Log-domain All-pass Filter-based Multiphase Sinusoidal Oscillators

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Abstract. Log-domain current-mode multiphase sinusoidal oscillators based on all-pass filters are presented in this paper. The first-order differential equation is used for obtaining inverting and non-inverting all-pass filters. The proposed oscillators are realized by all-pass filters whose natural frequency and stage gain can be electronically tuned by adjusting the bias currents. Each all pass filter contains 10 NPN transistors and a grounded capacitor. The validated BJT model which is used in SPICE simulation operated by a single power supply as low as 2.5 V. The frequency of oscillation can be controlled over four decades. The total harmonic distortions of these MSO at frequency 56.67 MHz and 54.44 MHz, obtained around 0.52% and 0.75%, respectively. The proposed circuits enable fully integrated in telecommunication systems and also suit to high-frequency applications. Nonideality studies and PSpice simulation results are included to confirm the theory.

Keywords

All-pass filter, log-domain filtering, high-frequency, low-voltage, electronically-controlled, multiphase sinusoidal oscillator.

1. Introduction

Log-domain circuits are useful building blocks for realizing high-performance current-mode analogue signal processing systems. In 1979, Adams introduced a novel class of continuous-time filters called log-domain filters which externally are linear systems, yet internally are nonlinear [1]. The proposed circuit is originated from the companding concept of log-domain circuits. Input linear current is initially converted to a compressed voltage. Compressed voltage is processed by the log-domain core block. The compressed output voltage is converted to a linear current to preserve the linear operation of the whole system. The compression and expansion of the corresponding signals are based on the logarithmic/exponential voltage–current relationship of a bipolar transistor.

In 1993, Frey introduced a general method for synthesizing log-domain filters of arbitrary order using a state-space approach [2], [3]. Frey also presented a highly modular technique for implementing such filters from a simple building block comprising a bipolar current mirror whose emitters are driven by complementary emitter followers. Log-domain filter operations are based on instantaneous companding [4]–[7] and these previous circuits are of theoretical and technological interest because they potentially offer high-frequency operation, tunability, and extended dynamic range under low power supply voltages [8]–[14]. Log-domain circuits based on CMOS technology were introduced [15] which need to bias in weak inversion region. Complexity and low-bandwidth are the drawback of this circuit.

Multiphase Sinusoidal Oscillator (MSO) is appropriate to use in many applications. For example, in telecommunications MSO is used in realizing phase modulator, quadrature mixers and single-sideband generators. For measurement purposes, MSO is used in realizing vector generators or selective voltmeters. Moreover, MSO constitutes an important unit in many communication and instrumentation systems [26]. Current-conveyors with grounded capacitors [16], [17] were used in MSO realization. OTAs and grounded capacitors were also introduced to use in realization of MSO and a third-order oscillator [18]. OPAMP with RC components [19], current-differencing transconductance amplifiers (CDTA) with floating capacitors [20] and current-controlled current-differencing transconductance amplifiers (CCCDTA) with grounded capacitors [21] are introduced to use in MSO based on the all-pass (AP) sections. The previous MSOs suit to IC production, but not to high-frequency operations. Log-domain MSO [22] and quadrature sinusoidal oscillator (QSO) [23] are also proposed including the following potential capabilities: low-voltage, high-frequency and wide electronic tuning. The circuit uses synthesis method of exponential and log cells, hence it suffers from high complexity and a high number of transistors per phase.

Low-complexity log-domain MSO and QSO have been introduced based on LP filter [24] and lossless integrator [25], respectively. Since 2012, log-domain MSO based on only inverting AP filter has been introduced [26].
This MSO can only operate in the odd number \((n=\text{odd})\) of inverting AP filters with cascade connection. This paper presents odd and odd/even MSOs realization based on inverting and non-inverting AP log-domain filters. Fast response and low-power supply are obtained. The proposed circuit possesses the following features:

1. Low complexity which can be easily configured and realized by using the minimum number of active and passive components per phase.
2. Use of grounded capacitors suits to integration.
3. A wide range electronic tunability of the oscillation frequency and electronic tunability of the oscillation condition.
4. High-frequency range of oscillation based on log-domain concept with electronic tunability and low-power supply feature.
5. High-output impedance, thus this allows interconnection with succeeding current-mode circuits.

