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Active-only current-mode first-order allpass filter and its application in quadrature oscillator

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The current-mode first-order allpass filter (APF) using only the active elements has been studied in the present paper. The proposed circuit comprises two operational transconductance amplifiers (OTAs) and one operational amplifier (OA) which is suitable to future development into an integrated circuit. The pole frequency and phase response can be electronically adjusted with changing the *dc* bias currents of OTAs. The APF has high output impedance, which is easy to cascade in high-order filter or drive load without using a buffering device. The current-mode quadrature oscillator is included to show the usability of the proposed filter. The results of PSPICE simulation are accordant with the theoretical analysis.

Keywords: Active-only APF, First-order allpass filter, Current-mode, Operational transconductance amplifiers, Operational amplifier

1 Introduction

The current-mode circuits have been found widely in analog signal processing circuits[1] ; for example current-mode biquadratic filter, quadrature oscillator, inductance simulator, multiphase sinusoidal oscillator etc, due to its advantages in term of inherently wide bandwidth, higher slew-rate, greater linearity, wider dynamic range, simple circuitry and low power consumption[1-4].

Mostly, the pole-model of the Operational amplifier (OA) has been used in the place of external capacitors[5-10], which is suitable for fabricating in monolithic chip[5-10]. The Operational Transconductance Amplifier (OTA) seems to be a versatile component in the realization of a class of analog signal processing circuits, especially analogue frequency filters. In addition, the output current of OTA can be electronically adjusted. These are advantages for motivating the circuit designers to develop filters and oscillator using only the OAs and OTAs[5-10]. First-order allpass filter (APF) or phase-shifter circuits are extremely useful in electronics and electrical engineering such as in modulating and demoduling systems, quadrature oscillator, multiphase oscillator and high Q band pass filter[11-24]. From literature survey, it is found that several implementations of first-order APF using different high performances active building block have been reported[11-27]. Unfortunately, these reported circuits suffer from one or more of following weaknesses. The excessively use[12,13,18,19,23,25] of the passive elements is not convenient to further fabricate IC and cannot provide electronic tenability. The reported circuits[26,27] enjoy single active element and electronic tuning by adjusted transconductance gain but they require multiple current output terminals (z and x port). Consequently, these circuits become more complicated. Moreover, the circuits in Refs (12,13, 15-20, 22,23, 25) use external passive resistors, which are not ideal for integration[27]. The circuit specifications of these reported APFs are compared with the proposed APF as presented in Table 1.

The current-mode first-order allpass filter is proposed, emphasizing on the use of an active element without external passive components. It employs 1 OA and 2 OTAs, which are suitable for fabricating in monolithic chip. To verify the workability of the proposed circuit, the PSPICE simulation results of a CMOS implementation and its application of the allpass filter as a quadrature oscillator have been included.

Table 1 — Comparison between various APFs

Ref	Active element	Number of active element	Number of R+C	Electronic tune	Matching Condition	Current-mode output
[11]	VDIBA	1	0+1	Yes	No	No
[12]	CCII	1	3+1	No	Yes	Yes
[13]	CCII	1	2+2	No	Yes	Yes
[14]	ZC-CITA	1	0+1	Yes	No	Yes
[15]	DVCCTA	1	1+1	Yes	No	No
[16]	DBTA	1	2+2	Yes	No	Yes
[17]	DBTA	1	1+1	Yes	No	No
[18]	CCII	2	2+2	No	No	No
[19]	CCII	1	3+1	No	Yes	Yes
[20]	OTA	2	1+1	Yes	Yes	Yes
[21]	OTA	3	0+3	Yes	Yes	Yes
[22]	OTA	2	1+1	Yes	Yes	Yes
[23]	DVCC+OTA	2	2+1	Yes	No	Yes
[24]	CCCCTA	2	0+1	Yes	No	Yes
[25]	FDCCII	1	2+2	No	No	Yes
[26]	CDTA	1	0+1	Yes	No	Yes
[27]	ZC-CFTA	1	0+1	Yes	No	Yes
Proposed APF	OTA+OA	3	0+0	Yes	No	Yes

2 Principle and Operation

2.1 Operational Transconductance Amplifier

A brief review of the OTA is given. Generally, the OTA has infinite input and output impedances. The output current of an OTA is given by:

$$I_O = g_m (V_+ - V_-) , \qquad \ldots(1)$$

where g_m is the transconductance gain of the OTA. For a CMOS OTA, the transconductance gain can be expressed by:

$$g_m = \sqrt{kI_B} . \qquad \ldots(2)$$

where $k = \mu C_{ox} (W / L)$ is the physical parameter of CMOS transistor. The symbol and the equivalent circuit of the OTA are shown in Fig. 1(a and b), respectively.

