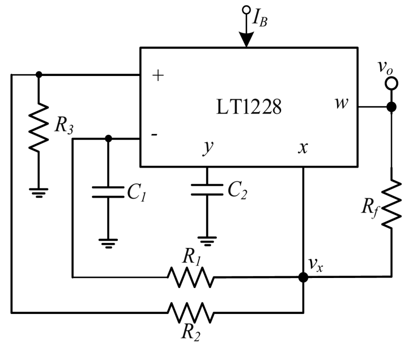
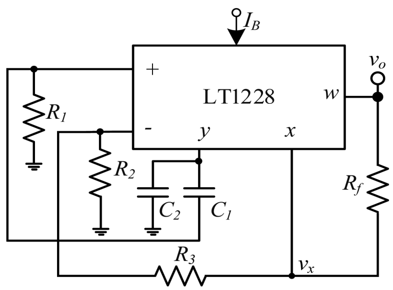
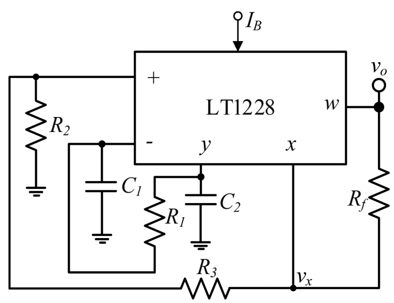
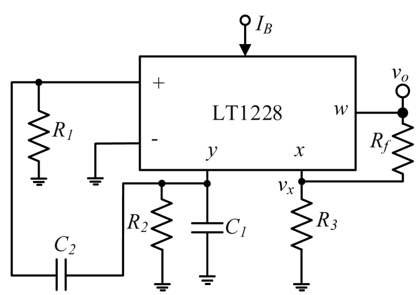
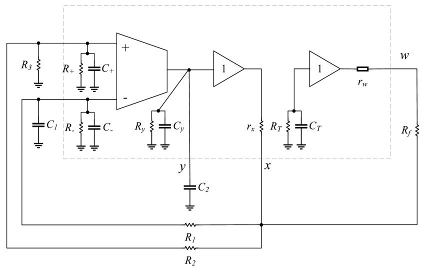
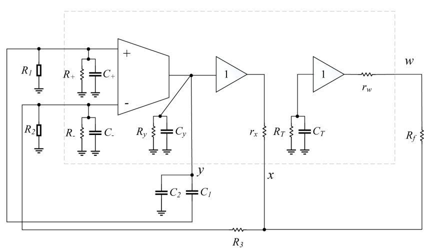
No.	Proposed Oscillator	Oscillation Parameters	Gain	Controllability
1		$\left[\begin{array}{l} s^2R_1C_1C_2+s\left(C_2-g_m\frac{R_3}{R_2+R_3}R_1C_1\right)+ \\ g_m\left(1-\frac{R_3}{R_2+R_3}\right)\end{array}\right]=0$ CO: $\frac{2}{g_m}\le R_1$; when $C_1=C_2$, $R_2=R_3$ FO: $\omega_0=\frac{1}{C}\sqrt{\frac{0.5g_m}{R_1}}$; when $C_1=C_2=C$, $R_2=R_3$	$\frac{v_o}{v_x}=\left[\begin{array}{l} R_f\left(\frac{1}{R_1}+\frac{1}{R_2}-\frac{R_3}{R_3^2+R_2R_3}\right)+ \\ 1-\frac{R_f}{R_1+sR_1^2C_1}\end{array}\right]$	CO by g_m, FO by C Gain by R_f for circuit no. 1–3. Gain by R_f or R_3 for circuit no. 4.
2		$\left[\begin{array}{l} s^2R_1C_1C_2+s\left(C_1+C_2-g_mR_1C_1+g_mR_1C_1\frac{R_2}{R_2+R_3}\right)+ \\ g_m\frac{R_2}{R_2+R_3}\end{array}\right]=0$ CO: $\frac{4}{g_m}\le R_1$; when $C_1=C_2$, $R_2=R_3$ FO: $\omega_0=\frac{1}{C}\sqrt{\frac{0.5g_m}{R_1}}$; when $C_1=C_2=C$, $R_2=R_3$	$\frac{v_o}{v_x}=\left(\frac{R_f}{R_3}+1\right)-\frac{R_2R_f}{R_2R_3+R_3^2}$	
3		$\left[\begin{array}{l} s^2R_1C_1C_2+s\left(C_1+C_2-g_mR_1C_1\frac{R_2}{R_2+R_3}\right)+ \\ g_m\left(1-\frac{R_2}{R_2+R_3}\right)\end{array}\right]=0$ CO: $\frac{4}{g_m}\le R_1$; when $C_1=C_2$, $R_2=R_3$ FO: $\omega_0=\frac{1}{C}\sqrt{\frac{0.5g_m}{R_1}}$; when $C_1=C_2=C$, $R_2=R_3$	$\frac{v_o}{v_x}=\left(\frac{R_f}{R_3}+1\right)-\frac{R_2R_f}{R_2R_3+R_3^2}$	
4		$s^2R_1R_2C_1C_2+s\left(R_2C_1+R_1C_2+R_2C_2-g_mR_1R_2C_2\right)+1=0$ CO: $\frac{3}{g_m}\le R$; when $C_1=C_2$, $R_1=R_2=R$ FO: $\omega_0=\frac{1}{CR}$; when $C_1=C_2=C$, $R_1=R_2=R$	$\frac{v_o}{v_x}=\frac{R_f}{R_3}+1$	

TABLE III. PROPOSED SINUSOIDAL OSCILLATORS WITH PARASITIC EFFECTS

No.	Proposed Oscillators with Parasitic Elements	Oscillation Parameters	Assumption
1		$0=\begin{cases} s^3C_1^*C_2^*C_+R_1R_2R_-R_y+s^2\left[R_1R_2\left(C_1^*C_2^*R_3^*R_-R_y+C_2^*C_+R_y+C_1^*C_+R_-\right)+C_1^*C_2^*R_1R_-R_y+C_2^*C_+R_2R_-R_y\right] \\ +s\left[R_1R_2\left(C_2^*R_3^*R_y+C_1^*R_3^*R_-+C_+\right)+C_2^*R_y\left(R_2R_3^*R_-+R_1+R_-\right)+\left(C_+R_2R_-+C_1^*R_1R_-\right)+g_mR_-R_y\left(C_+R_2-C_1^*R_1\right)\right] \\ +\left[\left(R_1R_2R_3^*+R_2R_3^*R_-+R_1+R_-\right)+g_mR_y\left(R_2R_3^*R_--R_1\right)\right] \end{cases}$ $\omega=\sqrt{\dfrac{R_1R_2R_3^*+R_2R_3^*R_-+R_1+R_-+g_mR_y\left(R_2R_3^*R_--R_1\right)}{R_1R_2\left(C_1^*C_2^*R_3^*R_-R_y+C_2^*C_+R_y+C_1^*C_+R_-\right)+C_1^*C_2^*R_1R_-R_y+C_2^*C_+R_2R_-R_y}}$ $\dfrac{C_1^*C_2^*C_+R_1R_2R_-R_y\left[R_1R_2R_3^*+R_2R_3^*R_-+R_1+R_-+g_mR_y\left(R_2R_3^*R_--R_1\right)\right]}{R_1R_2\left(C_1^*C_2^*R_3^*R_-R_y+C_2^*C_+R_y+C_1^*C_+R_-\right)+R_-R_y\left(C_1^*C_2^*R_1+C_2^*C_+R_2\right)}\geq\begin{bmatrix} R_1R_2\left(C_2^*R_3^*R_y+C_1^*R_3^*R_-+C_+\right) \\ +C_2^*R_y\left(R_2R_3^*R_-+R_1+R_-\right) \\ +R_-\left(C_+R_2+C_1^*R_1\right)+g_mR_-R_y\left(C_+R_2-C_1^*R_1\right) \end{bmatrix}$	$R_3^*=R_3//R_+$ $C_1^*=C_1+C_-$ $C_2^*=C_2+C_y$
2		$0=\begin{cases} s^3\left[R_3R_yC_-C_A^*\right]+s^2\left[R_2^*R_3R_yC_A^*+C_-R_3\left(R_1^*R_yC_B^*+C_1^*-g_mR_yC_1\right)+R_yC_A^*\right] \\ +s\left[R_3\left(R_1^*R_2^*R_yC_B^*+R_2^*C_B^*+R_1^*C_-\right)+R_1^*R_yC_B^*-C_1^*+g_mR_y\left(C_+-C_1R_3R_2^*\right)\right] \\ +R_1^*\left(R_3R_2^*+1+g_mR_y\right) \end{cases}$ $\omega=\sqrt{\dfrac{R_1^*\left(R_3R_2^*+1+g_mR_y\right)}{R_3\left[R_2^*R_yC_A^*+C_-\left(R_1^*R_yC_B^*+C_1^*-g_mR_yC_1\right)\right]+R_yC_A^*}}$ $\dfrac{C_-C_A^*R_1^*R_3R_y\left(R_3R_2^*+1+g_mR_y\right)}{R_3\left[R_2^*R_yC_A^*+C_-\left(R_1^*R_yC_B^*+C_1^*-g_mR_yC_1\right)\right]+R_yC_A^*}$ $\geq R_3\left(R_1^*R_2^*R_yC_B^*+R_2^*C_B^*+R_1^*C_-\right)$ $+R_1^*R_yC_B^*-C_1^*+g_mR_y\left(C_+-C_1R_3R_2^*\right)$	$R_1^*=R_1//R_+$ $R_2^*=R_2//R_-$ $C_1^*=C_1+C_y$ $C_2^*=C_2+C_y$ $C_A^*=C_1C_2^*+C_B^*C_+$ $C_B^*=C_2^*+C_1$

(*Continued*)

TABLE III. PROPOSED SINUSOIDAL OSCILLATORS WITH PARASITIC EFFECTS (CONTINUED)