## 2. Theory and Principle

### 2.1 Odd and Odd/Even Multiphase Sinusoidal Oscillators Based on AP Filtering Concept

The generalized structure of odd MSO is shown in Fig. 1. It consists of identical inverting AP filters, hence \(n\) can only be odd number. The current output \((I_0)\) of the last stage is fed back to the input of the first stage. An inverting AP filter is determined by the following transfer function.

\[
H(s) = \left[ -k \left( \frac{1-sA}{1+sA} \right) \right]^n = 1
\]  

(1)

where \(k\) is the low-frequency stage-gain and \(A\) is the system time constant which determined for natural frequency \((f_0)\). Using Barkhausen’s condition, the system transfer function in Fig. 1 is satisfied as

\[
H(s) = \left[ -k \left( \frac{1-sA}{1+sA} \right) \right] = 1 \tag{2}
\]

which is equivalent to

\[
|H(j\omega_0)| = 1 \tag{3}
\]

\[
\angle H(j\omega_0) = 2n\phi = 2n(-2 \tan^{-1} \omega_0 A) = -2\pi \tag{4}
\]

The frequency of oscillation \(\omega_0 = 2\pi f_0\) becomes

\[
\omega_0 = \frac{1}{A} \tan(\pi / 2n) \cdot \tag{5}
\]

The oscillation condition can be achieved by \(k = 1\). A design of odd/even MSO based on AP filter is shown in Fig. 2. It can be realized by using one inverting AP filter as the last stage and non-inverting AP filters are the rest, hence \(n\) can be odd or even number. The current output \((I_0)\) of the last stage is fed back to the input of the first stage. The transfer function can be expressed as

\[
H(s) = \left[ k \left( \frac{1-sA}{1+sA} \right) \right] = 1 \cdot \tag{6}
\]

\[
\text{Fig. 2. Block diagram of MSO } (n=\text{odd/even}).
\]

Phase and frequency of oscillation of odd/even MSO are same as odd MSO which described in (4) and (5).

### 2.2 Log-domain AP Filter Realized by LP Filter

Fig. 3 shows a log-domain filtering scheme based on a translinear type-B (balance) cell [7] which is called log-domain low-pass (LP) filter. Assuming that each transistor has an ideal exponential characteristic (base-current is neglected) and using Kirchoff’s current law (KCL), the base-emitter voltage relations can be written as

\[
V_{be1} + V_{be2} - V_{be3} - V_{be4} = 0 \tag{7}
\]

The collector current of the transistor is given by

\[
I_C = I_s \exp \left( \frac{V_{be}}{V_T} \right) \tag{8}
\]

where the different terms have their usual meaning. Now, applying the translinear principle (TLP) to \(Q_1-Q_4\) gives

\[
I_{C1}I_{C2} = I_{C3}I_{C4} \tag{9}
\]

If \(I_{C1} = I_1, I_{C2} = I_2\) and \(I_{C4} = I_{Q3}\), equation (9) becomes
\[ I_1 I_2 = I_c I_o. \] (10)

The collector current of \( Q_1 \) can be expressed as
\[ I_{c1} = I_1 + C_1 V_{c1}'. \] (11)

The derivative of the voltage across the capacitor \( C_1 \) is
\[ V'_{c1} = \frac{dV_{c1}}{dt} = \frac{d}{dt} \left( I_o \right) = \frac{V_{c1} I_o}{I_o} \] (12)

where \( I_o = I_s \exp(V_{c1}/V_T) \), the derivative of the output current yields
\[ I_{o'} = \frac{dI_o}{dt} = \frac{I_s}{V_T} V_{c1} \frac{dV_{c1}}{dt}. \] (13)

Substituting (11), (12) and (13) into (10), we get
\[ I_1 I_2 = \left( I_1 + \frac{C V_{c1} I_o}{I_o} \right) I_o. \] (14)

Suppose we define the currents \( I_2 = kI_3 = kI \), then equation (14) becomes
\[ kl = I_o + \frac{C V_{c1} I_o}{I}. \] (15)

By taking the Laplace transform of (15) and rearranging, the transfer function of the circuit in Fig. 3(a) is given by
\[ H(s) = \frac{I_o(s)}{I(s)} = \frac{k}{s(C V_T / I) + 1}. \] (16)

From (16), where \( k = I_2/I_3 \) and \( V_T = 26 \text{ mV} \) at room temperature, it can be seen that \( H(s) \) corresponds to the transfer function of a LP filter. The natural frequency is controlled by the bias current \( I \).