2.2 Operational Amplifier

The open-loop gain of the operational amplifier[5-10] is approximately given by:

$$A(s) = \frac{B}{s} , \qquad \ldots(3)$$

where B is the gain-bandwidth product.

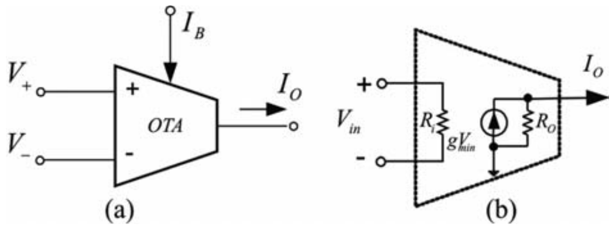

Fig. 1 — OTA (a) Symbol (b) Equivalent circuit

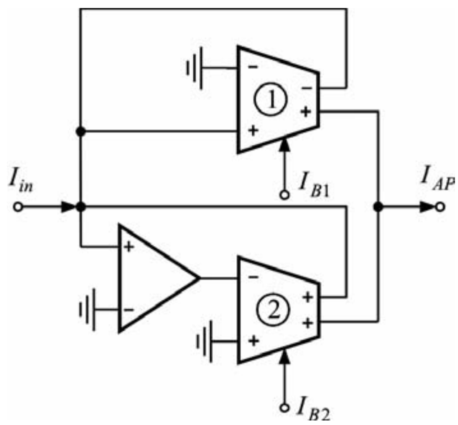

Fig. 2 — Proposed current-mode first-order APF

2.3 Proposed Current-mode First-order Allpass Filter

The proposed active-only current-mode first-order APF filter is shown in Fig. 2. It consists of 2 OTAs and 1 OA which is suitable for fabricating in monolithic chip for use in portable electronics equipments. From the OTA and OA properties, the following current transfer function is subsequently obtained

$$\frac{I_{Out}(s)}{I_{in}(s)} = \frac{s - \frac{g_{m2}}{g_{m1}}B}{s + \frac{g_{m2}}{g_{m1}}B}. \quad \ldots(4)$$

From Eq.(4), the pole frequency, current gain and phase response of the proposed current-mode first-order APF circuit are:

$$\omega_0 = \frac{g_{m2}}{g_{m1}}B, \quad \ldots(5)$$

$$G(\omega) = \left|\frac{I_{Out}}{I_{in}}\right| = 1, \quad \ldots(6)$$

and

$$\phi(\omega) = 180 - 2\tan^{-1}\left(\frac{g_{m1}\omega}{g_{m2}B}\right). \quad \ldots(7)$$

Substituting the transconductance g_m as given in Eq. (2) into Eqs (5) and (7), the pole frequency and phase response of the proposed circuit are given by:

$$\omega_0 = B\sqrt{\frac{I_{B2}}{I_{B1}}}, \quad \ldots(8)$$

and

$$\phi(\omega_0) = 180 - 2\tan^{-1}\left(\frac{\omega}{B}\sqrt{\frac{I_{B1}}{I_{B2}}}\right). \quad \ldots(9)$$

It is clear that the pole frequency and phase response of the proposed current-mode first-order APF can be electronically adjusted by either I_{B1} or I_{B2}. In addition, the output-current port is of high-impedance which is easy to drive a load without using a buffering device.

