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Low-output-impedance First-order All-pass Filter Based on Single Active Element and Its Application in Multiphase Sinusoidal Oscillator

***Abstract**. This article proposes a voltage-mode first-order all-pass filter and its application in a multiphase oscillator. The proposed circuit is designed with a single commercially available IC LT1228, single capacitor and single resistor. The proposed circuit performance can be operated at a wide frequency range and the phase response is shifted from 180º to 0º at a low-output-impedance port. Moreover, the amplitude of the signal can be directly controlled by adding external resistors without affecting the pole frequency and phase response. In addition, the proposed all-pass filters can be applied to the multiphase sinusoidal oscillator. The presented circuits were verified via a computer simulation and an experiment that confirmed the theoretical analysis.*

Streszczenie.** W artykule zaproponowano napięciowy filtr wszechprzepustowy pierwszego rzędu i jego zastosowanie w wielofazowym oscylatorze. Proponowany obwód został zaprojektowany z jednym dostępnym na rynku układem scalonym LT1228, pojedynczym kondensatorem i pojedynczym rezystorem. Proponowana wydajność obwodu może pracować w szerokim zakresie częstotliwości, a odpowiedź fazowa jest przesunięta od 180º do 0º na porcie o niskiej impedancji wyjściowej. Ponadto amplituda sygnału może być bezpośrednio kontrolowana przez dodanie zewnętrznych rezystorów bez wpływu na częstotliwość biegunową i odpowiedź fazową. Ponadto proponowane filtry wszechprzepustowe mogą być zastosowane do wielofazowego oscylatora sinusoidalnego. Przedstawione obwody zweryfikowano za pomocą symulacji komputerowej i eksperymentu, który potwierdził analizę teoretyczną.* (Niskoimpedancyjny filtr wszechprzepustowy pierwszego rzędu oparty na pojedynczym elemencie aktywnym i jego zastosowaniu w wielofazowym oscylatorze sinusoidalnym***)

Keywords: low-output-impedance, voltage-mode, all-pass filter, LT1228
Słowa kluczowe: filtr wszechprzepustowy, mała impedancja wyjściowa

Introduction

First-order all-pass filter (APF) or phase shift is kept being constant the amplitude and shift the phase of the signal. It has become popular these days because the properties of APF can be applied in electronic measurements, communications, automatic control, neural network systems, etc [1-4]. The quadrature oscillators, multiphase sinusoidal oscillators, and high-Q band-pass filters are examples of other circuits that use first-order all-pass filters as a part of the design. Therefore, the APFs have been continuously developed and researched [5-21]. They are constructed with high performance active elements such as CCCII, OTA, CDTA, CFTA, VDTA, CCCTA, CCCCTA, DO-CCTA, MO-CCCCTA, FB-VDBA, CCCDTA, CCCCTA, DDCC, CDIBA, OTRA, and VDIBA. Their details are reported as follows. Some circuits of all-pass filters designed in [1-13, 22] can be adjusted to the pole frequency and phase response by electronic adjustment. Furthermore, they have low-output-impedance and can be easily cascaded to other circuits [1, 2, 14-20]. The APF in [13] used only a single active element, which is compact and can be easily constructed. The amplitude of the APF is that it can be adjusted irrespective of the pole frequency [8, 17] and provides both inverting and non-inverting outputs [20]. Additionally, first-order all-pass filters can be applied to a high-Q band-pass filter [11], a quadrature oscillator [2, 13, 16, 18, 20], a multiphase oscillator [15, 17], and a four-phase oscillator [18, 20]. These first-order all-pass filters, on the other hand, have at least one of the following drawbacks:

- They lack electronic controllability [14-21].
- Their high output impedance requires the use of a voltage buffer for cascading [3-13, 21].
- They cannot be implemented from a single commercially available IC [1-12, 14-21].
- They are unable to adjust the amplitude [1-19].

Table 1 below shows the advantages and characteristics of the proposed voltage-mode first-order all-pass filter compared with those previously published [1-21].