![Fig. 4. Inverting log-domain LP filter [24].](image)

From Fig. 3, if the currents \( I_1, I_2 \), and \( I_3 \) are, respectively, replaced by \( I_1 = I + I_m, I_2 = kI \) and \( I_3 = I \). A current source \( kI \) will be inserted at the output for cancelling the DC-offset. Then Fig. 3 is transformed to Fig. 4 [24]. The current output of completed inverting log-domain low-pass filter is obtained in \( s \)-domain function as
\[ \frac{I_{out}(s)}{I_o(s)} = \frac{-k}{s(C V_T / I) + 1}. \] (17)

Fig. 5(a) shows the block diagram of the proposed AP filter realized from a LP filter. The AP filter consists of a LP filter, two amplifiers (gain = 2 and gain = \( k \)) and a summing junction. Then the inverting AP filter transfer function of Fig. 5(a) can be written as
\[ \frac{Y(s)}{X(s)} = k \left( \frac{1 - sA}{s + sA} \right). \] (18)

![Fig. 5. AP filter realized by LP filter block diagram: (a) Inverting, (b) Non-inverting.](image)

Considering Fig. 5(b), the non-inverting AP filter can be obtained by assigning the both amplifier blocks to negative. The non-inverting AP filter transfer function can be written as
\[ \frac{Y(s)}{X(s)} = k \left( \frac{1 - sA}{1 + sA} \right). \] (19)

![Fig. 6. The proposed log-domain first-order AP filter: (a) Inverting, (b) Non-inverting.](image)

Using methodology in Fig. 5(a) to realize the circuit then it can be depicted as Fig. 6(a). Transistors \( Q_4, Q_5, Q_6 \) and \( Q_8 \) are realized to inverting LP filter with gain = 2. At the same time, transistors \( Q_5, Q_7 \) and \( Q_9 \) are realized to inverting current gain \( (k) \) then its output connects to the other inverting function which is provided by current mirror \( Q_7 \) and \( Q_9 \). Non-inverting current gain is achieved by the collector output of \( Q_5 \). Summing the current outputs of LP filter with gain = 2 \( Q_4 \) and \( Q_6 \) and non-inverting current...
Fig. 7. Log-domain allpass-based MSO structures: (a) odd $n = 3$, (b) odd/even $n = 3$. 
gain \((Q_T)\), the inverting AP filter is achieved. The current transfer functions can be written as

\[
\frac{I_{\text{out}}}{I_n} = -k, \quad (20)
\]

\[
\frac{I_{\mu_n}}{I_n} = -k \left( \frac{1 - sCV_f/I}{1 + sCV_f/I} \right). \quad (21)
\]

Using methodology in Fig. 5(b) to realize the circuit then it can be depicted as Fig. 6(b). Using similar concept to Fig. 6(b), the current gain transfer function is the same as (20), but the current output of AP function \((Q_T, Q_k\) and \(Q_q)\) becomes non-inverting transfer function as

\[
\frac{I_{\text{out}}}{I_n} = k \left( \frac{1 - sCV_f/I}{1 + sCV_f/I} \right). \quad (22)
\]

Considering (21) and (22) with AP function in section 2.1, \(A = CV_f/I\) and \(k = I_2/I\) for inverting and non-inverting AP filters. The frequency response and stage gain can be independently tuned through bias current.

### 3. Current-mode Log-domain MSO

A three-phase MSO concept based on Fig. 1 and 2 is implemented to confirm the theory shown in Fig. 7. The first AP-based MSO is realized by cascading three inverting AP filters. The second AP-based MSO is also realized by cascading two non-inverting and one inverting AP filters.

