Design and Analysis of Novel Tunable Low Pass Filter with higher cut off Frequency for Application in PLL Frequency Synthesizers

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Abstract*: This work proposes the design and simulation of a novel Chebyshev low pass filter. This proposed design incorporate the use of floating inductor, resistor and also the grounded resistor with the help of CMOS based operational transconductance amplifier (OTAs). The value of proposed floating inductor can be modified by adjusting the bias current input. The filters are synthesized from 3rd to 5th order low pass LC prototype and designed using ladder structure. All the simulations are done on Verilog AMS. The results of simulation show that the novel structure design exhibit better cut off frequency, tuning range, less ripples as compared with the conventional design. The overall performance of the filter is improved by using floating inductor.

***Index Terms*: cut off frequency, floating inductor & resistor, OTA, transconductance**

I. INTRODUCTION

In CMOS circuit technology, Chebyshev filter is famous for voice synthesizer for video applications. In integrated wireless receivers, active filter is a major source of the current consumption of the whole circuit and therefore, a filter must be carefully designed so that it can reduce both cost and power consumption. The filters with on chip capacitors and resistors usually deviate from their original value and will result in a deviation of frequency [1]. The size of the filter must be small on chip as per the requirement. The OTA is capable to be designed as a tuned inductor whose value can be controlled using the transconductance [2]-[3] of the OTA and the g_m will have a variation using bias control voltage.

In microelectronics circuits the active inductors are used in a variety of applications because they offer various advantages as compared with their passive counterparts. Keeping in view the video application of the Chebyshev filter [4]-[5] a filter is designed by replacing all its passive elements by an active device. The OTA is the best option to design active elements.

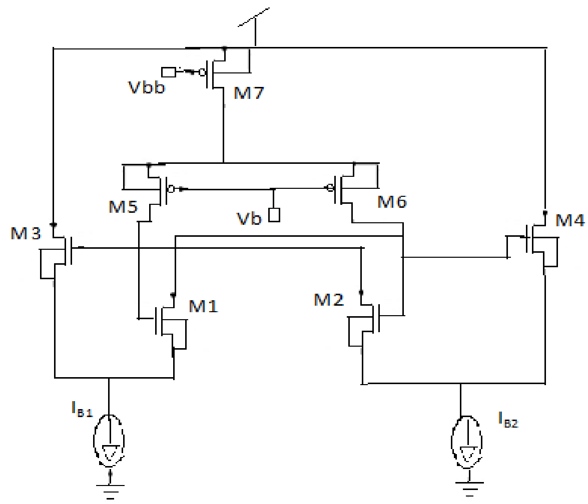
As per the research done in last few years [6]-[7] resistors are used to change the voltage into current for designing the floating elements [8]-[9]. Thus designing of OTA is a cost effective and attractive method to design floating inductor [10]-[11]. This paper shows the technique to design a floating inductor and further a Chebyshev filter is designed.

This paper is divided into four sections. In Section 2, the floating inductor is proposed. Section 3 presents the 3rd order and 5th order Chebyshev low pass filter. Section 4 deals with the simulation results and the conclusion is reported in Section 5.

II. PROPOSED INDUCTOR

For synthesis of a filter inductor plays an important role because it can make filter very bulky and expensive, thus choosing a filter is very cautious task. OTA is the obvious choice for designing an inductor. OTA is voltage controlled current source and its major advantage is its transconductance can be adjusted by bias current [12]-[13]. The design of conventional inductor using 3 OTA [14] is shown in Fig. 1(b). The proposed design of inductor is demonstrated below in the Fig.1 (a). In the proposed design the voltage V_1 is taken as input voltage of the first OTA (OTA_1).

In case of CMOS technology the use of proposed floating inductor will be more beneficial as compared with the conventional one. In the proposed design all the OTAs are taken to be identical.



