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Current Operational Amplifier Based Voltage-Mode MOS-C All-Pass Filter and Its Application

Araştırma Makalesi / Research Article

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ABSTRACT

In this work, a novel first order voltage-mode all-pass filter employing single active element named current operational amplifier (COA), two resistors, one capacitor and it's application as sinusoidal oscillator is presented. The resistors are implemented by using MOSFETs, so the resulting MOS-C circuit is suitable for integration and the central frequency of the filter is electronically tunable. Workability of the proposed filter and it's application is validated by PSPICE simulation software using TSMC 0.18 micron CMOS model parameters. Simulation results are in good consistency with theoretical analysis. The proposed circuit features precise frequency tuning, operability at low voltage, low distortion and low phase error.

Keywords: All-pass filter, current operational amplifier, MOS-C, sinusoidal oscillator, voltage-mode.

Akım İşlemsel Kuvvetlendiricisi Tabanlı Gerilim-Modlu MOS-C Tüm-Geçiren Süzgeç ve Uygulaması

ÖZ

Bu çalışmada akım işlemsel kuvvetlendiricisi adlı tek aktif eleman, iki direnç ve bir kapasitör ile çalışan, gerilim-modlu, MOS-C birinci dereceden tüm-geçiren süzgeç devresi ile sinüzoidal osilatör uygulaması sunulmuştur. Devredeki dirençler MOSFET kullanarak gerçeklenmiş olup sonuçta elde edilen MOS-C devresi tümleşik devre tekniğine uygundur ve süzgecin merkez frekansı elektronik olarak ayarlanabilmektedir. Önerilen devrenin ve uygulamasının çalışabilirliği PSPICE benzetim yazılımı ile TSMC 0.18 mikron CMOS model parametreleri kullanarak doğrulanmıştır. Benzetim sonuçları ile teorik analiz sonuçları iyi bir uyum içerisindedir. Önerilen devre hassas frekans ayarı, düşük voltajda çalışabilirlik, düşük gürültü ve düşük faz hatası gibi özelliklere sahiptir.

Anahtar Kelimeler: tüm-geçiren süzgeç, akım işlemsel kuvvetlendiricisi, MOS-C, sinüzoidal osilatör, gerilim-mod.

1. INTRODUCTION (GİRİŞ)

All-pass (AP) filter is one of the most used filter type and it is used in various applications to perform time-alignment or time-displacement function over a desired frequency range at constant gain. It can also be considered as a phase corrector. Moreover, all-pass filters are used to be the main building blocks of high-Q band-pass filters and sinusoidal oscillators [1,2]. First order all-pass filters find wide range applications in audio and video signal processing systems where the such as current conveyor (CCII, CCIII) and its derivatives [3-6], operational trans-conductance amplifier (OTA) [7], current-feedback operational amplifier (CFOA) [8], current differencing buffered amplifier (CDBA) [9,10] and four terminal floating nullor (FTFN) [11] have been reported. The COA active element is introduced as the current-mode dual of the traditional operational amplifier (op-amp) by applying the theory of adjoint networks [12,13] with the features of current-mode low impedance input, high impedance output and high current gain to be efficient in current mode analog electronic circuit design. However, literature survey shows that the consideration given to filter design using COA is still insufficient and only few COA based filter realizations have been reported [14-17]. The object of this study is to introduce a new first-order voltage-mode all-pass filter using single COA with MOS-C realization and its practice as sinusoidal oscillator to be used in low voltage applications as well as where electronic tunability and compatibility for integration are important design parameters. Table 1 shows a comparison of previously reported COA based all-pass filters to represent the advancements of the proposed circuit.