From Fig. 7(a), loop-gain of this circuit is actually adjusted to unity for obtaining the oscillation condition. Unity stage gain \((k = 1)\) is defined for obtaining the oscillation condition. The bias currents are assigned to \(k = 1\) by setting \(kI_1 = I\). Each negative stage (AP1-AP3) provides high output impedance that drives to the succeeding stage. The inverting first-order AP filter sections are given by

\[
\frac{I_{\text{out}}}{I_n} = k \left( \frac{1 - sCV_f/I}{1 + sCV_f/I} \right). \quad (23)
\]

The result in three cascaded AP filter yields

\[
H(s) = \left[ \frac{1 - s(CV_f/I)}{1 + s(CV_f/I)} \right]^3. \quad (24)
\]

From (5), the frequency of oscillation gives

\[
\omega_0 = \frac{A}{\sqrt{3}} = \frac{I}{\sqrt{3}CV_f}. \quad (25)
\]

From Fig. 7(b), three-phase MSO based on Fig. 2 is also implemented to confirm the theory. The non-inverting first-order AP filter sections are given by

\[
\frac{I_{\text{out}}}{I_n} = k \left( \frac{1 - sCV_f/I}{1 + sCV_f/I} \right). \quad (26)
\]

The result in three cascading two non-inverting and one inverting AP filters yields

\[
H(s) = \left[ \frac{1 - s(CV_f/I)}{1 + s(CV_f/I)} \right]^3. \quad (27)
\]

From (5), the frequency of oscillation gives

\[
\omega_0 = \frac{A}{\sqrt{3}} = \frac{I}{\sqrt{3}CV_f}. \quad (28)
\]

### 4. Influence of Non-idealties

Log-domain filter suffers from transistor non-idealities effect. The study of non-ideal log-domain filters is complicated by the fact that the non-linear logarithmic-exponential operations inherent the circuit result in transcendental equations. This qualitative analysis shows that the transistor non-idealities including the parasitic resistances and parasitic capacitances are the sources of error within log-domain circuits. This paper derives equations describing the non-ideal characteristics of log-domain circuit as a consequence of the deviations in non-ideal parameters. This section shows the effects of transistor parasitic in Fig. 8 based on a small-signal model using transconductance \(g_m = I_e/V_T\), base-emitter resistance \((r_e)\), and base-collector capacitance \((C_{\pi})\), and base-collector capacitance \((C_{\mu})\). We assume that the other parasitic capacitances are very small and the impedance of the collector-emitter \((r_{ce})\) is high. Physical parameters such as area mismatch and early voltage are also discussed.

![Fig. 8. Simple small signal of BJT transistor.](image)

Taking the model in Fig. 8 into log-domain AP filter in Fig. 6, the input and output resistances are obtained around \(1/g_m\) and \(r_e/3\), respectively. As resulting of input and output resistances, the circuit is agreed well in current-mode approach.

#### 4.1 Parasitic Capacitance \((C_{\pi} and C_{\mu})\)

Parasitic base-emitter capacitance \((C_{\pi})\) is also a major limitation of translinear circuit accuracy, particularly in high-frequencies. Using the small-signal model of the bipolar transistor with parasitic capacitances, the \(C_{\pi}\) that affects inverting and non-inverting all-pass filter transfer functions can, respectively, be approximated to (29) and (30). Similarly, parasitic base-collector capacitance \((C_{\mu})\) is
also a major limitation to translinear circuit accuracy. The effect of the base-collector capacitance that affects inverting and non-inverting all-pass filter transfer functions are given by (31) and (32), respectively.