(a)

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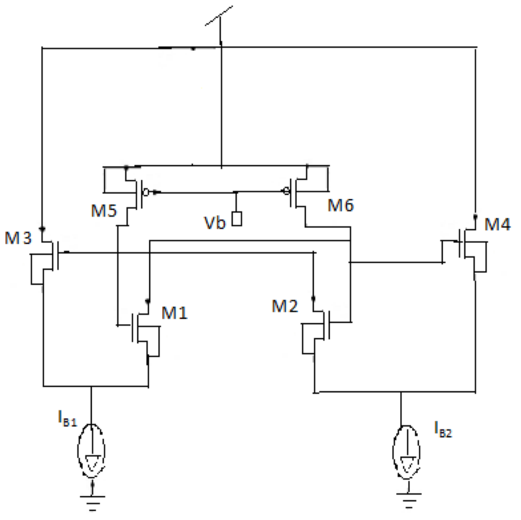

(b)

Fig 1(a) Proposed active inductor (b) Conventional Active Inductor

The proposed inductor is having 7 CMOS out of which 4 NMOS and 3 PMOS are there. CMOS M1 and M2 forms the cross coupled pair. CMOS M3 and M4 are in common drain configuration. At the Q point M1 to M4 are satisfied. Fig 2(a) shows the small signal model of the proposed inductor and the fig 2(b) represents the corresponding equivalent circuit.

The input impedance at the differential port, for given input voltage and input current, is given by:-

$$Z_{in} = \frac{V_{in}}{I_{in}} \qquad (1)$$

$$= \frac{[j\omega(C_{gs1} + C_{gs3}) - g_{m1} + g'_{ds5}]}{g'_{ds5}[g_{m1} + g_{m3} + j\omega(C_{gs1} + C_{gs3})]}$$

The value of equivalent inductance L_{eq} is given by approximation-

$$L_{eq} = \frac{(C_{gs1} + C_{gs3})}{g'_{ds5}(2g_{m1} + g_{m3} - g'_{ds5})} \qquad (2)$$

The value of g'ds5 is expressed as:-

$$g'_{ds5} = \frac{(g_{ds7} + g_{ds6}M_1)g_{ds5}}{g_{ds7} + g_{ds6}M_1 + g_{ds5}} \qquad (3)$$

The value of gds6M1 and gds6M2 is as below:-

$$g_{ds6}M_2 = g_{ds6}\frac{K}{1-K} \qquad (4)$$

$$g_{ds6}M_1 = \frac{g_{ds6}}{1-k} \qquad (5)$$

Where gds_1,gds_2,gds_3,gds_4,gds_5,gds_6 represent the transconductance of the CMOS M_1,M_2,M_3,M_4,M_5,M_6 respectively.

From equation 2 we can observe that the value of L depends upon the transconductance and capacitance. Thus by changing the value of drain conductance the tuning of the filter can be changed.

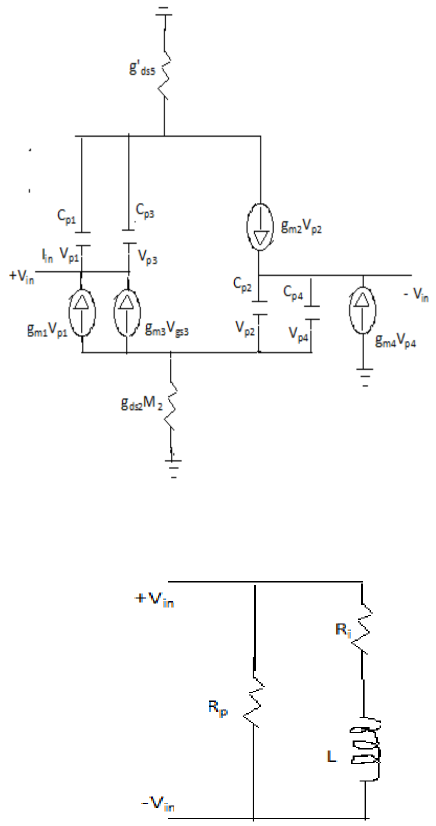

Fig.2 Proposed active inductor (a) Small signal model (b) Equivalent circuit

III. FILTER

Active filters comes under the category of analog filters and are the essential part of a phase locked loop. Active filters requires an additional power source unlike passive filters. OTA is the obvious choice for this because of its superior qualities like high Q factor, selective output response, wider bandwidth etc. [15].