2.4 Proposed Current-mode Quadrature Oscillator

The proposed first-order APF is used to design a current-mode quadrature oscillator by cascading a non-inverting and an inverting APF as shown in

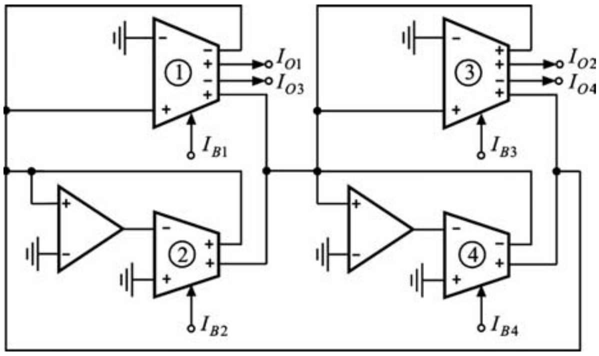

Fig. 3 — Proposed current-mode quadrature oscillator

Fig. 3. The characteristic equation of the current-mode quadrature oscillator (assuming B_1=B_2=B), can be obtained:

$$s^2 + \frac{g_{m2}g_{m4}}{g_{m3}g_{m1}}B^2 = 0. \quad \ldots(10)$$

From Eq.(10), the oscillation frequency (ω_{osc}) can be concluded to be:

$$\omega_{osc} = B\sqrt{\frac{g_{m2}g_{m4}}{g_{m1}g_{m3}}}. \quad \ldots(11)$$

Substituting the transconductance g_m as given in Eq. (2) into Eq. (11), the oscillation frequency (ω_{osc}) is given by:

$$\omega_{osc} = B\left(\frac{I_{B2}I_{B4}}{I_{B1}I_{B3}}\right)^{\frac{1}{4}}. \quad \ldots(12)$$

It is obviously found from Eq. (12), the oscillation frequency can be electronically adjusted by setting I_{B1}, I_{B2}, I_{B3} or I_{B4}.

2.5 Analysis of the Non-idealities of OA and OTA

For a complete analysis of the circuit, it is necessary to take into account the non-idealities of the OA and OTA on the transfer function of proposed current-mode first-order APF circuit. The parasitic pole of the OA and OTA for the open loop gain $A(s)$ and transconductance gain $g_m(s)$ are presented[5-10] by:

$$A_{ni}(s) = \frac{B_i\omega_{2i}}{s(s+\omega_{2i})} \quad \ldots(13)$$

$$g_{mnj}(s) = \frac{g_{mj}\omega_{gj}}{s+\omega_{gj}}, \quad (j = 1, 2) \qquad \ldots(14)$$

where ω_{2i} and ω_{gj} denote the second pole of the OA and the first pole of OTA, respectively. The $A_{ni}(s)$ and $g_{mnj}(s)$ can be assumed [5-10] as:

$$A_{ni}(s) \cong \frac{B_i}{s}(1-\tau_i s), \qquad \ldots(15)$$

$$g_{mnj}(s) \cong g_{mj}(1-\mu_j s), \qquad \ldots(16)$$

where $\tau_i = 1/\omega_{2i}$ and $\mu_j = 1/\omega_{gj}$

Using Eqs (15) and (16) and reanalysis of the proposed current-mode first-order APF circuit (assuming OTA_1 and OTA_2 are of same ability, that is $\mu_1 = \mu_2$), the current transfer function of Fig. 2 becomes:

$$\frac{I_{Out}(s)}{I_{in}(s)} = \frac{s - \dfrac{g_{m2}B}{g_{m1}+g_{m2}\tau}}{s + \dfrac{g_{m2}B}{g_{m1}+g_{m2}\tau}}, \qquad \ldots(17)$$

It is found from Eq. (17) that the current gain is equal to unit. The pole frequency and phase response of the proposed circuit are expressed as:

$$\omega_0 = \frac{g_{m2}B}{g_{m1}+g_{m2}\tau}, \qquad \ldots(18)$$

and

$$\phi(\omega) = 180 - 2\tan^{-1}\left[\frac{\omega(g_{m1}+g_{m2}\tau)}{g_{m2}B}\right]. \qquad \ldots(19)$$

Then, the oscillation frequency of the current-mode quadrature oscillator shown in Fig. 3 is changed to:

$$\omega_{osc} = \sqrt{\frac{g_{m2}g_{m4}B_1B_2}{(g_{m1}+g_{m2}\tau_1)(g_{m3}+g_{m4}\tau_2)}}. \qquad \ldots(20)$$