\[
\begin{align*}
I_{e\rightarrow s}(s) &= \frac{g_{m2}g_{m3}(g_{m9} - 2g_{m4}) - s[2g_{m3}g_{m4}(C_{x1} + C_{x2} + C_{x9}) - g_{m5}g_{m6}(C_{x3} + C_{x4} + C_{x5}) + 2C_{x5}g_{m6}g_{m4} - C_{x2}g_{m6}g_{m5}]}{g_{m1}g_{m2}g_{m3} + s[g_{m2}g_{m3}(C_{x1} + C_{x2} + C_{x9}) + g_{m5}g_{m6}g_{m3} + C_{x2}g_{m6}g_{m5}]} , \\
I_{m}(s) &= \frac{g_{m2}g_{m3}(g_{m9} - 2g_{m4}) + s[2g_{m3}g_{m4}(C_{x1} + C_{x2} + C_{x9}) - g_{m5}g_{m6}(C_{x3} + C_{x4} + C_{x5}) + 2C_{x5}g_{m6}g_{m4} - C_{x2}g_{m6}g_{m5}]}{g_{m1}g_{m2}g_{m3} + s[(C_{x1} + C_{x2} + C_{x9})g_{m1}g_{m2}g_{m3} + C_{x2}g_{m6}g_{m5} + g_{m5}g_{m6}g_{m3} + C_{x2}g_{m6}g_{m5}]} , \\
I_{e\rightarrow s}(s) &= \frac{g_{m2}g_{m3}(g_{m9} - 2g_{m4}) - s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})]}{g_{m1}g_{m2}g_{m3} + s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})] + 1} , \\
I_{m}(s) &= \frac{g_{m2}g_{m3}(g_{m9} - 2g_{m4}) + s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})]}{g_{m1}g_{m2}g_{m3} + s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})] + 1} , \\
I_{e\rightarrow s}(s) &= \frac{s(C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9}) - 3C_{x9})}{g_{m1}g_{m2}g_{m3} + s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})] + 1} , \\
I_{m}(s) &= \frac{s(C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9}) - 3C_{x9})}{g_{m1}g_{m2}g_{m3} + s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})] + 1} , \\
I_{e\rightarrow s}(s) &= \frac{s(C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9}) - 3C_{x9})}{g_{m1}g_{m2}g_{m3} + s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})] + 1} , \\
I_{m}(s) &= \frac{s(C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9}) - 3C_{x9})}{g_{m1}g_{m2}g_{m3} + s[C_{x1} + C_{x4} + C_{x9} - 2(C_{x1} + C_{x9})] + 1} .
\end{align*}
\]

Assuming that the transconductances of the transistors are matched, the transfer function becomes (33)-(36).

\[
\lambda \bar{d} I = I_{o} + \frac{C_{o} I_{o} V_{s}}{I} ,
\]

where \( \lambda = I_{o} / I_{s} = A_{o} A_{s} \).

From (38), it is clear that area mismatches introduce only a change in the proportionality constant or DC gain of the low-pass filter without affecting the linearity or the time constant of the circuit. The gain error can be easily compensated by adjusting one of the DC bias currents.

### 4.3 Early Effect

Early effect (base-width modulation) causes the collector current error by the collector-emitter and base-collector voltages. Considering the variation of collector-emitter voltage, the collector current can be written as

\[
I_{c} = (1 + V_{ce} / V_{sat}) I_{E} \exp(V_{ce} / V_{sat}) ,
\]

where \( V_{sat} \) is the forward-biased early voltage. An analysis of the integrator shows the early effect with a scalar error to the DC gain of the circuit as in case of area mismatches. Since \( V_{sat} \) has been signal-dependent, the device base-width modulation also introduces distortion. Since the voltage swings in the current-mode companding circuits have been very low \((\Delta V_{sat})\), the early effect is not a major source of distortion.

### 4.4 Parasitic Resistance (\( r_{p} \))

Parasitic base-emitter resistance \((r_{p})\) is a major limitation of the translinear circuit accuracy in high-frequencies. Base-emitter resistance has generally been identified as the most problematic error sources in lower frequencies [28] and also produced noise temperature.

From the small-signal model of bipolar transistor, when the parasitic capacitances are neglected, the \( r_{p} \) that affects inverting and non-inverting all-pass filter transfer functions are, respectively, described in (39) and (40).
The positive \((I_P)\) and negative \((I_N)\) current sources are respectively replaced by positive and negative current mirrors as shown in Fig. 9. The transconductances of transistors are respectively replaced by positive and negative current mirrors in Fig. 9. The transconductances of transistors are listed in Table 1(a). The bias currents realized by using the accurate bias currents as cascode current mirrors.

Errors of Bias Currents

As we see from (45), there is a slight deviation in the pole of zero frequency due to the mismatch in bias currents. The error can be eliminated by using the accurate bias currents as cascode current mirrors.