The outline of remaining part of this paper is composed as following: Section 2 describes the circuit definition of COA active element. Proposed circuit topology is introduced in Section 3. Circuit analysis is carried out, non-ideal effects are discussed and MOS-C implementation of the circuit is also presented in this chapter. Section 4 includes a quadrature oscillator application which is showing the usability of the

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proposed filter. Simulation results of both the all-pass filter and its application are given in Section 5. Tunability of the filter and quadrature oscillator is investigated in this section. Section 6 presents the outcomes of the study and briefs a conclusion.

offset current [19]. Taking into consideration that both CCII+ and CCII- can be obtained from DOCCII (dual-output CCII), then the COA can be implemented by using only DOCCII elements. This technique also enables us to implement the COA using commercially available integrated circuits which can be used as current conveyor.

Table 1. Comparison of previously reported COA based all-pass filters

Ref. number	Active element number	Number of R/C	Circuit mode	Technology	Supply voltage	MOS-C realization	Measured THD	Power Consumption
[14]	1	1/1	Current	1.2 μm CMOS	±2.5 V	No	N/A	N/A
[15]	1	1/1	Current	0.35 μm CMOS	±1.5 V	No	N/A	N/A
[16]	1	2/2 (Topology 1&4) 3/1 (Topology 2&3)	Voltage	0.35 μm CMOS	±1.25 V	No	0.86 % (For input voltage of 100 mV amplitude)	2.40 mW
Proposed	1	2/1	Voltage	0.18 μm CMOS	±0.9 V	Yes	0.33 % (For input voltage of 100 mV amplitude)	1.85 mW

N/A: Not available

2. CIRCUIT DESCRIPTION OF COA (COA DEVRE AÇIKLAMASI)

The circuit schematic of COA element is as shown in Figure 1 [12].

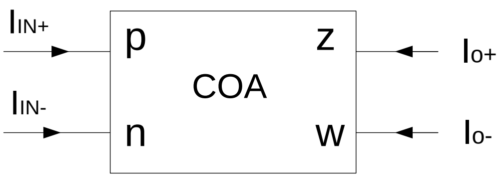


Figure 1. Circuit schematic of COA

COA's definition equation can be represented as

$$\begin{bmatrix} V_{IN+} \\ V_{IN-} \\ I_{O+} \\ I_{O-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ A & -A & 0 & 0 \\ -A & A & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{IN+} \\ I_{IN-} \\ V_{O+} \\ V_{O-} \end{bmatrix} \quad (1)$$

In Equation (1), A denotes the current gain in open-loop of COA and it approaches to infinity in ideal case. Thus, the COA employing circuits must be feedback configured that is counterpart to the op-amp. The COA's input impedance should be very low and output impedance should be very high, which are respectively equal to zero and infinite in ideal case. Through the high output impedance, COA employing circuits can be cascade connected without using additional buffers. Signal differentiation at input terminals reduce the noise and increase the dynamic range [17]. Furthermore, internally grounded inputs of COA enable MOS-C implementation of COA-based circuits [18]. In this work, the COA active element is implemented by connecting three CCIIs as given in [12]. This method provides the COA to exhibit lower input resistance and smaller input offset current [19]. Taking into consideration that both CCII+ and CCII- can be obtained from DOCCII (dual-output CCII), then the COA can be implemented by using only DOCCII elements. This technique also enables us to implement the COA using commercially available integrated circuits which can be used as current conveyor.

3. PROPOSED CIRCUIT TOPOLOGY (ÖNERİLEN DEVRE TOPOLOJİSİ)

3.1 Circuit Analysis (Devre Analizi)

The proposed circuit topology is represented in Figure 2.

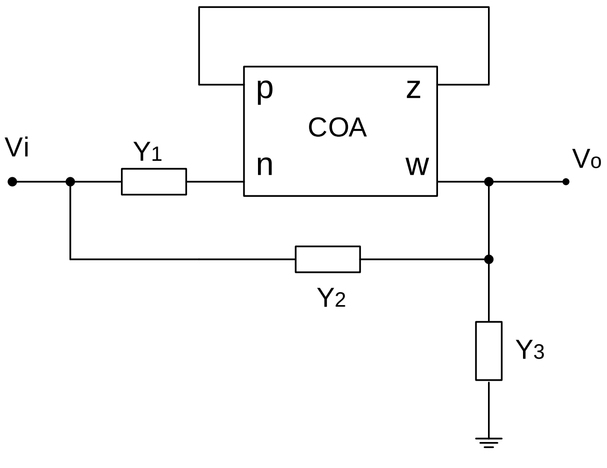


Figure 2. Proposed circuit topology

By using Equation (1) and performing circuit analysis, the transfer function can be calculated as