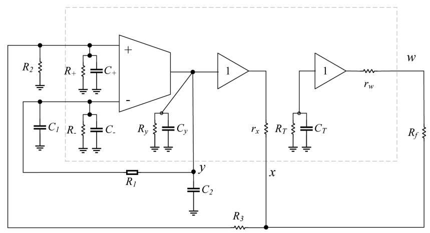
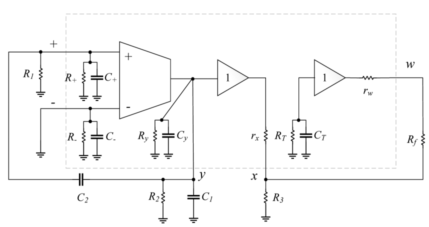
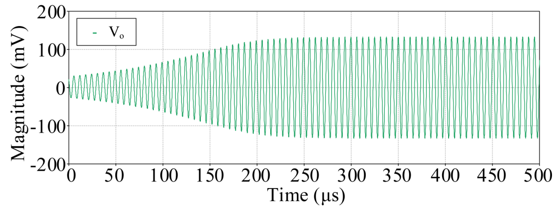
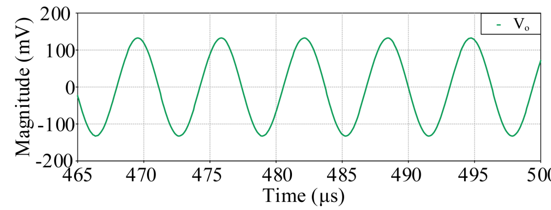
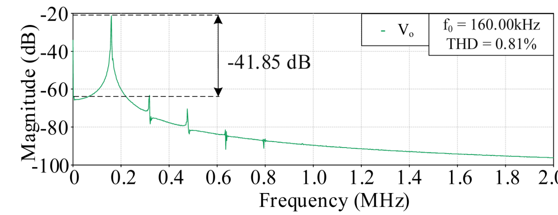
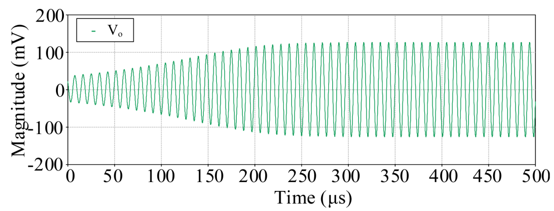
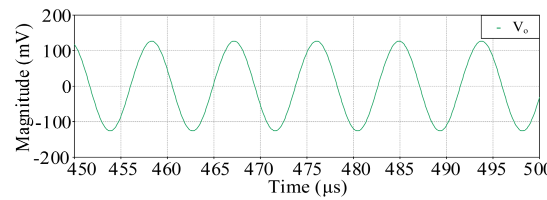
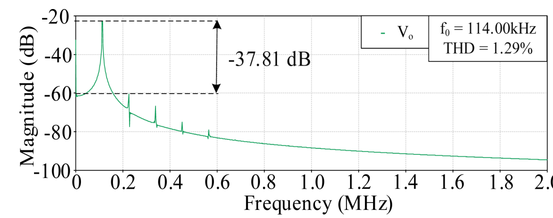
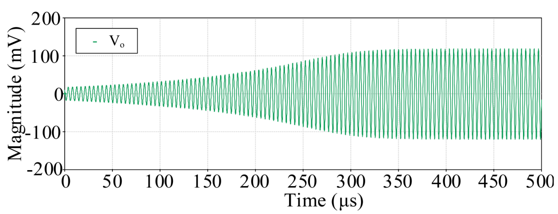
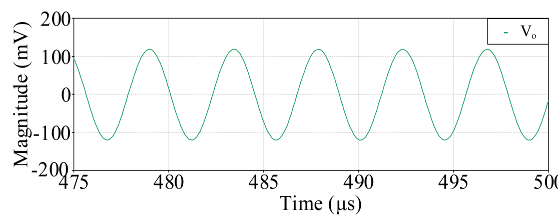
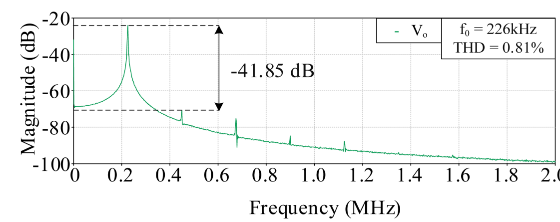
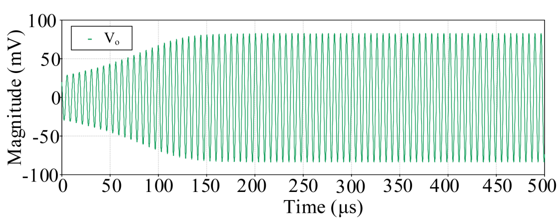
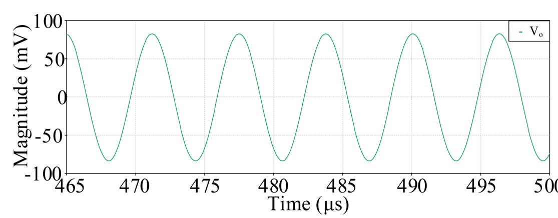
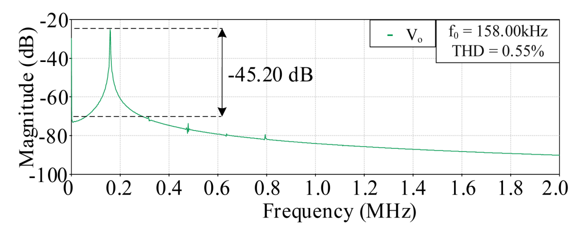
No.	Proposed Oscillators with Parasitic Elements	Oscillation Parameters	Assumption
3		$0=\left\{ s^3C_2^*C_1^*C_+R_1R_3R_-R_y + s^2\left[R_1R_3\left(R_2^*R_-R_yC_1^*C_2^* + C_1^*C_+R_- + C_2^*C_+R_y\right) + R_-R_y\left(C_2^*C_+R_3 + C_1^*C_+R_3 + C_1^*C_2^*R_1\right)\right] + s\left[R_1R_3\left(C_1^*R_2^*R_- + C_2^*R_2^*R_y + C_+\right) + R_3R_-\left(C_2^*R_2^*R_y + C_+ + C_1^*R_2^*R_y\right) + R_y\left(C_+R_3 + C_2^*R_1 + C_1^*R_- + C_2^*R_-\right) + C_1^*R_1R_- + g_mR_-R_y\left(C_+R_3 - C_1^*R_1\right)\right] + R_2^*R_3\left(R_1 + R_- + R_y\right) + R_1 + R_- + 1 + g_m\left(R_3R_2^*R_-R_y - R_1R_y\right)\right\}$ $\omega=\sqrt{\frac{R_1R_3R_2^* + R_3R_2^*R_- + R_3R_2^*R_y + R_1 + R_- + 1 + g_m\left(R_3R_2^*R_-R_y - R_1R_y\right)}{R_1R_3R_2^*R_-R_yC_1^*C_2^* + C_1^*C_+R_1R_3R_- + C_2^*C_+R_1R_3R_y + C_2^*C_+R_3R_-R_y + C_1^*C_+R_3R_-R_y + C_1^*C_2^*R_1R_-R_y}}$ $\frac{C_2^*C_1^*C_+R_1R_3R_-R_y\left[R_1R_3R_2^* + R_3R_2^*R_- + R_3R_2^*R_y + R_1 + R_- + 1 + g_mR_y\left(R_3R_2^*R_- - R_1\right)\right]}{\left(R_1R_3R_2^*R_-R_yC_1^*C_2^* + C_1^*C_+R_1R_3R_- + C_2^*C_+R_1R_3R_y + C_2^*C_+R_3R_-R_y + C_1^*C_+R_3R_-R_y + C_1^*C_2^*R_1R_-R_y\right)} \geq \left(C_1^*R_1R_3R_2^*R_- + C_2^*R_1R_3R_2^*R_y + C_+R_1R_3 + C_2^*R_3R_2^*R_-R_y + C_+R_3R_- + C_1^*R_3R_2^*R_-R_y + C_+R_3R_y + C_1^*R_1R_- + C_2^*R_1R_y + R_-R_yC_1^* + R_-R_yC_2^* + g_mR_-R_y\left(C_+R_3 - R_1C_1^*\right)\right)$	$R_2^* = R_2 // R_+$ $C_1^* = C_1 + C_-$ $C_2^* = C_2 + C_y$
4		$0=s^2\left(C_1^*C_+R_2R_y + C_1^*C_2R_2R_y + C_2C_+R_2R_y\right) + s\left(C_+R_2 + C_1^*R_1^*R_2R_y + C_2R_1^*R_2R_y + C_2R_2 + C_+R_y + C_2R_y - g_mC_2R_2R_y\right) + R_1^*R_2 + R_1^*R_y$ $\omega=\sqrt{\frac{R_1^*\left(R_2+R_y\right)}{R_2R_y\left(C_1^*C_+ + C_1^*C_2 + C_2C_+\right)}}$ $g_mC_2R_2R_y \geq R_y\left(C_1^*R_1^*R_2 + C_2R_1^*R_2 + C_2 + C_+\right) + R_2\left(C_2 + C_+\right)$	$R_1^* = R_1 // R_+$ $C_1^* = C_1 + C_y$

TABLE IV. SIMULATION RESULTS

No.	Transient Response	Steady-State Response	FFT Response
1			
	$R_1 = R_2 = R_3 = R_f = 1k\Omega$, $C_1 = C_2 = 1nF$, $I_B = 210\ \mu A$		
2			
	$R_1 = 2\ k\Omega$, $R_2 = R_3 = R_f = 1\ k\Omega$, $C_1 = C_2 = 1\ nF$, $I_B = 210\ \mu A$		
3			
	$R_1 = R_2 = R_3 = R_f = 1\ k\Omega$, $C_1 = C_2 = 1\ nF$, $I_B = 418\ \mu A$		
4			
	$R_1 = R_2 = R_3 = R_f = 1k\Omega$, $C_1 = C_2 = 1\ nF$, $I_B = 310\ \mu A$		

the amplitude of the output signal can be enhanced by adjusting R_f without affecting the condition or frequency. The final column of Table II concludes this controllability.

C. Study of Parasitic Impedance Effect

This section performs a thorough study of the proposed oscillators, considering the parasitic elements present on different terminals of LT1228. The presence of these parasitic elements would have an unfavorable effect on the accuracy and performance of the proposed oscillators, particularly in relation to the operating frequency range, conditions, and frequency of oscillation. LT1228 contains parasitic elements at both the input and output terminals, as depicted in Fig. 2. The parasitic elements present at the high-impedance input terminals are composed of capacitance and resistance connected in parallel: terminals V_+ ($R_+//C_+$) and V_- ($R_-//C_-$), terminal y ($R_y//C_y$), and trans-resistance impedance ($R_T//C_T$). Additionally, LT1228 contains two parasitic resistances, r_x and r_w, which are interconnected in series at low-impedance output terminals, x and w, respectively [21]. As stated above regarding the effects of parasitic elements on LT1228, the proposed oscillators with parasitic elements are shown in the second column (Table III). The study conducted in ref. [28] found that the operating frequency of the CFA, with the feedback resistor R_f connected between the x and y terminals, is approximately equal to $1/(2\pi C_T R_f)$. Therefore, if the operating frequency of the proposed oscillator is lower than $1/(2\pi C_T R_f)$, the r_x, r_w, R_T, and C_T will be ignored. The second column of Table III displays the characteristic equation, CO, and FO for each proposed oscillator with these parasitic elements.

III. RESULTS

A. Simulation

The performance of the proposed sinusoidal oscillator was initially evaluated by simulations performed using the LT1228 macro models in the Pspice program. The LT1228 was biased using DC power supply voltages V_{CC} and V_{EE}, which were ±5V. All the capacitors, $C_1 = C_2 = 1$ nF, and all the resistors, $R_1 = R_2 = R_3 = R_f = 1$ kΩ (except $R_1 = 2$ kΩ for circuit 2), were chosen. In order to sustain the oscillation situation, the bias current I_B for circuits 1–4 was adjusted to 210 µA, 210 µA, 310 µA, and 418 µA, respectively. Table IV displays the graphical representation of the Pspice program's results. The first and second columns of Table IV display the time domain results of the oscillator circuits in transient response and steady-state response, respectively. The Fast Fourier Transform (FFT) analysis in column 3 of Table IV reveals the simulated oscillation frequencies of the proposed oscillators 1–4 are 160 kHz (2.35% error), 114 kHz (0.47% error), 224 kHz (0.48% error), and 158 kHz (0.73% error), respectively. The total harmonic distortions (THDs) of the proposed oscillators 1–4 obtained from the simulation are 0.808%, 1.287%, 0.808%, and 0.549%, respectively.

B. Experiment

Although the oscillators were previously validated in the previous section, it is essential to note that in practical applications, numerous factors can significantly impact the performance of these oscillators. In this section, the performance of the proposed oscillators will be experimentally demonstrated. Fig. 3 shows the experimental setup for testing the proposed sinusoidal oscillators, Fig. 3a shows the equipment connection, and Fig. 3b shows the breadboard circuit implementation. For the experiment, the value of the passive elements is the same as in the simulation, but the bias current for sustaining the condition of oscillation for the proposed oscillators 1–4 was set to 196 µA, 194 µA, 397 µA, and 290 µA, respectively. The oscilloscope Keysight DSOX1202G was used to measure the sinusoidal output voltage signal. The first column of Table V shows the measured sinusoidal output signal of the proposed oscillators in steady-state response. The measured FFT analysis in the third column of Table V reveals the measured oscillation frequencies of the proposed oscillators 1–4 are 165.80 kHz (1.19% error), 116.37 kHz (1.59% error), 236.20 kHz (4.94% error), and 163.34 kHz (2.62% error), respectively. The THD of the proposed oscillators 1–4 obtained from the experiment are 0.22%, 0.32%, 0.13%, and 0.24%, respectively. Table VI compares the oscillation frequency of generated sinusoidal signals from three sets of results: ideal, simulation, and experiment outcomes. The measured frequency with the most inaccuracy was observed in oscillator 1, with a deviation of 1.19%. On the other hand, the experiment showed that oscillator 3 exhibited the most error, with a deviation of 4.94%. The simulation and the experiment produced an output waveform with a THD of less than 1%.

The voltage gain for each oscillator can be changed by adjusting the R_f resistor, as indicated in column 3 of Table I. This section deals with adjusting the resistance to control the magnitude of the sinusoidal output signal. We confirmed the gain adjustment by changing the R_f value within the range of 0.5–15 kΩ (the other active and passive elements are still the same as appeared above). Fig. 4 shows the