3 Simulation Results

To prove the performances of the proposed current-mode first-order APF circuit, the PSPICE simulation was performed for examination. Figure 4 shows the schematic description of the CMOS OTA and CMOS OA[28] used in the simulations. The parameters of the NMOS and PMOS transistor are a 0.25μm TSMC CMOS technology[28] with ±2 supply voltages. The CMOS OA used C_1=30 pF with bias voltages V_{B1} =−1 V and V_{B2}=−1.3 V. The aspect transistor ratios of CMOS OA and OTA are listed in Tables 2 and 3, respectively. These transistor ratios are taken from Ref. 28.

The bandwidth of CMOS OA is shown in Fig. 5. It is found that the-3dB frequency is 2.06 MHz. Figure. 6 shows the transconductance value where I_B is varied from 1 μA-500 μA. The result in Fig. 7 shows the gain and phase responses of the proposed current-mode APF where I_{B1}=I_{B2}=200 μA. It is evident that the pole frequency is about 2.05 MHz,

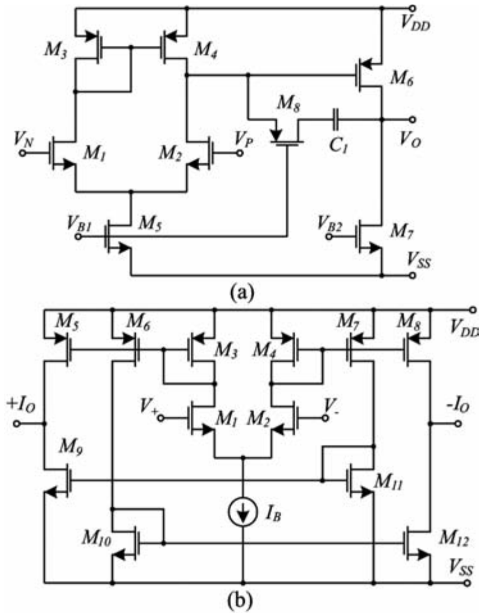

Fig. 4 — Schematic of CMOS (a) OA (b) OTA

Table 2 — Aspect transistor ratio of the CMOS OA

Transistor	W (μm)	L (μm)	Transistor	W (μm)	L (μm)
M_1, M_2	250	3	M_6	392	1
M_3, M_4	100	3	M_7	232	3
M_5	80	32	M_8	39	1

Table 3 — Aspect transistor ratio of the CMOS OTA

Transistor	W (μm)	L (μm)	Transistor	W (μm)	L (μm)
M_1, M_2	25	0.5	M_5, M_8	5	1
M_3, M_4	5	1	M_9,M_{12}	3	0.5
M_6, M_7	5	1	M_{10},M_{11}	3.2	0.5

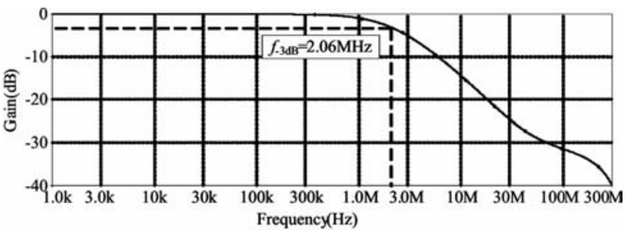

Fig. 5 — Frequency response of the CMOS OA

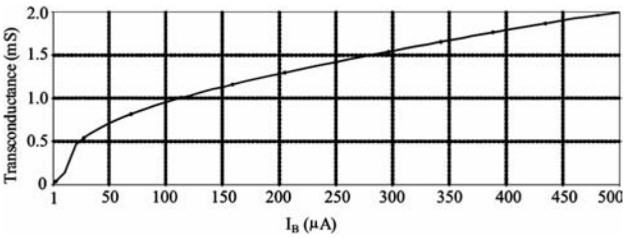

Fig. 6 — Transconductance value of the CMOS OTA relative to I_B

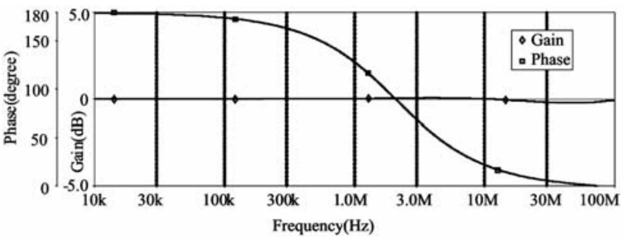

Fig. 7 — Gain and phase response of the proposed current-mode first-order APF

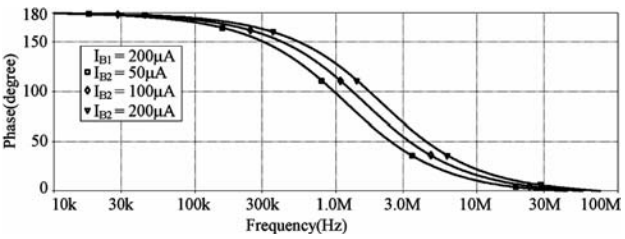

Fig. 8 — Phase response of the APF for different value of I_{B2}

that is in correspondence with the theoretical value of 2.06 MHz. The error of the pole frequency stems from the non-ideal parameters is displayed. The electronic tunability of allpass filter is shown in Fig. 8. In this case, the bias current I_{B2} is varied to 50 μA, 100 μA and 200 μA, respectively.

To illustrate the time-domain performance of the proposed APF, the result is shown in Fig. 9. The input signal is a sinusoidal signal with 2.06 MHz and peak-to-peak values of 160 μA, where I_{B1}=I_{B2}=200 μA. The phase shift angle of output signal is about 88.99°. The

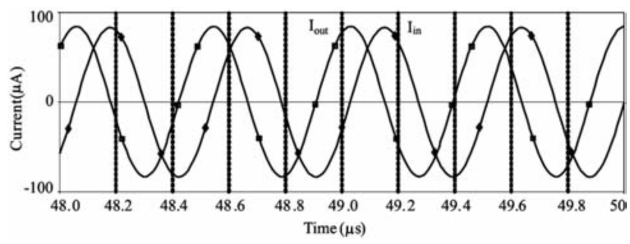

Fig. 9 — Time-domain response of the APF at a 2.06 MHz sinusoidal input signal

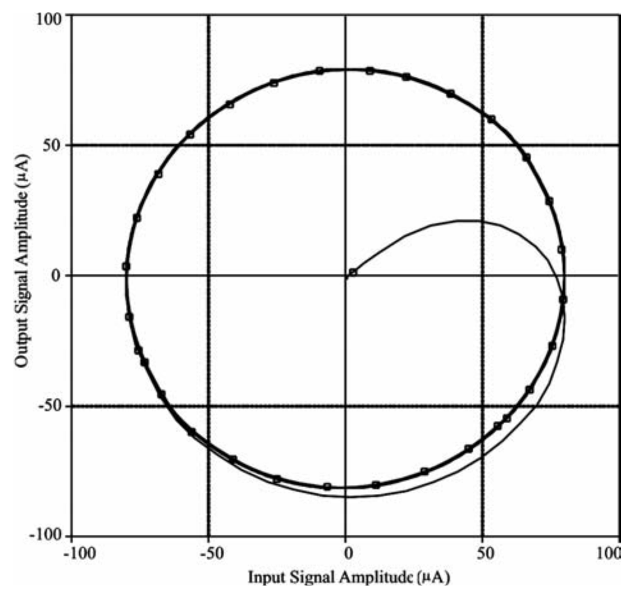

Fig. 10 — Relative between magnitudes of input and output

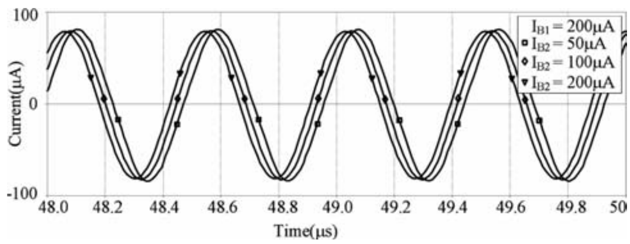

Fig. 11 — Output currents for difference values of I_{B2}

Lissajous pattern in Fig. 10 shows the relative between magnitudes of input and output signals. The output currents for difference values of *dc* bias current I_{B2} are shown in Fig. 11. It is seen that the phase shift can be electronically tuned as expressed in Eq. (9). The total harmonic distortion (THD) of sinusoidal output signal of 2.06 MHz with respect to peak-to-peak amplitude of sinusoidal input signal is shown in Fig. 12. The minimum of THD values is 0.58% with 160 μA peak-to-peak amplitude.

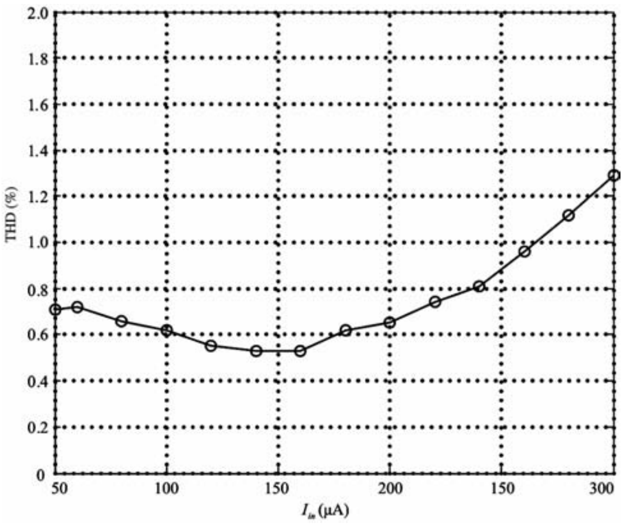

Fig. 12 — THD variation versus peak-to-peak amplitude of the applied sinusoidal input current

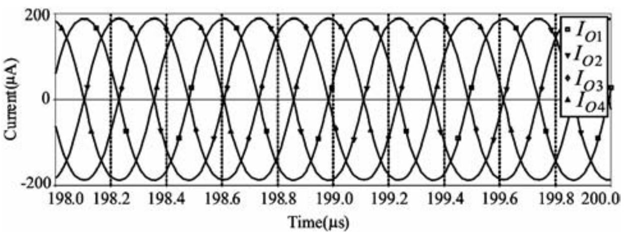

Fig. 13 — Output waveforms of quadrature oscillator

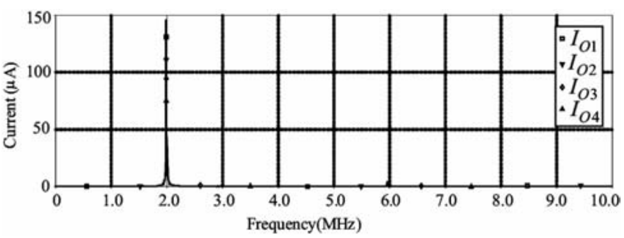

Fig. 14 — Output spectrum of quadrature oscillator

Figure 13 shows the simulated output waveforms of the current-mode quadrature oscillator in Fig. 3, where the bias currents I_{B1}=I_{B2}=I_{B3}=I_{B4}=210 μA. The oscillation frequency is found to be 1.98MHz which is closed to the theoretical value (2.06MHz). Figure 14 shows the simulated output spectrum, where the total harmonic distortion (THD) is about 3.78%

4 Conclusions

An electronically adjustable current-mode first-order allpass filter (APF) has been presented. It employs only the active elements, 2 OTAs and 1 OA, which are suitable for fabricating in monolithic chip for use in portable electronics equipments such as mobile communication systems or wireless communication devices. The pole frequency and phase response of APF can be adjusted with electronic tuning by *dc* bias currents of OTAs. Moreover, the output current of APF has high output impedance which facilitates cascading in current-mode configuration. Moreover, an application as current-mode quadrature oscillator by cascading APF is produced. The current-mode first-order APF and current-mode quadrature oscillator are verified through PSPICE simulations using 0.25μm TSMC CMOS parameters. The simulation results agree well with the theoretical anticipation.

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