$$\frac{V_o}{V_i} = \frac{Y_2 - Y_1}{Y_2 + Y_3} \quad (2)$$

Taking the admittance combinations as $Y_1=G_1$, $Y_2=sC_2$ and $Y_3=G_3$, then the transfer function can be found as

$$\frac{Vo}{Vi} = \frac{sC_2 - G_1}{sC_2 + G_3} = \frac{s - \frac{1}{R_1 C_2}}{s + \frac{1}{R_3 C_2}} \quad (3)$$

The condition for the circuit to work as first-order all-pass filter, the resistors must be chosen as $R_1=R_3=R$. Taking $C_2=C$, then the transfer function become as

$$\frac{Vo}{Vi}=\frac{s-1/RC}{s+1/RC} \tag{4}$$

The radian frequency can be found as

$$\omega_0=\frac{1}{RC} \tag{5}$$

Phase equation of the all-pass filter can be written as

$$\varphi=\pi-2\tan^{-1}\omega_0 RC \tag{6}$$

Equation (6) shows that the filter provides a phase shift varying from 0 to -180^0. The radian frequency sensitivity over the passive component variations is calculated as

$$S_R^{\omega_0}=S_C^{\omega_0}=-1 \tag{7}$$

3.2 Non-Ideality Analysis (İdeal Olmayan Etkilerin Analizi)

The main non-ideal effects of COA element are considered as current tracking error between z and w terminals and non-zero voltage at p and n terminals. In non-ideal case the equation between z and w terminal currents can be represented by $I_z=\alpha I_w$ where α denotes the current tracking error and approaches to unity in ideal case. Input impedance of p and n terminals are considered as zero in ideal case. But in non-ideal case it can be considered that two parasitic impedances which are represented by Z_p and Z_n are connected between the ground and p and n terminals respectively. Taking into consideration these non-ideal effects of COA element, the transfer function of the circuit can be modified as follows.

$$\frac{V_0}{V_i}=\frac{Y_2-\frac{1}{\alpha}\left(\frac{Y_1Y_n}{Y_1+Y_n}\right)}{Y_2+Y_3} \tag{8}$$

It can be seen from Equation (8) that Z_p parasitic impedance has no effect to the transfer function. The effect of Z_n parasitic impedance can be reduced by an appropriate circuit realization of COA providing very low input impedance of n terminal. The current tracking error can be minimized by using the differential floating current source providing two balanced output currents at the output stage of COA. This issue is discussed in [13].

3.3 MOS-C Implementation of the Proposed Circuit (Önerilen Devrenin MOS-C Olarak Gerçeklenmesi)

To realize the MOS-C implementation of a circuit, the resistors must be replaced with their MOSFET conjugates which are operatated in triode region with non-linearity cancellation [20]. A linear resistor can be realized by using two depletion type MOS transistors connected as shown in Figure 3.