This work discusses voltage-mode first-order all-pass filters with low-output impedance and multiphase oscillator applications. The recommended circuit uses the LT1228 IC, a single capacitor, and a single resistor, all of which are commercially available. External resistors can be added to the proposed APF to adjust the output gain. The results show the performance of the proposed circuit, and can be used to confirm the principles and theories.

Materials and methods

LT1228 Description

The LT1228 includes an operational transconductance amplifier (OTA) and a current feedback amplifier (CFA) in an 8-pin package produced by the Linear Technology Corporation [13]. Figure 1 shows the electrical symbol, equivalent circuit and pin configuration of LT1228. The input voltages (pin 2 and 3) of the OTA are high-impedances. The current output (pin 1) is high-impedance and connected to the non-inverting voltage input of CFA. The supply voltage of LT1228 can be operated by ±2V to ±15V. The transconductance gain (g_m) is set by I_{SET} through Pin 5. Pin 8 and Pin 6 of the CFA are low-impedance inverting voltage input and voltage output, respectively. The ideal electrical characteristics of LT1228 are shown in equation (1).

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

Where R_T is the transresistance of the LT1228. The g_m of LT1228 is controlled by external bias current (I_{SET}) which is called electronically controlled as shown in equation (2).

(2) $$g_m = 10 I_{SET}$$

(a)

Table 1. Comparison between various voltage-mode all-pass filters

Ref.	Active Element.	No. of Active elements	No. C+R	Low- output-impedance	Voltage-mode	adjusting gain output	App.	Results
1	FB-VDBA	1	1+1	Yes	Yes	No	-	Experimental
2	CCCII	2	1+0	No	Yes	No	OSC	Simulation
3	CCCTA	1	1+0	No	Yes	No	-	Simulation
4	OTA	3	1+0	No	Yes	No	-	Simulation
5	OTA	3	1+0	No	Yes	No	-	Simulation
6	VDTA	1	1+0	No	Mix	No	-	Simulation
7	CCCII+OP	1+1	1+0	No	Yes	No	-	Simulation
8	OTA	3	1+0	No	Yes	Yes	-	Simulation
9	VDCC	1	1+2	No	Yes	No	-	Simulation
10	CC-VCIII	1	1+0	No	Yes	No	-	Simulation
11	CCCII	1	1+1	No	Yes	No	High-Q	Simulation
12	MO-CCCCTA	1	1+0	No	Yes	No	-	Experimental
13	LT1228	1	1+2	No	Yes	No	OSC	Simulation
14	CCCDBA	1	1+1	Yes	Yes	No	-	Simulation
15	FDCCII	1	1+2	Yes	Yes	No	OSC	Simulation
16	CCII	1	1+3	Yes	Yes	No	OSC	Experimental
17	OTRA	1	1+3	Yes	Yes	Yes	OSC	Simulation
18	DDCC	1	1+1	Yes	Yes	No	OSC	Simulation
19	DDCC	2	1+1	Yes	Yes	No	OSC	Experimental
20	VDIBA	1	1+0	Yes	Yes	No	OSC	Experimental
21	CCII	1	1+2	No	Yes	No	-	Simulation
Proposed circuit	LT1228	1	1+1	Yes	Yes	Yes	OSC	Experimental

a) b) c)

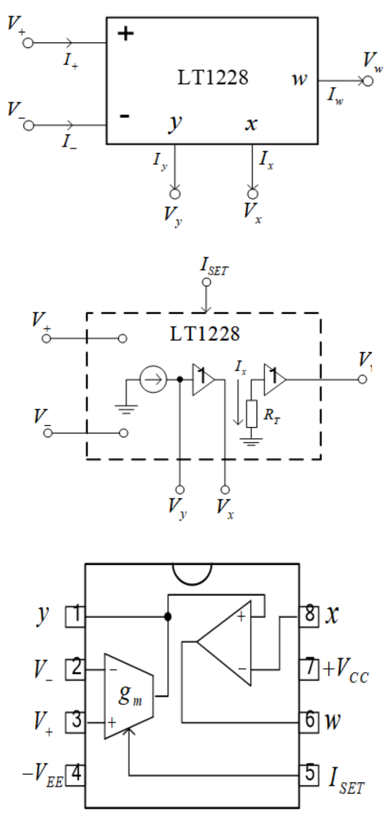


Fig.1. The LT1228 (a) electrical symbol (b) equivalent circuit (c) pin configuration