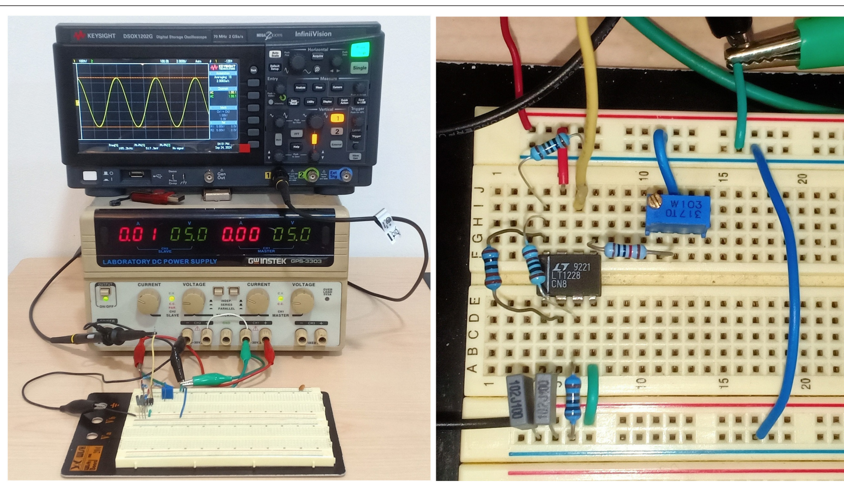
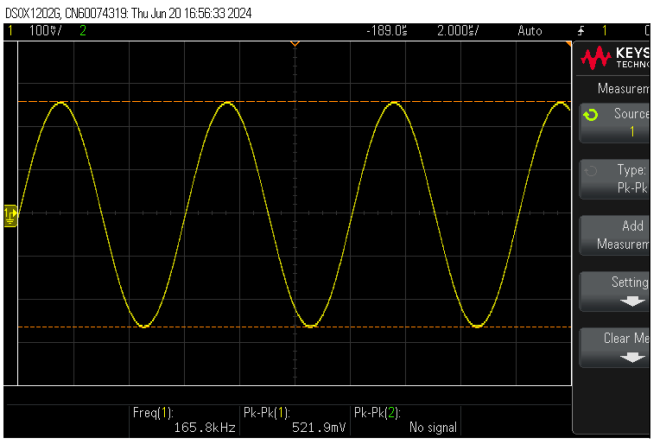
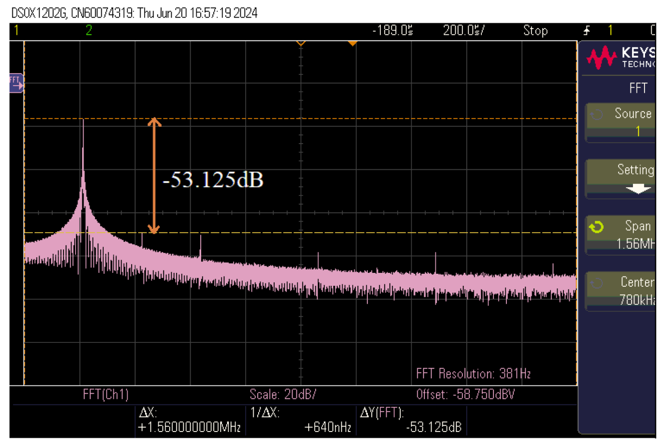
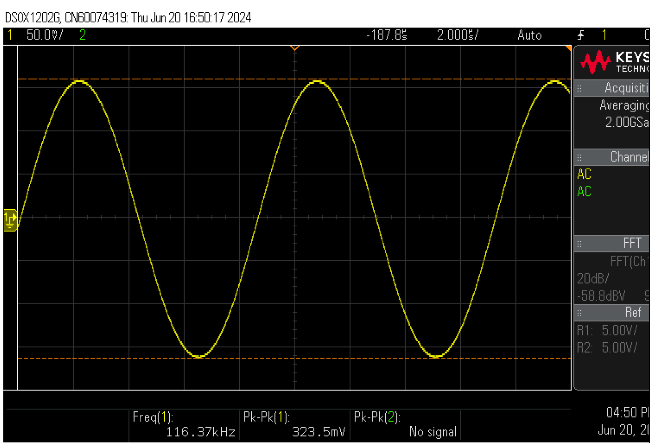
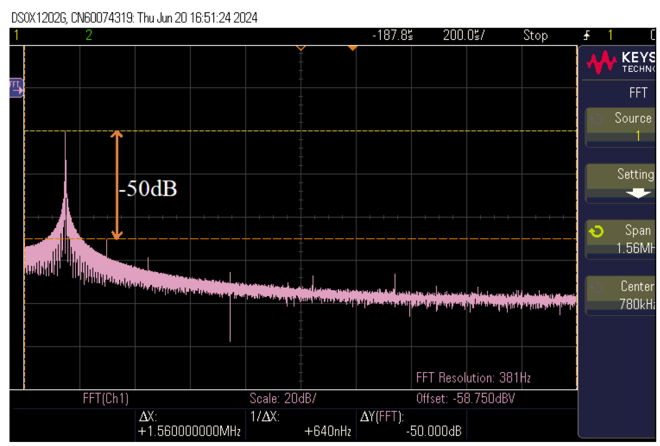
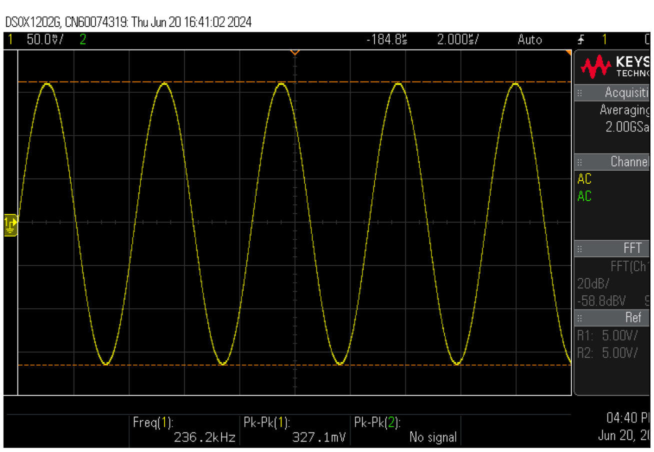
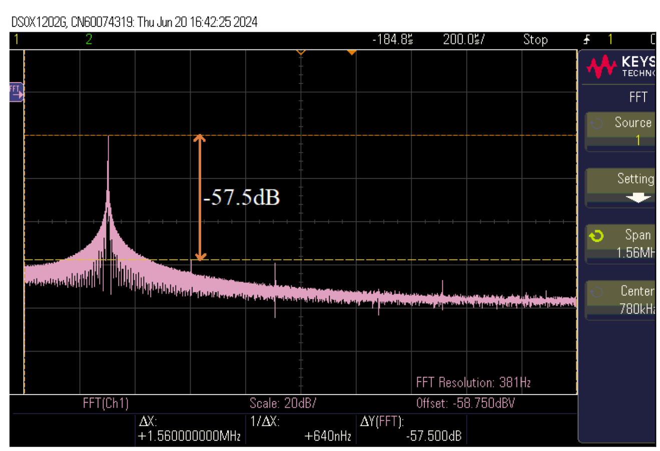


Fig. 3. Experimental setup (a) the equipment connection and (b) the breadboard circuit implementation.

TABLE V. THE MEASURED RESULTS

No	Time-Domain Response	FFT Response
1		
	$R_1 = R_2 = R_3 = R_f = 1$ kΩ, $C_1 = C_2 = 1$ nF, $I_B = 196$ μA	
2		
	$R_1 = 2$ kΩ, $R_2 = R_3 = R_f = 1$ kΩ, $C_1 = C_2 = 1$ nF, $I_B = 194$ μA	
3		
	$R_1 = R_2 = R_3 = R_f = 1$ kΩ, $C_1 = C_2 = 1$ nF, $I_B = 397$ μA	

(*Continued*)

TABLE V. THE MEASURED RESULTS (CONTINUED)

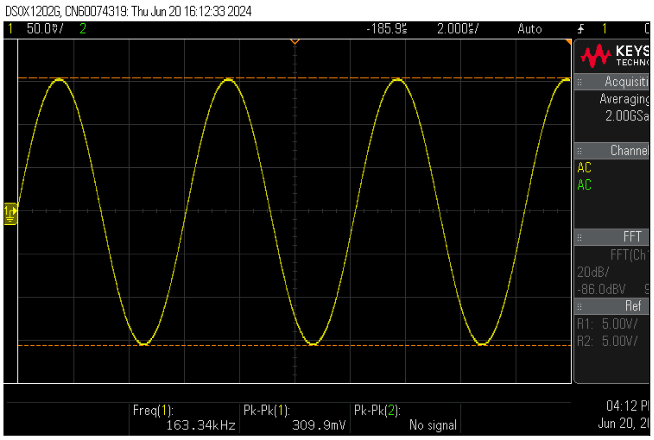
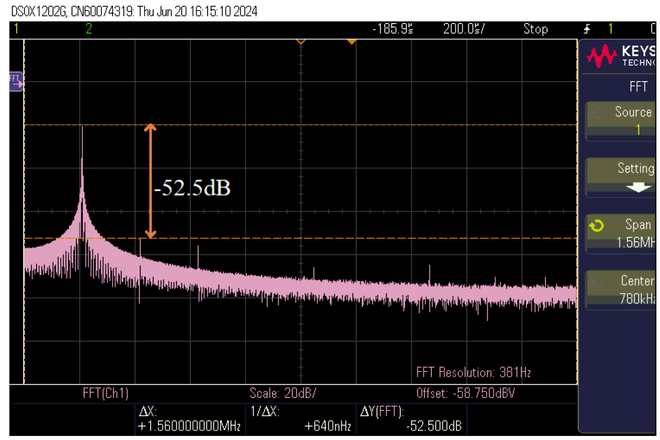
No	Time-Domain Response	FFT Response
4		
	$R_1 = R_2 = R_3 = R_f = 1$ kΩ, $C_1 = C_2 = 1$ nF, $I_B = 290$ μA	

TABLE VI. IDEAL, SIMULATED, AND EXPERIMENTAL FREQUENCY, AND THE PERCENTAGE OF THD

	Frequency of Oscillation					THD (%)	
	Frequency (kHz)			error (%)			
Circuit	**Idea**	**Sim.**	**Exp.**	**Sim.**	**Exp.**	**Sim.**	**Exp.**
1	163.85	160.00	165.80	2.35	1.19	0.81	0.22
2	114.54	114.00	116.37	0.47	1.59	1.29	0.32
3	225.08	224.00	236.20	0.48	4.94	0.81	0.13
4	159.16	158.00	163.34	0.73	2.62	0.55	0.24

*Sim. = Simulation, Exp. = Experiment

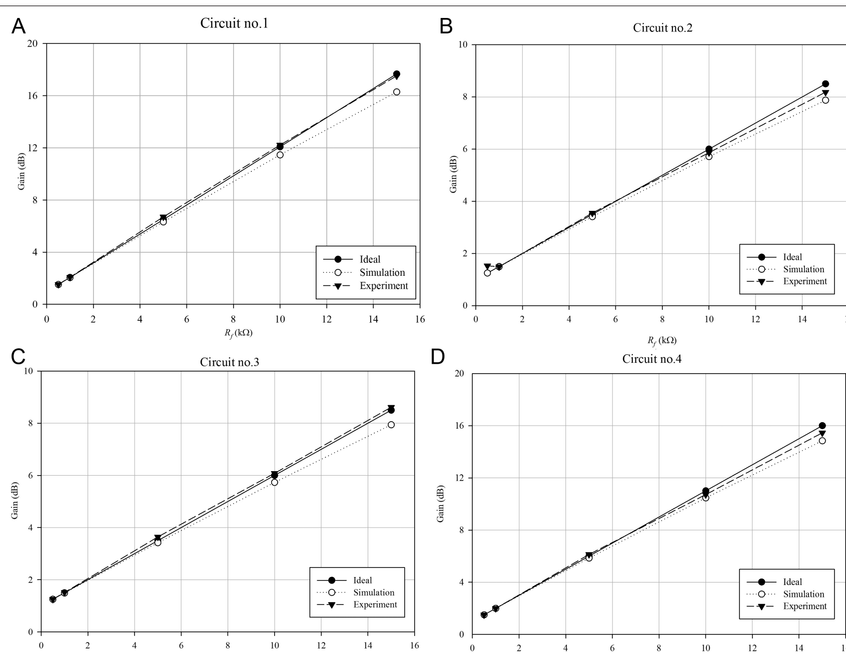


Fig. 4. Voltage gain relative to the various resistor R_f.

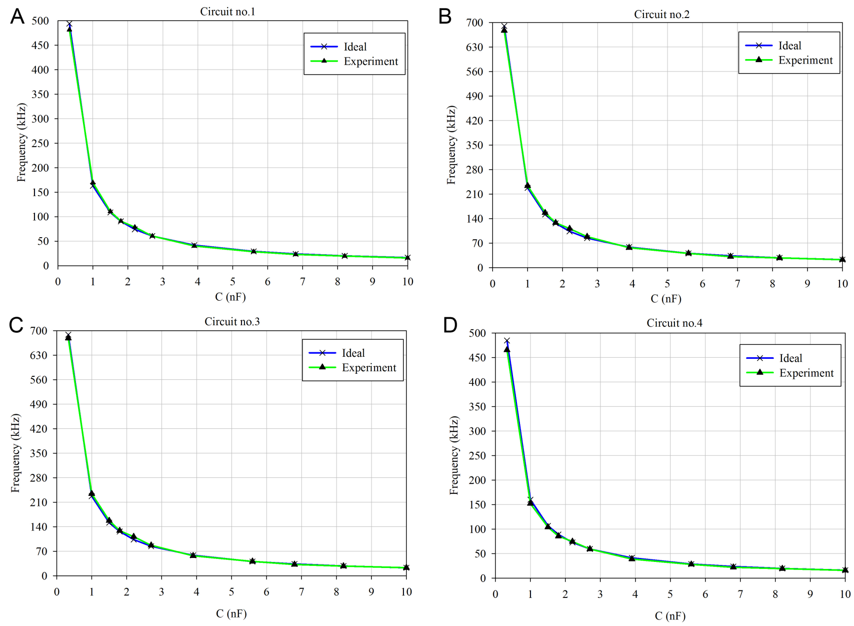


Fig. 5. Frequency of oscillation related to the various capacitor C ($C = C_1 = C_2$).

plots of ideal, simulation, and experiment voltage gains with varying R_f resistances. The measured voltage gains of oscillators 1–4 are approximately 1.50–17.60 dB, 1.50–8.10 dB, 1.25–8.60 dB, and 1.50–15.50 dB, respectively. Fig. 5 presents the plots of ideal and experiment frequency of oscillation with various capacitance values (C_1 and C_2 changed from 0.33 nF to 10 nF). The measured frequency of oscillations for the proposed oscillators 1–4 varied from 15.82 kHz to 481.30 kHz, 22.50 kHz to 677.10 kHz, 22.84 kHz to 678.60 kHz, and 15.75 kHz to 465.30 kHz, respectively. The dependence of THD of the proposed oscillators on changing capacitances ($C = C_1 = C_2$) is shown in Fig. 6 (THD below 2%).

IV. CONCLUSIONS

This research focused on designing, simulating, and conducting experiments on four simple sinusoidal oscillators. The proposed oscillator's output voltage node has a low impedance, enabling direct connection to other circuits without the need for an additional buffer. Simultaneously changing the capacitance values adjusts the oscillation's frequency and condition orthogonally. The condition of oscillation is electronically controlled. Moreover, the amplitude of the sinusoidal waveform is adjustable. We used the PSPICE simulation and a prototype experiment to validate the circuit's performance. The obtained results align with theoretical expectations. The percentage of frequency errors is less than 5% for both simulation and experiment. The experiment yielded THDs of 0.22%, 0.32%, 0.13%, and 0.24% for oscillators 1–4, respectively. By changing the R_f value within the range of 0.5–15 kΩ, the measured voltage gains of oscillators 1–4 are approximately 1.50–17.60 dB, 1.50–8.10 dB, 1.25–8.60 dB, and 1.50–15.50 dB, respectively. The simplicity of the proposed oscillators makes them an excellent choice for instructing students in electronics laboratories. The proposed oscillators can also be employed in frequency modulation to provide a sinusoidal signal as a carrier signal with a constant frequency and a desired adjusted amplitude.

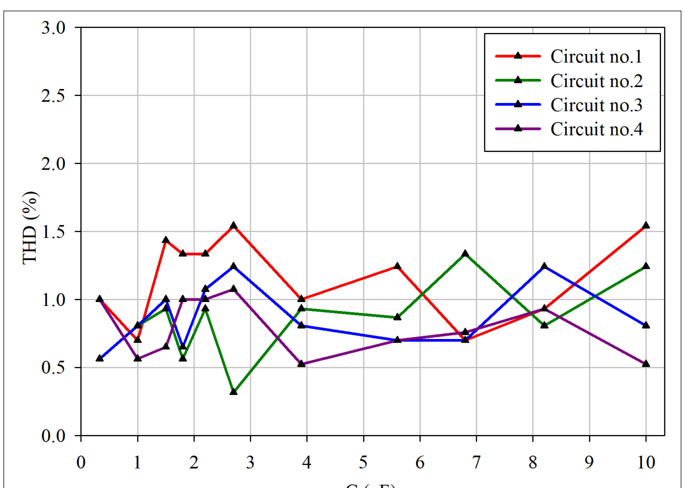


Fig. 6. Dependence of THD on changing capacitances ($C = C_1 = C_2$).

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.D., W.J.; Design – S.D., W.J.; Supervision – P.S., M.S., R.S., W.J., W.S.; Resources – S.D.; Materials – S.D.; Data Collection and/or Processing – S.D.; Analysis and/or Interpretation – S.D., W.J.; Literature Search – S.D.; Writing – S.D., M.S., R.S., W.J.; Critical Review – S.D., P.S., M.S., R.S., W.J.

Declaration of Interests: The authors have no conflicts of interest to declare.

Funding: This research work has been supported by KMITL Research and Innovation Services (Grant no: KREF016623), King Mongkut's Institute of Technology Ladkrabang (KMITL) and King Mongkut's University of Technology North Bangkok (Grant no: KMUTNB-66-BASIC-22).

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