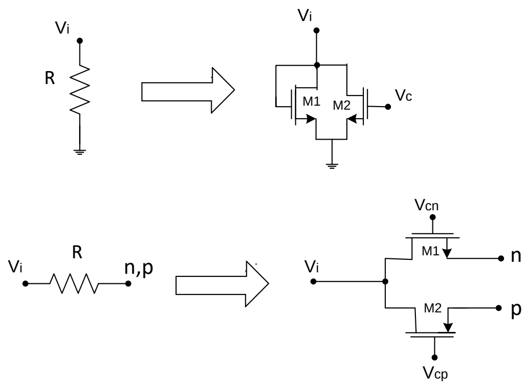


Figure 3. Linear resistor realization using MOSFETs

The resistance value can be expressed as

$$R=\frac{1}{\mu_n C_{ox}(W/L)(V_c-2V_T)} \tag{9}$$

for the grounded resistor, and

$$R=\frac{1}{\mu_n C_{ox}(W/L)(V_{cn}-V_{cp})} \tag{10}$$

for the resistor connected to the n or p terminal of the active element. Here, W and L are the channel width and length and V_T denotes the threshold voltage of the MOSFET. μ_n is the free electron mobility in the channel and C_{ox} denotes the gate oxide capacitance per unit area.

Figure 4 shows the resulting MOS-C implementation of the proposed filter obtained by replacing the MOSFET conjugates of the resistors in the circuit.

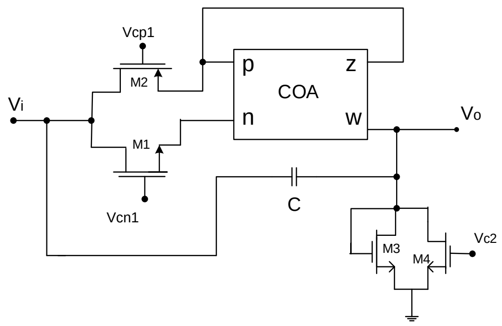
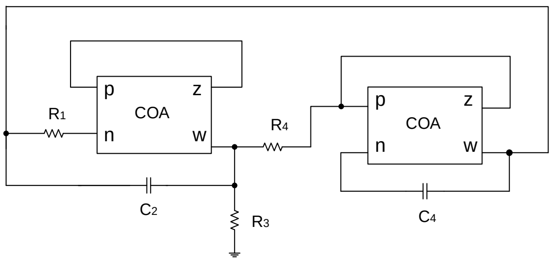


Figure 4. MOS-C implementation of the proposed filter

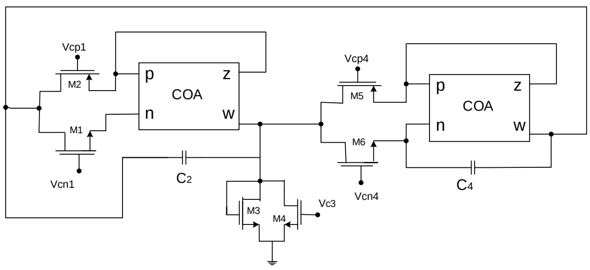
Through this implementation, the central frequency can be externally tuned by gate voltages of the MOS transistors.

4. OSCILLATOR APPLICATION (OSİLATÖR UYGULAMASI)

To demonstrate a utilization of the proposed filter, a sinusoidal oscillator is configured by cascade connection of all-pass filter and inverting integrator, forming closed loop with a gain equal to -1. The resulting circuit and its MOS-C implementation are given in Figure 5.



(a)



(b)

Figure 5. Sinusoidal oscillator application of the proposed filter: (a) Circuit schematic, (b) its MOS-C Implementation

Remembering that resistors has been chosen as R_1=R_3=R in the all-pass circuit, oscillator's characteristic equation can be calculated as

$$s^2C_2C_4R_4 + s\left(\frac{C_4R_4}{R} - \frac{C_2}{2}\right) + \frac{1}{2R} = 0 \qquad (11)$$

The oscillation condition can be found as

$$\frac{C_2}{C_4} = \frac{2R_4}{R} \qquad (12)$$

The radian frequency equation is

$$\omega_{osc} = \frac{1}{\sqrt{2RR_4C_2C_4}} \qquad (13)$$

The passive component sensitivites are all calculated as

$$S_R^{\omega_{osc}} = S_{R_4}^{\omega_{osc}} = S_{C_2}^{\omega_{osc}} = S_{C_4}^{\omega_{osc}} = -1/2 \qquad (14)$$

5. SIMULATION RESULTS (BENZETİM SONUÇLARI)

To evaluate the performance of the proposed filter and its application as oscillator, PSPICE simulation has been carried out by using the TSMC 0.18 µm CMOS model parameters. MOS implementation of DOCCII used in simulation is shown in Figure 6. The circuit is operated by supply voltage of ± 0.9 V.