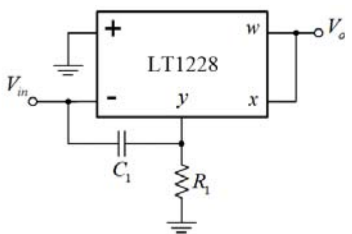


Fig.2. Proposed APF

Voltage-mode first-order all-pass filter

The circuit of the proposed APF is depicted in Fig. 2, which is simply compacted since it is designed with a single LT1228, a single capacitor, and a single resistor. In addition, the voltage output port is low-impedance that can be conveniently cascaded or connected to other stages or circuits. The voltage transfer function of the proposed APF circuit in equation (3) is demonstrated by using the electrical properties of LT1228 in the following equation (1).

(3) $$\frac{V_o}{V_{in}} = \frac{sC_1 - g_{m1}}{sC_1 + \frac{1}{R_1}}$$

The pole frequency, voltage gain, and phase response of the proposed APF will be analyzed with the setting $g_{m1} = \frac{1}{R_1}$, which is demonstrated in equations (4), (5), and (6), respectively.

(4) $$\omega_p = \frac{1}{C_1 R_1},$$

(5) $$G(\omega) = \left|\frac{V_o}{V_{in}}\right| = 1,$$

and

(6) $$\phi(\omega) = 180 - 2\tan^{-1}\left(\omega C_1 R_1\right).$$

From equation (6), the phase response is shifted from 180º to 0º and can be controlled via R_1 and g_{m1}.

Effect of parasitic elements

In practice, parasitic components can be found at all terminals/pins of the LT1228. The details are presented in Fig. 3. They are high-impedance terminals V_+, V_-, and y that are linked to the ground by resistors and capacitors. These parasitic elements are assigned by R_+, C_+, R_-, C_-, R_y, and C_y. Moreover, the x and w terminals which appear in the series resistors R_x and R_w have low-impedance. The parasitic elements of LT1228 are included in the characteristic equation of the proposed APF, where $R_1 >> R_x$ and R_w, as follows:

(7) $$\frac{V_o}{V_{in}} = \frac{sC_1 - g_{m1}}{sC_1 + \left(G_1 + G_y + C_y\right)}.$$

APF circuits' pole frequency and phase response are modified to (8) and (9), respectively.

(8) $$\omega_o = \frac{G_1 + G_y + C_y}{C_1},$$

(9) $$\phi = 180 - 2\tan^{-1}\frac{C_1}{G_1 + G_y + C_y},$$

and

(10) $$G_1 + G_y + C_y = g_{m1},$$

where $G_1 = \frac{1}{R_1}$ and $G_y = \frac{1}{R_y}$.

The performance of the proposed APF is affected by parasitic elements. However, the effect of the pole frequency and phase response can be directly solved by slightly adjusting the transconductance gain.