Active filters are easier to design with good performance characteristics and good accuracy.

As we increase the order of the filter its complexity to design is increased. Various issues comes in picture as size of the circuit, number of MOS transistors, power consumption. So the designing of the filter depends upon the type of application [16]. In this paper a 3rd order and 5th order filter based on OTA structure is proposed.

A. *3rd Order Filter*

Active filter implementations requires the desired filter with active circuitry i.e. amplifiers. Replacing all passive elements by their active counterparts' results in design of active Filter. For describing the electronically tunable feature of the inductor we are designing a 3rd order filter with active inductor which is shown in fig 3. The structure includes 6 OTA structures to complete the filter. C1 and C2 are external parasitic capacitances.

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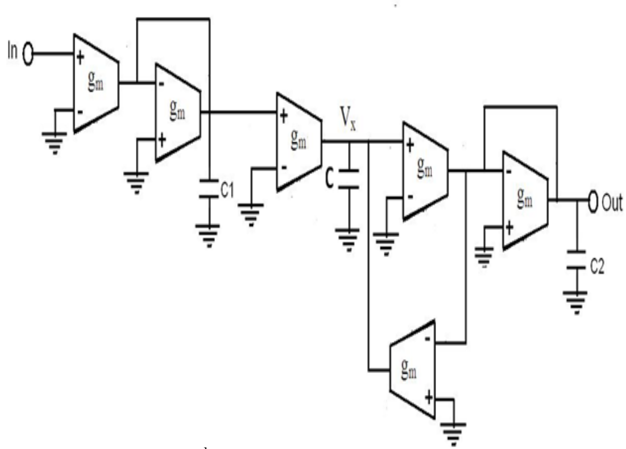

Fig 3. 3rd order Chebyshev filter with OTA

B. *5th Order Filter*

For describing the flexibility feature of the inductor we are designing a 5th order filter with active inductor shown in Fig 3 which includes 9 OTA structure to complete the filter. External parasitic capacitances are also connected in circuit.

The output frequency response of the third order and the fifth order filter is plotted in fig 4. The response curve of 5th order filter shows a 3dB frequency of 149.12 MHz .

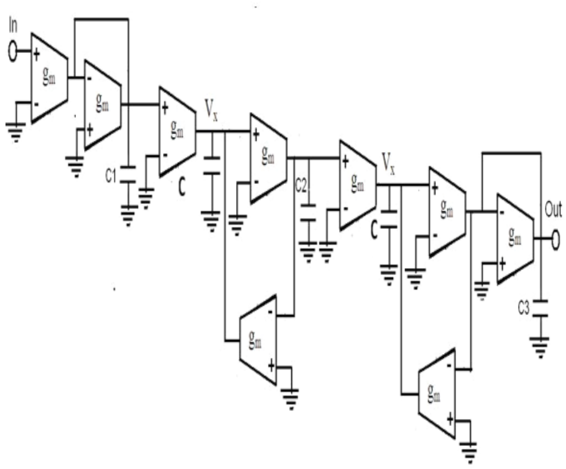

Fig 3. 5th order Chebyshev filter with OTA

Order of the filter n:

$$n = \frac{\cosh^{-1}\left(\epsilon^{-1}\sqrt{10^{\frac{atten}{10}}-1}\right)}{\cosh^{-1}\frac{f_s}{f_p}} \quad (6)$$

Where ϵ parameter related to pass band ripple is given:

$$\epsilon = \sqrt{10^{\frac{ripple}{10}}} - 1 \quad (7)$$

Where ripple: Maximum pass band ripple
f_s: stop band corner frequency
f_p: pass band corner frequency
Atten: stop band attenuation

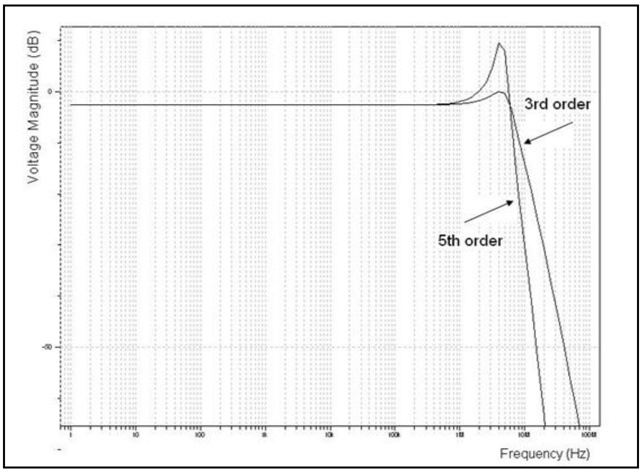

Fig 4. Frequency response of 3rd and 5th order filter

The proposed 3rd order filter is having the maximum pass band ripple of 2.2 dB. , stop band attenuation of 73 dB, stop band corner frequency of 83 MHz and pass band corner frequency of 7.1 MHz .
The proposed 5th order filter is having the stop band attenuation of 150 dB, stop band corner frequency of 91.8 MHz and pass band corner frequency of 4.6 MHz .

IV. SIMULATION RESULTS

In case of CMOS technology the use of proposed floating inductor will be more beneficial as compared with the conventional one. In the proposed design all the OTAs are taken to be identical.
Table 1 is showing the values for the variation of 3dB frequency with the variation in transconductance and the bias current. Table 2 shows the value of inductor required for particular 3dB frequency for 3rd order filter. All results are simulated with the help of Verilog AMS.

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Table1. (Variation of 3dB frequency with trans conductance and bias current for 3rd order filter)

I_B (µA)	g_m (µA/V)	3dB Frequency (MHz)		
		Passive network	Proposed Active Network	Conventional Network
2	15.3	3.16	2.43	2.82
6	26.43	5.77	4.23	4.35
10	34.20	7.42	7.12	6.1
15	42.77	8.76	8.23	7.65
25	54.23	11.77	10.48	9
35	64.98	13.33	12.45	10.04
40	69.28	14.56	13.65	11.22
45	73.45	15.03	14.34	11.55

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Fig. 5and Fig.6 is showing a plot of 3 dB frequency with bias voltage and plot of variation in g_m with bias voltage respectively for 3rd order filter.

Table 2. (Value of L required for particular 3dB frequency for 3rd order filter)

I_B (μA)	g_m (μA/V)	L(mH)	3dB frequency of passive network(MHz)
2	15.3	4.2	3.16
6	26.43	1.7	5.77
10	34.20	0.84	7.42
15	42.77	0.53	8.76
25	54.23	0.30	11.77
35	64.98	0.24	13.33
40	69.28	0.21	14.56
45	73.45	0.19	15.03

Fig. 7and Fig.8 is showing a plot of 3 dB frequency with bias voltage and plot of variation in g_m with bias voltage respectively for 5th order filter.

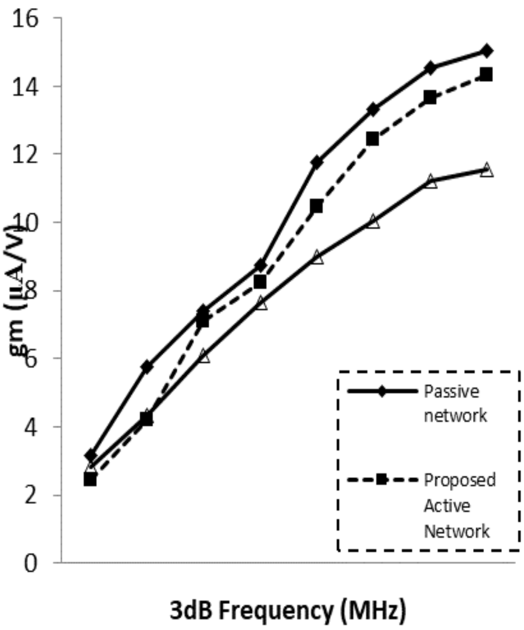

Fig 5. Variation of 3dB frequency with g_m of 3rd order filter

The filter with the proposed inductor will show the better results that the conventional one. If we increase the order of the filter then size of the filter increases and the cut off frequency decreases.

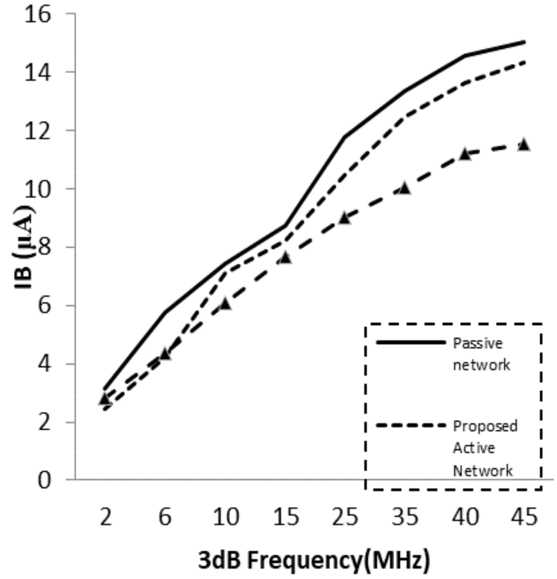

Fig 6. Variation of 3 dB frequency with Bias current of 3rd order filter

Table 3 is showing the values for the variation of 3dB frequency with the variation in transconductance and the bias current. Table 4 shows the value of inductor required for particular 3dB frequency for 5th order filter.

Table3. (Variation of 3dB frequency with trans conductance and bias current for 5th order filter)

I_B (μA)	g_m (μA/V)	3dB Frequency (MHz)		
		Passive network	Proposed Active Network	Conventional Network
4	21.3	3.16	2.43	2.82
8	30.43	4.77	3.23	3.35
12	37.20	6.42	5.12	4.1
18	46.77	8.76	6.23	4.65
30	60.23	10.77	8.48	5
35	64.98	11.33	9.45	5.04
40	69.28	13.56	10.65	6.22
45	73.45	13.03	10.34	6.55

From the graphs of Fig.5 and Fig 7 it is observed that there is a linear relation between g_m and 3 dB frequencies. As g_m is varied over a wide range for the estimation of value of g_m required for particular 3dB frequency.

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The graphs of Fig 6 and Fig 8 shows a relation between bias current I_B and 3dB frequency. Bias current is varied over wide range to get a particular value of I_B at a particular 3 dB frequency.

Table 4. (Value of L required for particular 3dB frequency for 5th order filter)

I_B (µA)	g_m (µA/V)	L(mH)	3dB frequency of passive network(MHz)
4	21.3	2.1	3.16
8	30.43	1.0	4.77
12	37.20	0.7	6.42
18	46.77	0.53	8.76
30	60.23	0.27	10.77
35	64.98	0.24	11.33
40	69.28	0.21	13.56
45	73.45	0.19	13.03

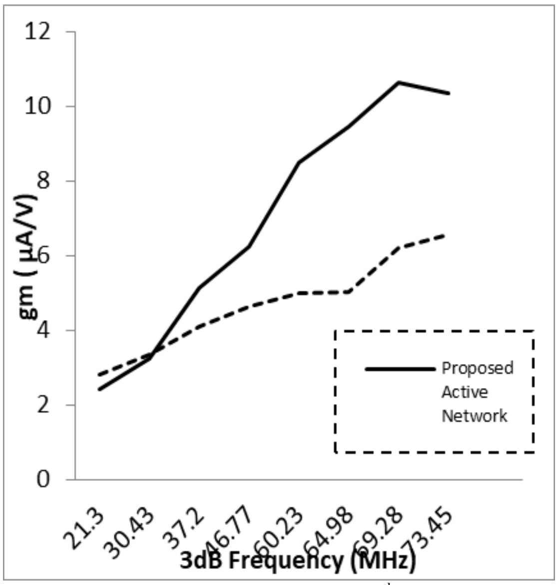

Fig 7. Variation of 3dB frequency with g_m of 5th order filter

The variation of the cut off frequency with the bias voltage is shown in fig 9 and fig 10 for third and fifth order filter respectively.

