High Frequency VCO-derived filters

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Abstract- A new method of designing continuous-time monolithic filters derived from well known voltage controlled oscillators (VCOs) is introduced. These VCO-derived filters are capable of operating at very high frequencies in standard CMOS processes. