



# First Order Lowpass and Highpass Filter Using Pole Model of Operational Amplifier

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A novel first order lowpass (LP) and Highpass (HP) filter using VDTA and operational amplifier is presented. It is a new kind of filter structure as it uses pole model of OA and VDTA. The OA pole model as a design parameter has been successfully utilized for realization of filters resulting high performance filters. The proposed circuit uses minimum number of components. The filter offers electronic tunability of the pole frequency which is highly required in IC technology. The sensitivities of the circuit are low. The workability of the proposed filter is verified using PSPICE simulation.

**Keywords:** Operational amplifier; Pole model; Voltage difference transconductance amplifier; First-order filter

## 1 Introduction

Active filters are those networks that use operational amplifiers (OA) or transistors in conjunction with RC networks to perform filtering function. The non-idealities of OA or transistor deteriorate the performance of the realized filters. The frequency-dependent gain of active device poses serious problems in the synthesis of the filters. It is observed that the gain of the device falls with increasing frequency and has a non-zero phase. These difficulties limit the application of filters in a low-frequency range besides causing sensitivity and stability problems. Compensation methods have been developed to eliminate or minimize their effects on the filter performance factors. Frequency-dependent gain of transistor and OA, instead of causing trouble, were exploited to implement active inductive and/or capacitive impedance. This behaviour of transistors was successfully employed to realize microwave filters. Transistor-based filters, suffer from the drawbacks such as temperature dependence of parasitic parameters, input and output impedance, interference of a. c. transfer functions, and d.c. bias circuitry. However, it was soon recognized that the method used for transistors can be used successfully for operational amplifiers. This led to the development of active-R filters. Using this approach large number of research papers on filters, oscillators, and inductors are reported in the technical literature<sup>1</sup>. The inception of operational transconductance

amplifier (OTA) which is voltage controlled current source (VCCS) along with other devices like current controlled current conveyor second generation (CCCII), has successfully replaced resistors in filters resulting in electronically tunable resistorless filters. These structures have revolutionized the analog field, especially filters. These filters employ active devices and capacitors only which offer the following advantages;

- i) Suitability in IC implementation,
- ii) Electronic tunability, which is highly desirable in integrated circuits.
- iii) Low sensitivity figures

In literature numerous active-C filters have been reported, as the above mentioned devices do not employ resistors. A new topology of filters which use only active devices such as OA, OTA *etc.* called active-only filters were introduced in the field of analog signaling processing. In this communication active-R filters and active-only filters are presented in Table 1, which are reported in the literature from the early eighties and onwards. The detail study of active-R filters up to late eighties are presented in the reference<sup>1</sup>.

The purpose of this communication is to introduce a new active-only filter that OA and recently introduced active device VDTA. VDTA is more versatile devices and offers several advantage over the other devices<sup>37</sup>. The filter implements first-order LP (lowpass) and HP (highpass) filtering function

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Table 1

Ref. No.	Year of Publication	Order filter	Number of Devices used		Number of Input output		Filtering function implemented	Independent tunability of filter parameters
			Active	Passive				
2	1980	2 <sup>nd</sup>	2OA	4R	1	1	BP	yes
3	1983	2 <sup>nd</sup> and VM	1	1C, 4R	1	1	LP	yes
4	1986	New Active-R filter using 2 <sup>nd</sup> -order blocks for realization of higher-order filters (nth-order) is presented in this paper						
5	1991	FDNR and FDNC techniques are used for realization of higher-order filter.						
6	1992	2 <sup>nd</sup> and CM	2	7R	1	1	HP	yes
7	1992	2 <sup>nd</sup> and CM	1	1C, 2R	1	2	HP and BP	yes
8	1993	2 <sup>nd</sup> and CM	2	5R	1	1	LP	yes
9	1993	2 <sup>nd</sup> and CM	1	2R, 1C	1	3	LP, BP and HP	
10	1993	2 <sup>nd</sup> and CM	1	3R, 1C	1	2	BP and LP	yes
11	1995	2 <sup>nd</sup> and CM	3	11R	1	3	LP, BP, HP, BS and AP	yes
12	1996	2 <sup>nd</sup> and CM	2	3MO-OTA	1	1	All filtering functions	yes
13	1997	2 <sup>nd</sup> and CM	2	5OTA	3	1	All filtering functions, by choosing inputs	yes
14	2000	2 <sup>nd</sup> and CM	2	3MO-OTA	1	1	All filtering functions	yes
15	2001	2 <sup>nd</sup> and VM	2	5OTA	5	3	All filtering functions, by choosing inputs	yes
16	2002	2 <sup>nd</sup> and CM and VM	The circuit implements higher order filter and second-order filter is presented as an example					
17	2002	1 <sup>st</sup> and CM	1	2OTA	1	1	AP	
18	2002	2 <sup>nd</sup> and CM	2OA	5OTA	1	4	All filtering function	No, tunability, except gain
19	2002	2 <sup>nd</sup> and MM VM and CM	2 OA	15 OTA	1VM 1CM	3VM 3CM	All filtering function	yes
20	2003	3 <sup>rd</sup> and VM	3OA	4R	1	3	LP, BP and HP	yes
21	2003	2 <sup>nd</sup> and CM	2OA	3 CCCII	1	3	All filtering functions	yes
22	2003	Inductance simulation using 1 OA and CCCII						
23	2003	2 <sup>nd</sup> and CM and VM	2OA	2 OTA for VM and 5 OTA for CM	1	3 for VM 4 for CM	LP, BP and HP for VM And LP BP HP and BS	No Gain of CM is independently tunable
24	2003	2 <sup>nd</sup> CM and VM	3 OA	8 OTAs	1	1	All filtering functions by satisfying conditions in terms of $g_m$ of OTA	yes
25	2003	2 <sup>nd</sup> and CM	2 OA	3 OTA	1	3	All filtering functions	yes
26	2004	2 <sup>nd</sup> and CM, VM	2 OA	4 OTA	4	1	All filtering functions	yes
27	2005	2 <sup>nd</sup> and TIM	2 OA	4 OTA	1	3	LP, BP and HP	yes
28	2005	2 <sup>nd</sup> and TAM	1 OA	2R, 1C	1	2	LP and BP	yes
29	2006	2 <sup>nd</sup> and VM	2 OA	4 OTA	2	3	LP, BP and HP	yes
30	2006	2 <sup>nd</sup> and CM	2 OA	2 MO-OTA	3	4	LP, BP HP and HP	no
31	2007	2 <sup>nd</sup> and VM	1 OA	2R, 1C	3	1	All filtering functions	yes
32	2008	2 <sup>nd</sup> and CM	2 OA	3OTA, 3R	3	1	All filtering functions	no
33	2011	2 <sup>nd</sup> and VM	OA	6 MO-OTA	1	5	All filtering functions	yes
34	2015	1 <sup>st</sup> and CM	1 OA	2 OTA	1	1	AP	yes
35	2017	1 <sup>st</sup> and CM	1 OA	2 MO-OTA	1	1	LP	yes
36	2021	2 <sup>nd</sup> and 8 <sup>th</sup>	2 and 8	6 R and 24R	1	1	BP	yes

FDNR stands for frequency dependent negative resistance

FDNC stands for frequency dependent negative conductance

CM stands for Current-mode

VM stands for Voltage-mode

TIM stands for Transimpedance mode

TAM stands for Transadmittance-mode

MO-OTA stands for multiple output operational transconductance amplifier

OA stands for Operational amplifier

LP lowpass, BP bandpass HP highpass BS bandstop and AP allpass

simultaneously. The pole frequency is electronically tunable through bias current of transconductance gain of VDTA. The circuit is highly suitable for integrated circuit (IC) implementation.

**2 Circuit Description**

Voltage Operational Amplifier or simply operational amplifier (OA) is a voltage controlled voltage source (VCVS) and is described by the port relation:

$$V_o(s) = A(s)[V^+(s) - V^-(s)] \quad \dots (1)$$

$V^+$  and  $V^-$  are non-inverting and inverting terminals.  $A(s)$  is the open-loop gain of OA and is of our concern.  $A(s)$  being a function of frequency that is by increasing frequency, the gain decreases. The open-loop gain of OA which is frequency-dependent is assumed to be of the form,

$$A(s) = \frac{B_i \sum_{j=1}^m \omega_i}{s \prod_{j=1}^m (s + \omega_j)} \approx \frac{B}{s} \left(1 - \prod_{j=1}^m \tau_j s\right) \quad \dots (2)$$

For first-order approximation the above equation reduces to,

$$A(s) = \frac{A_0}{1 + s\tau_1} = \frac{A_0\omega_0}{s + \omega_0} \approx \frac{B}{s} \text{ for } s \gg \omega_0 \quad \dots (3)$$

where  $A_0$  is the open loop dc gain,  $\omega_0$  is the 3db-frequency of the OA and is given by  $\omega_0 = \frac{1}{\tau_1}$  and  $B$  is the gain bandwidth product. It follows from Eq. (2) that the OA acts as an ideal integrator neglecting the effects of 3-db frequency.

VDTA has two input voltage ( $V_p, V_n$ ) which is transferred to the current at the terminal  $Z$  by the first transconductance gain, and the voltage drop at the terminal  $Z$  is transferred to the current at the terminals  $X^+$  and  $X^-$  by second transconductance gain. The circuit symbol of VDTA is shown in Fig. 1. The port relation of VDTA is given by

$$\begin{bmatrix} I_Z \\ I_{X^+} \\ I_{X^-} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ 0 & 0 & g_{m2} \\ 0 & 0 & -g_{m2} \end{bmatrix} \begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} \quad \dots (4)$$

$$\text{where } g_{mi} = \sqrt{I_{Bi} \mu_n C_{ox} \left(\frac{W}{L}\right)_i} \quad i = 1 \quad \dots (5)$$

Both transconductance gains ( $g_m$ ) are electronically controllable by external bias currents  $I_B$ .

Active-only proposed filter using OA and VDTA is shown in Fig. 2. The routine analysis of the circuit using pole model of OA given by equation (3) and port relation of VDTA given by equation (4) gives the following transfer function.

$$\frac{V_{LP}}{V_{in}} = \frac{B g_1 / g_2}{s + B g_1 / g_2} \quad \dots (6)$$

$$\frac{V_{HP}}{V_{in}} = \frac{s g_1 / g_2}{s + B g_1 / g_2} \quad \dots (7)$$

The natural angular frequency  $\omega_0$  is given by

$$\omega_0 = B g_1 / g_2$$

$$H_{HP} = g_1 / g_2$$

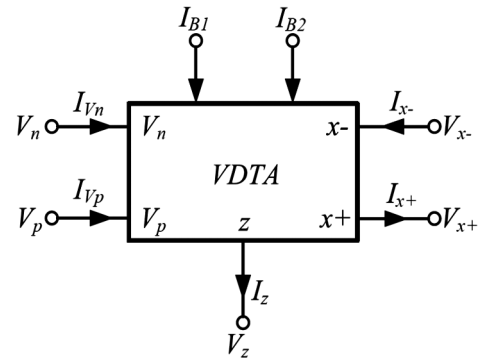


Fig. 1 — Circuit symbol of VDTA.

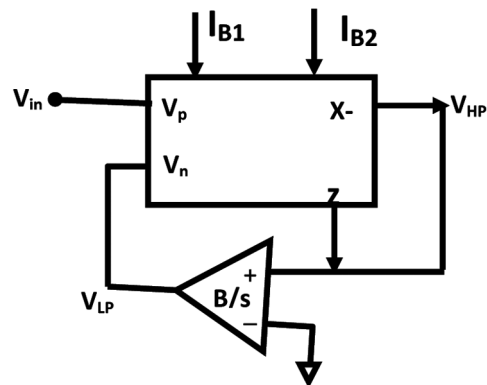


Fig. 2 — Proposed LP and HP filter.

It is clear that the frequency is electronically tunable through bias current of transconductance gains  $g_m$  of VDTA.

**3 Non-idealities of OA**

If the open-loop gain of OA is assumed to be

$$A(s) = \frac{B}{s} [1 - s(\tau_2 + \tau_3)] \text{ where } \tau_2 = \frac{1}{\omega_2} \text{ and } \tau_3 = \frac{1}{\omega_3}$$

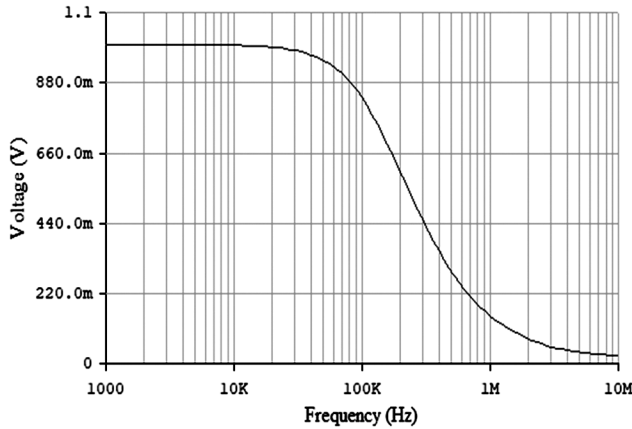


Fig. 3 — Frequency response for LP filter.

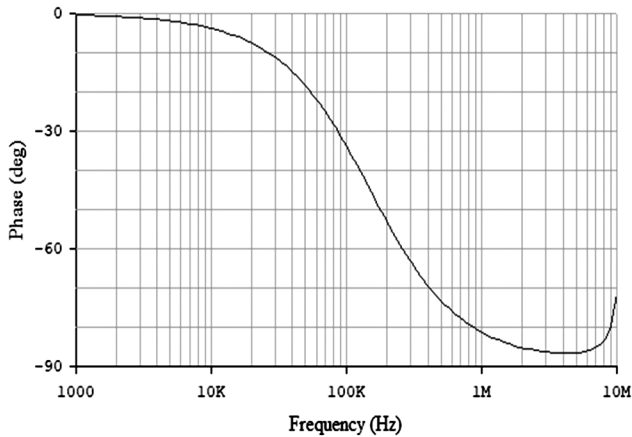


Fig. 4 — Phase response for LP filter.

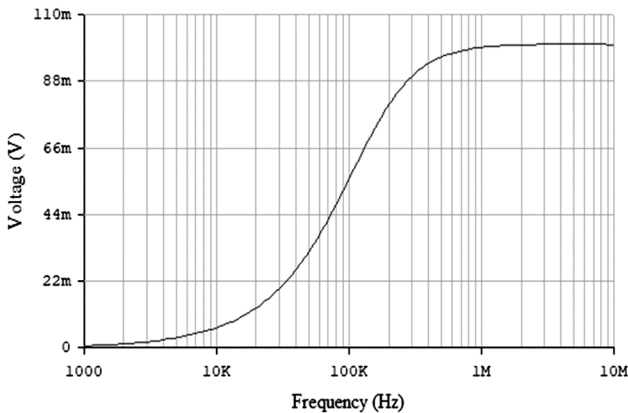


Fig. 5 — Frequency response for HP filter.

are second and third pole in the frequency range of interest, then the transfer function is given by:

$$\frac{V_{LP}}{V_{in}} = \frac{B \frac{g_1}{g_2} - \left(\frac{B \frac{g_1}{g_2}\right) s(\tau_1 + \tau_2)}{s[1 + \left(\frac{B \frac{g_1}{g_2}\right)(\tau_1 + \tau_2)] + B \frac{g_1}{g_2}}$$

It is seen that undesirable terms appear in transfer function due to higher poles of OA. However, these effects can be minimized by satisfying the condition  $g_2 \gg g_1$ .

**4 Simulations**

In order to verify the proposed circuit, simulation were carried out by using PSPICE. VDTA was obtained by cascading two LT 1228 OTAs ( $g_{mi} = 10I_i, i = 1,2$ )<sup>38</sup> and OA LM 741 with gain bandwidth product  $B = 1.5$  MHz. The circuit was constructed for a pole frequency of 150 KHZ. The value of transconductance  $g_{m1} = 1mS$  and  $g_{m2} = 10ms$ . The magnitude and phase responses of the proposed circuit is shown in Figs. 3 & 4 for LP filter and in Figs. 5 & 6 for 6 HP filter. Figs. 7 & 8 shows the transit response for LP and HP filter respectively.

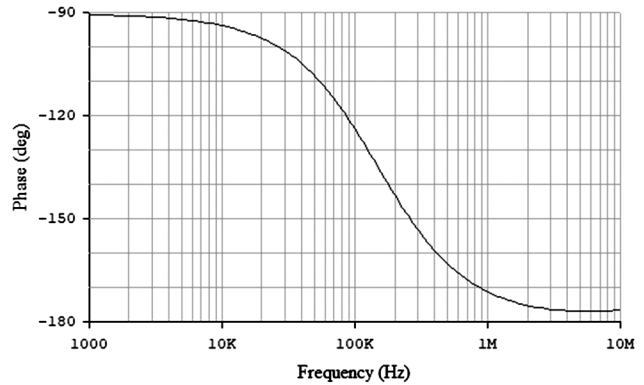


Fig. 6 — Phase response for HP filter.

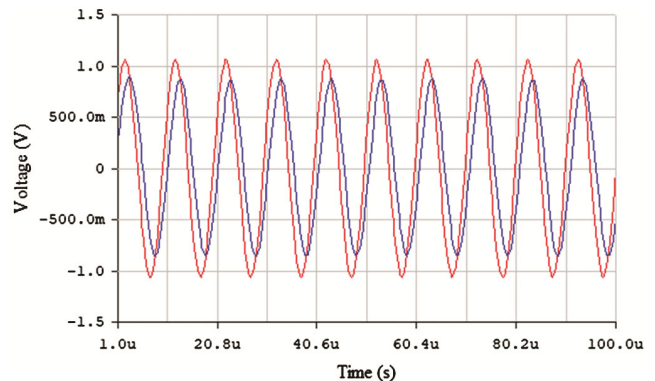


Fig. 7 — Transit response of LP filter (Red trace is input and Blue trace is output).

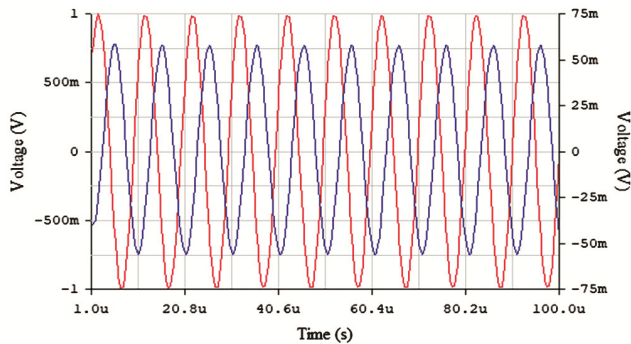


Fig. 8 — Transit response of HP filter (Red trace is input and Blue trace is output).

The input of 1V and 100 KHz sinusoidal signal was used to study the larger signal behavior of the proposed filter and the simulated response is shown in Figs. 7 & 8. The applied signal is in the pass band in LP case and stop band in HP filter.

## 5 Conclusion

In this paper active-only filters using OA and VDTA is presented. The circuit uses only two active devices and implements LP which is having low impedance and HP filtering function simultaneously. The circuit has an advantage of electronic tunability of the pole frequency which is highly desirable in IC technology. PSPICE simulation is used to check the proposed filter and the results are confirming workability of the proposed filter.

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