From the plots it is observed that the cut off frequency of the proposed filter is showing the same variation in the filter by passive elements but it is much more and better than the conventional inductor circuit.

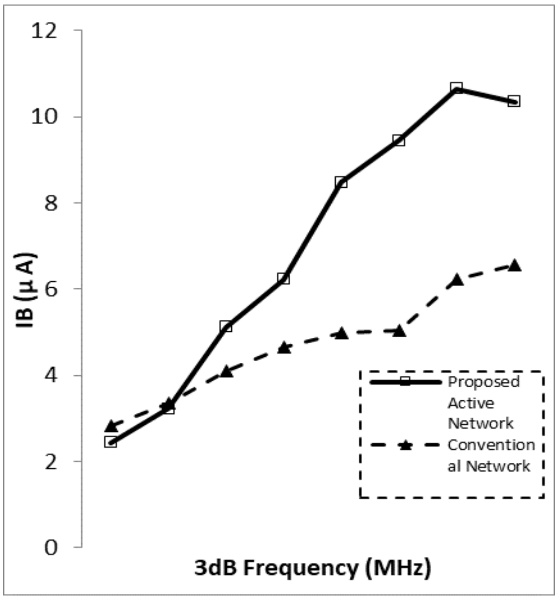

Fig 8. Variation of 3 dB frequency with Bias current of 5th order filter

As the number of components increases with the increment in the order of the filter power consumption and power delay increases as per the order of filter.

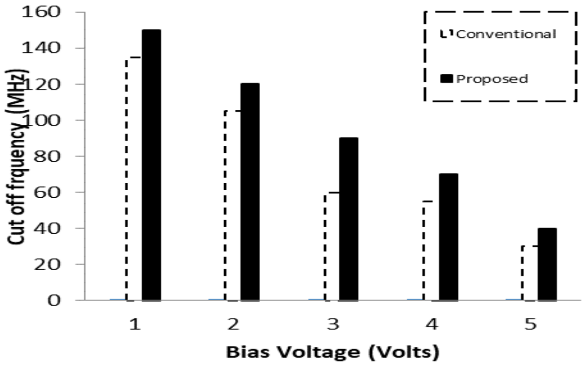

Fig 9. Variation of cutoff frequency with bias voltage for 3rd order filter

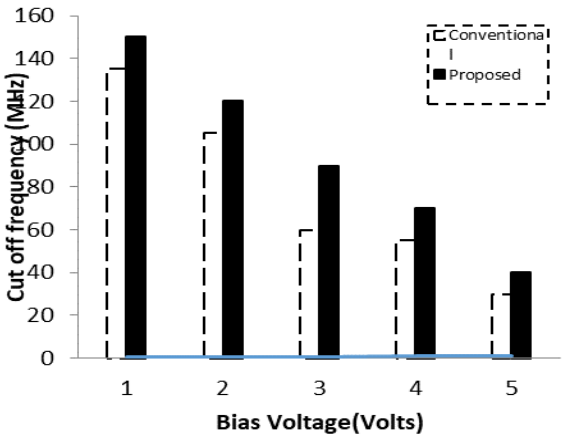

Fig 10. Variation of cutoff frequency with bias voltage for 5th order filter

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V. CONCLUSION

In the paper 3^{rd} order and 5^{th} order Chebyshev low pass filter is designed using the proposed OTA structure. Basic elements floating inductor and resistors are designed using the OTAs. The simulated inductance is totally dependent on the bias current of the each OTA. The 3^{rd} order designed Chebyshev filter has the pass band frequency of 7.2 MHz and a DC gain of 2.2 dB. So this designed filter is suitable for video frequency and has its wide application in video processing applications like HDTV. The 5^{th} order designed filter has its pass band frequency of 4.7 MHz and a DC gain of 2.2 dB. The results of simulation show that the proposed design exhibit better cut off frequency as compared with the conventional design.

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