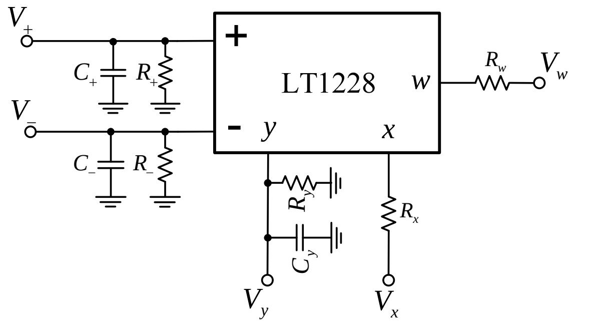


Fig.3. LT1228 with the parasitic element

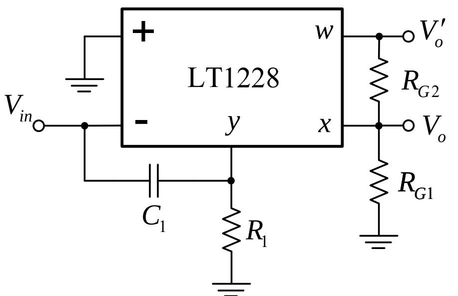


Fig.4. Proposed APF with amplitude adjustment

The amplitude adjustment APF

Fig. 4 presents the proposed APF with added external resistors to tune the voltage gain of the output signal. The voltage output (V'_o) can be directly adjusted by the value of R_{G1} and R_{G2} or both without affecting the pole frequency and phase response. The transfer function of APF became:

(11) $$\frac{V'_o}{V_{in}} = K\frac{sC_1 - g_{m1}}{sC_1 + \frac{1}{R_1}}.$$

While, K is voltage gain that is

(12) $$K = \frac{V'_o}{V_o} = \frac{R_{G2}}{R_{G1}} + 1.$$

Also, voltage gain of the transfer function can be rewritten as

(13) $$G'(\omega) = \left|\frac{V'_o}{V_{in}}\right| = \frac{R_{G2}}{R_{G1}} + 1.$$

The gain controllability of the first-order APF is very useful for designing a multiphase sinusoidal oscillator to avoid using external amplifiers for the condition of oscillation.

Voltage-mode multiphase sinusoidal oscillator

The proposed first-order APF is used to design a multiphase sinusoidal oscillator (MSO) by cascading three APFs and placing them in a feedback loop. The implementation of MSO is shown in detail in Fig. 5. Moreover, the output voltage ports are low-impedances. The proposed MSO demonstrates the loop gain as follows:

(14) $$LG(s) = K\left(\frac{sC_1 - g_{m1}}{sC_1 + \frac{1}{R_1}}\right)^n.$$

The phase of the system loop gain can be expressed in (15), with the setting $g_{m1} = \frac{1}{R_1}$.

(15) $$\angle H(s) = 2n\phi = 2n\left(-2\tan^{-1}\left(\omega C_1 R_1\right)\right) = -2\pi.$$

Equation (14) can be used only when the value of n is an odd number (n=3). The phase of the output signals is equal to 360/n. From equation (14), the oscillator circuit can generate sinusoidal signals when the condition of oscillation is successful, as in:

(16) $$K = \frac{R_{G2}}{R_{G1}} + 1 \geq 1.$$

The frequency of oscillation is given by:

(17) $$\omega_{osc} = \frac{1}{C_1 R_1}\tan\frac{\pi}{6}.$$

It can be seen that the condition of oscillation can be freely adjusted by adjusting K without affecting the frequency. Also, the frequency of oscillation can be adjusted by C_1 and R_1.

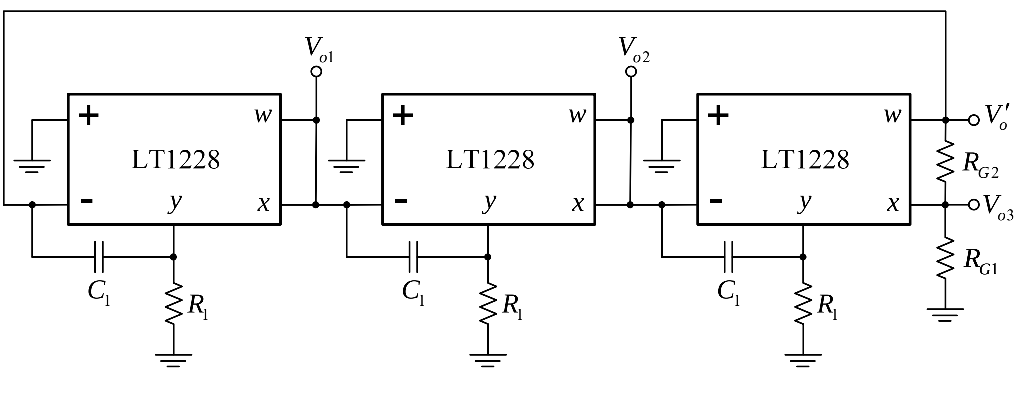


Fig.5. Proposed voltage-mode multiphase sinusoidal oscillator

Performance Verifications

Simulation results

To verify the circuit performance and theoretical validity of the proposed voltage-mode all-pass filter circuit in Fig. 2, it is necessary to use the PSPICE program. The macro-model of LT1228 was used to simulate. The passive elements are chosen by the standard values $R_1 = 1k\Omega$, and $C_1 = 1nF$. The supply voltage is set at ±2V. The proposed APF is electronically set by configuring the transconductance gain at $g_{m1} = 1000\mu A/V$, with a bias current of $I_{SET} = 100\mu A$. The simulation results in Fig. 6 show the gain and phase responses of the proposed APF. It can be seen that the phase response changed from 180º to 0º and the voltage gain was about 0dB. The pole frequency was about 157.13 kHz, while the calculation of the pole frequency as in equation (4) is approximately 159.15 kHz.

The passive devices have tolerance errors in practice. In this case, The Monte Carlo (MC) analysis is appropriate. The MC simulation of the proposed APF is set with a Gaussian distribution and 100 samples, as well as the tolerance errors of the resistor and the capacitor, are set at 10%. The statistical outputs of the pole frequency according to the MC analysis are shown in Table 2. They are the mean, median, and standard deviation of the gain responses that are -0.05, -0.01, and 0.41, respectively. Also, the phase responses show that the mean, median and standard deviations are 89.00º, 88.13º and 5.41 respectively. The simulation results of the statistical studies can be plotted showing the histograms of gain and phase responses of pole frequency in Fig. 7 (a) and (b), respectively.

Fig. 8 illustrates the simulation results of the total harmonic distortion (THD) of the sinusoidal output when the amplitude of the input signals is varied from 0.1Vp-p – 1Vp-p. The minimum and maximum %THD are 0.04% and 4.77%, respectively.

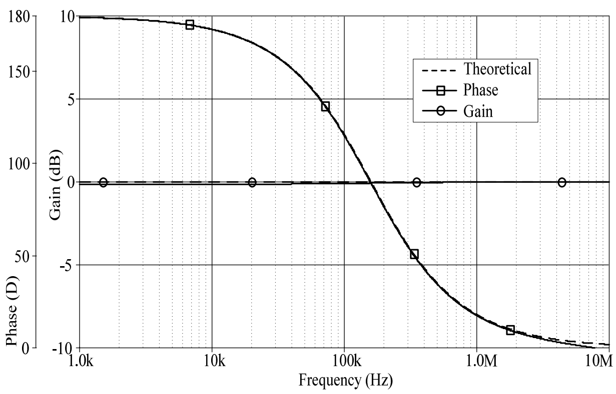
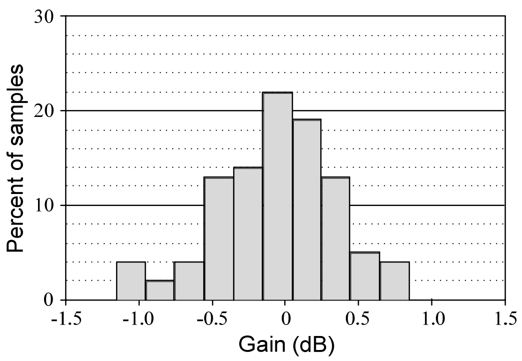
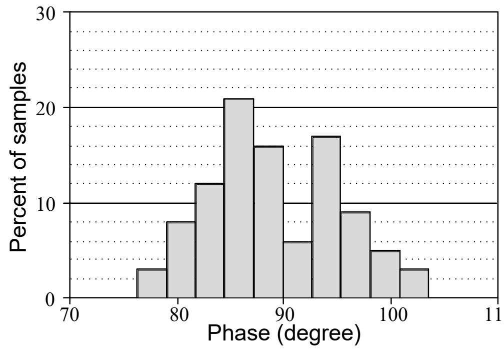


Fig.6. Gain and phase responses of proposed APF



(a)



(b)

Fig.7. MC analyses with 10% tolerance errors (a) Gain and (b) Phase

Table 2. Statistical outputs of MC analysis

No.	Response	Statistical components and their values			
		Number of simple	Mean	Median	Standard deviation
1	Gain	100	-0.05 dB	-0.01 dB	0.41
2	Phase	100	89.00 Degree	88.13 Degree	6.16

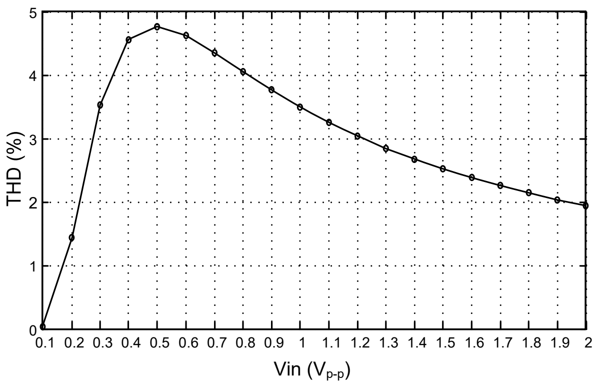


Fig.8. The relation of %THD and amplitude of input signals

Experimental results

The experiment was conducted by using the commercially available IC: LT1228. The proposed APF in Fig. 4 was connected to a supply voltage by the Siglent SPD3303C power supply. A Keysight DSOX3024T oscilloscope was used to measure the performance of the circuit. An external current was utilized with the LM334 IC and measured with a Keysight 34461A multimeter to test any bias in the circuit.

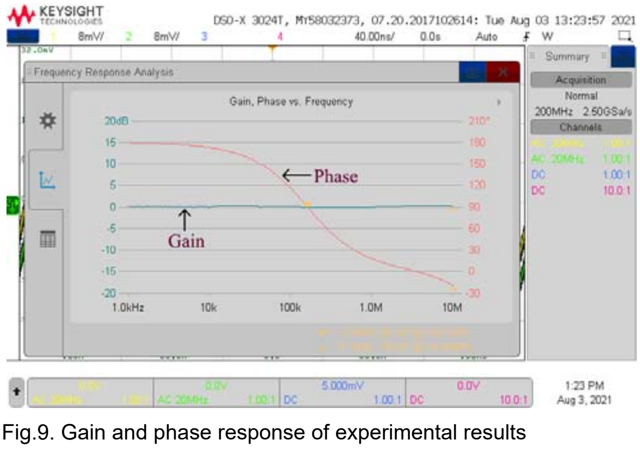


Fig.9. Gain and phase response of experimental results

The voltage and current biases are configured as ±2V and $I_{SET} = 100\mu A$, respectively. The passive elements are chosen as $R_1 = 1k\Omega$, $R_{G1} = 10k\Omega$, $R_{G2} = 10k\Omega$ and $C_1 = 1nF$. The experimental results of the output voltage (V_o) in Fig. 9 show the gain and phase response. It was found that the gain responses were about 0 dB for all frequencies and the phase responses varied from 180 degrees to 0 degrees. The corresponding pole frequency was about 158.5 kHz with a 90° phase shift. These results are in accordance with the theoretical analysis and the simulation results.

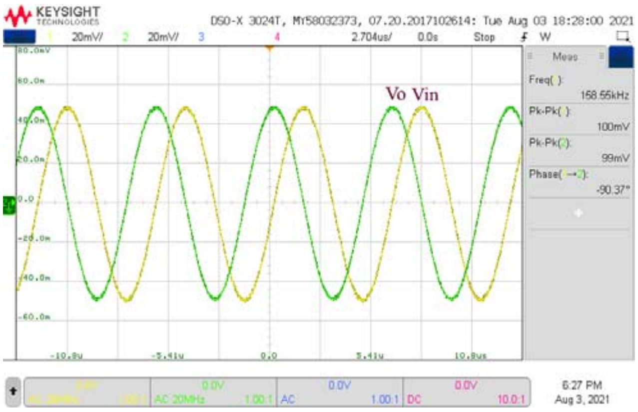


Fig.10. The time-domain response of APF

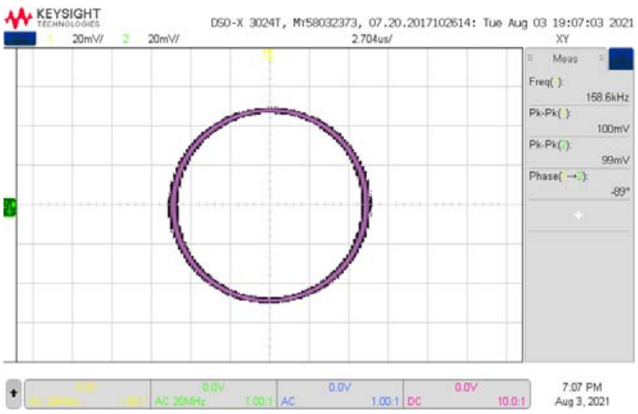


Fig.11. Lissajous figure of sinusoidal waveforms

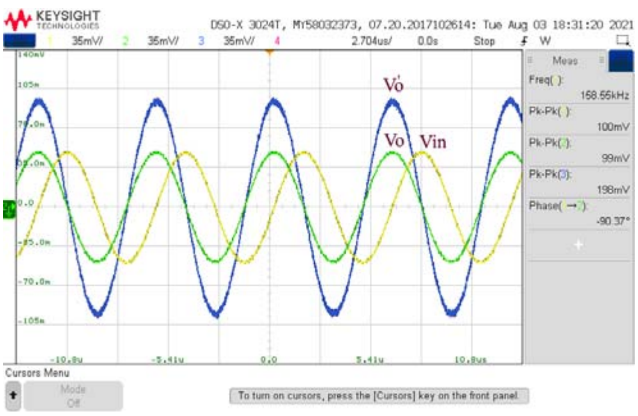


Fig.12. The time-domain responses for outputs gains *K*=2

Fig. 10 shows the waveforms of the output voltage (V_o) and the input voltage (V_{in}) when the sinusoidal signal is applied as an input at a 158.5 kHz frequency and 100mVp-p amplitude. The phase relationship between waveforms is about 90 degrees and it can be plotted by using the XY-mode as shown in Fig. 11.

Fig. 12 shows the output waveforms of the V_o' and V_o compared with the input voltage when the circuit in Fig. 4 is set K=2. The results of the V_o' agree with the theoretical analysis in equation (12).