5. Simulation Results

In order to verify the operation of MSO topology in Fig. 7, power supply voltage is assigned to \(V_{CC} = 2.5\) V, current-gain \(k = 1.047\) and the bias current \(I\) is varied from 0.01 \(\mu\)A to 1.000 \(\mu\)A. To prevent the parasitic effects of the filter, capacitors should be much larger than \(4C_x + 3C_y\) (around 0.5 pF) by assigning \(C_1 = C_2 = 50\) pF. According to section 2, the low-frequency stage gain of each all-pass filter must be unity based on identical current bias \(I\). The NPN high-speed bipolar technology (HSB2) provided by ST Microelectronics [25] is used in the simulations and listed in Tab. 1(a). The bias currents realized by using the current mirrors as shown in Fig. 9 are provided by NPN and PNP (HFA3128 transistor arrays) models in Tab. 1(a) and (b), respectively.
the current outputs that provided by adjustable current-gain based on varied bias currents.

Fig. 10. Magnitude response of LP filter with gain tunability when \( I = 1,000 \mu A \) and \( C = 50 \) pF.

Fig. 11. Waveform output of LP filter by varying \( kI \) when \( I = 100 \mu A \) and \( C = 50 \) pF.

Fig. 12. Magnitude and phase response of AP filter with gain tunability when \( I = 1,000 \mu A \) and \( C = 50 \) pF.

Fig. 13. Monte Carlo simulation of log-domain LP filter when transistors have 20% deviation of \( \beta \).

Fig. 14. Sinusoidal outputs (Odd Structure) when \( I = 1,000 \mu A \) and \( C = 50 \) pF.

Fig. 15. Sinusoidal outputs (odd/even structure) when \( I = 1,000 \mu A \) and \( C = 50 \) pF.

Fig. 16. Spectrum of signal in Fig. 14.

The frequency spectrum of the sinusoidal signal output of Fig. 14 is shown in Fig. 16. The \( 2^{nd} \) and \( 3^{rd} \) harmonic components are obtained around 1.56 \mu A, 941.77 nA, respectively, while the amplitude of the fundamental component (56.67 MHz) is around 346 \mu A; hence, the THD is obtained around 0.52%.
oscillation (from 750 Hz to 56.67 MHz) can be obtained by varying \( I_0 \) from 0.01 \( \mu A \) to 1,000 \( \mu A \). THD at frequency 56.67 MHz is obtained around 0.52%. Power consumption at 1,000 \( \mu A \) is obtained around 100 mW.

The frequency spectrum of the sinusoidal signal output of Fig. 15 is shown in Fig. 17. The 2nd and 3rd harmonic components are obtained around 1.67 \( \mu A \), 441.86 nA, respectively, while the amplitude of the fundamental component (54.44 MHz) is around 230.53 \( \mu A \); hence, the THD is obtained around 0.75%.

The tunable frequency of oscillation of AP filter based MSO can be accommodated by varying the current bias \( I \) from 0.01 \( \mu A \) to 1,000 \( \mu A \) with different capacitor values. A comparison between simulation and theoretical results are shown in Fig. 18. A wide-range of frequency of oscillation (from 750 Hz to 56.67 MHz) can be obtained based on \( C_1 = C_2 = 50 \) pF. PSpice simulation results agree well with the theory.

6. Conclusion

A novel low-voltage current-mode MSO based on log-domain AP filter has been presented. Inverting and non-inverting log-domain AP filters are realized based on LP filter. Both types of AP filters are realized by 10 transistors, a grounded capacitor and 7 bias currents. Due to log-domain concepts, inverting and non-inverting AP filter can provide the high performance feature, such as high frequency operation and linear wide range tuning. Two structures of MSO (odd and odd/even) can be realized based on cascading log-domain inverting and non-inverting AP filters. The proposed three phases MSOs consist of 30 transistors, 21 bias current sources and 3 grounded capacitors. Multiphase sinusoidal output currents with high output impedance are produced based on a 2.5 V power supply. A wide-range of tunable frequency response (from 750 Hz to 56.67 MHz) can be obtained by varying \( I_0 \) from 0.01 \( \mu A \) to 1,000 \( \mu A \). THD at frequency 56.67 MHz is obtained around 0.52%. Power consumption at 1,000 \( \mu A \) is obtained around 100 mW.

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