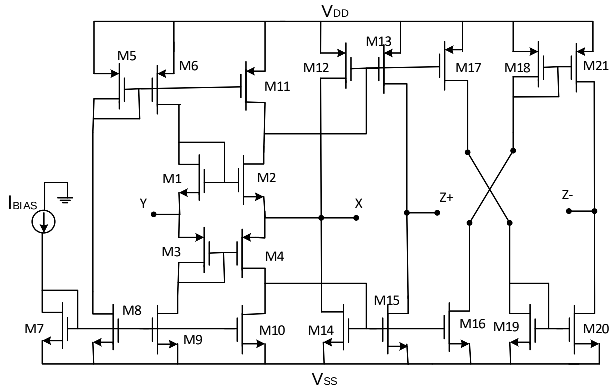


Figure 6. MOS Implementation of DOCCII [21]

Dimensions of MOSFETS used in DOCCII are given in Table 2. In simulation passive elements are taken as R=1 kΩ and C=100 pF. The dimensions of MOSFETs used to implement active resistors are taken as W=0.76 µm, L=0.18 µm for all M1, M2, M3 and M4. Gate voltages of MOSFETs are taken as $v_{cn1} = 0.9$ V and $v_{cp1} = v_{c2} = 0.45$ V to obtain required resistor values. Using these component values, the central frequency (f_c) is calculated as 1.59 MHz while the measured value in simulation is 1.52 MHz. THD (Total harmonic distortion) of the output is measured to be 0.33 % for a sinusoidal input signal of 100 mV amplitude. Phase error is measured to be 0.92 %. Phase-gain curves of the filter are given in Figure 7.

Table 2. MOSFET dimensions

Transistor	W(µm)	L(µm)
M1,M2	8.4	0.18
M3,M4	25.2	0.18
M5-M6, M11-M13, M17-18, M21	12.6	0.18
M7-M10, M14-M16, M19-M20	4.2	0.18

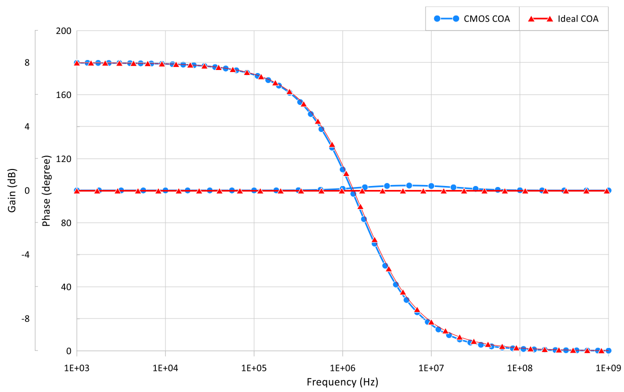


Figure 7. Phase-gain curves

Applying to the input a sinusoidal signal of amplitude 100 mV and frequency of 1.52 MHz, the filter gives time-domain response as shown in Figure 8.

Proposed filter's tunability is investigated by adjusting the MOSFET gate voltages in the range of 0.6 V- 0.9 V for v_{cn1} and 0.3 V - 0.45 V for $v_{cp1} = v_{c2}$. Frequency tunability graphic is shown in Figure 9.

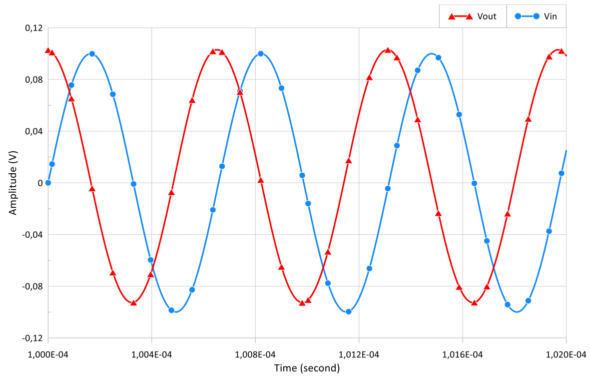


Figure 8. Time-domain response of the all-pass filter

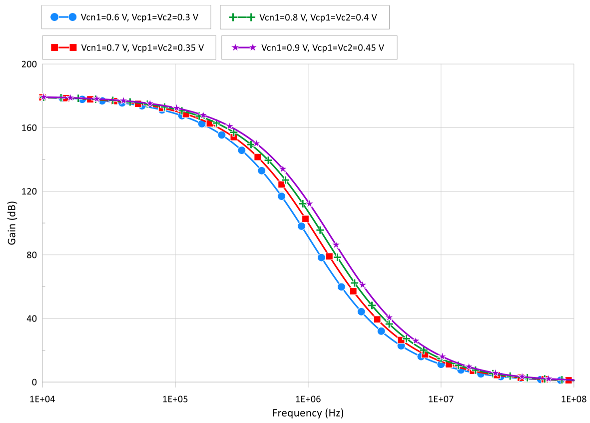


Figure 9. Frequency tuning of the all-pass filter

Another simulation has been carried out to evaluate the performance of the sinusoidal oscillator configured from the proposed filter circuit. Passive component values of the oscillator are taken as R=R_4=500 Ω, C_2=300 pF and C_4=150 pF. These values yield 1.06 MHz oscillation frequency while in simulation it is measured to be 1.02 MHz. THD values of the quadrature output signals are 3.4 % for V_1 (w-terminal voltage of first COA) and 1.8 % for V_2 (w-terminal voltage of second COA). Steady-state output waveform of the oscillator is shown in Figure 10.

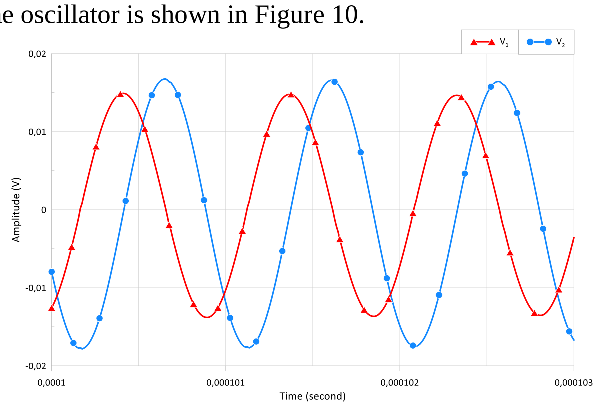


Figure 10. Steady-state output waveform of the quadrature oscillator

Frequency tunability of the oscillator is examined by adjusting the gate voltage of the NMOS transistors in the range of 0.6 V- 0.9 V and the results are illustrated in Figure 11.

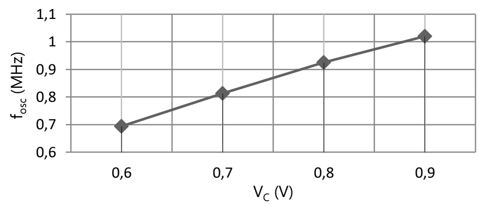


Figure 11. Frequency tuning of the quadrature oscillator

V_C denotes the gate voltages of NMOS transistors used to adjust R_1, R_3 and R_4.

6. CONCLUSIONS (SONUÇLAR)

A novel voltage-mode first-order MOS-C all-pass filter is introduced in this paper. The proposed filter topology consists of a single current operational amplifier, two resistors and a capacitor. Workability of the proposed circuit is validated by PSPICE simulation software. A tunable quadrature oscillator as an application example is also demonstrated. Remarkable features of the proposed circuit are voltage-controlled tuning, low distortion, low phase error, MOS-C implementation which is a desired feature for IC technique and suitability for low voltage applications.

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