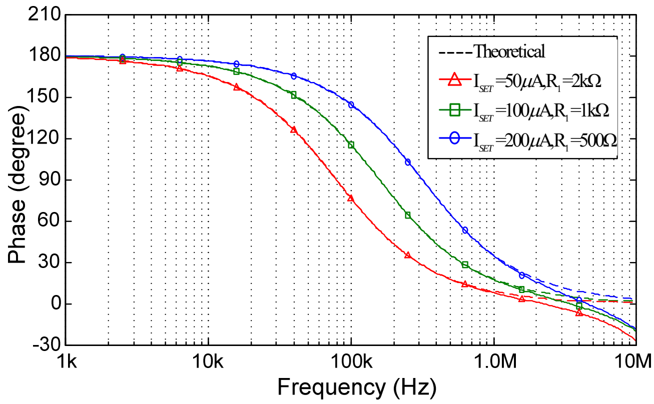


Fig.13. Phase response for different values of I_{SET} and R_1

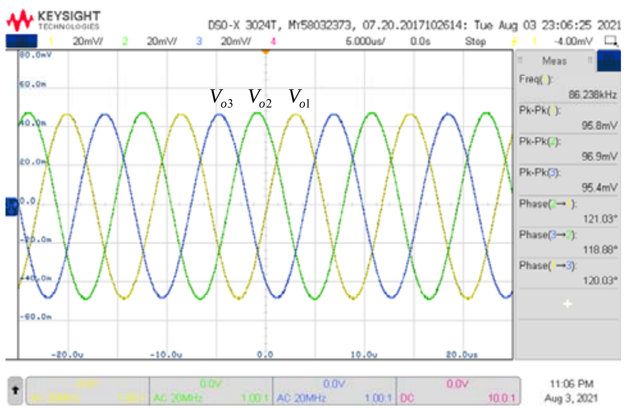


Fig.14. Multiphase output waveforms

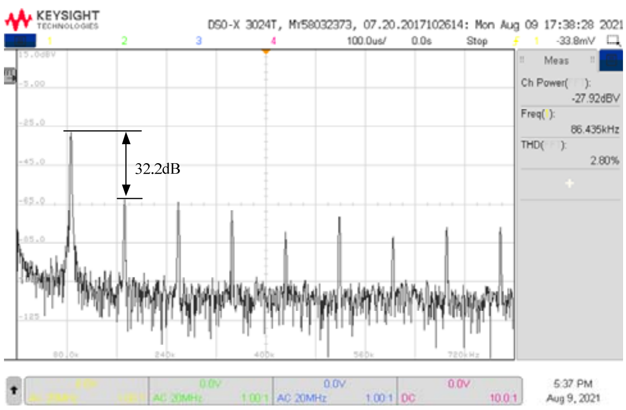


Fig.15. Frequency spectrum of output sinusoidal signals V_{o1}

The results in Fig. 13 demonstrate the adjustment in the phase response, while the external currents I_{SET} and R_1 are kept remained at the same ratio. They are chosen as $I_{SET} = 50\mu A,\ R_1 = 2k\Omega$, $I_{SET} = 100\mu A,\ R_1 = 1k\Omega$ and $I_{SET} = 200\mu A,\ R_1 = 500\Omega$. It is evident that the phase responses at 90° of the frequency transformed to 79.43 kHz, 158.55 kHz, and 316.22 kHz, respectively. The results of the phase responses agree with the theoretical analysis in equation (6).

The proposed multiphase sinusoidal oscillator in Fig. 5 is implemented by setting the voltage supply as ±2V and the external bias current at $I_{SET} = 100\mu A$. Also, the passive elements were designated as $R_1 = 1k\Omega$ and $C_1 = 1nF$, that the tolerance errors of the resistor and capacitor were about 1% and 5%. The circuit generated sinusoidal signals when oscillation was set at $R_{G1} = 10k\Omega$ and $R_{G2} = 1k\Omega$, which agrees with the equation (16). Fig. 14 displays the sinusoidal waveforms of the multiphase sinusoidal oscillator. The frequency of oscillation was 86.23 kHz, which deviated from the theoretical figure by about 6.14%. In addition, the phase relations between the output voltages V_{o1}, V_{o2}, and V_{o3} were 121.03º, 118.88º, and 120.03º, respectively. The total harmonic distortion (THD) of the sinusoidal output signals is displayed in Fig. 15, which corresponds to approximately 2.80%. The attenuation from the first to the second harmonic was 32.2dB.

Conclusions

The proposed voltage-mode first-order all-pass filter consists of a commercially available IC LT1228, a single capacitor, and a single resistor with low-output-impedance. The frequency and phase response were adjusted with the external resistors and bias current. Moreover, the amplitude of the signals was directly controlled by adding R_{G1} and R_{G2} without affecting the pole frequency and phase responses. A multiphase sinusoidal oscillator was used to demonstrate the application of the proposed APF. The circuits were verified via simulation and the experimental results agreed with the theoretical analysis.

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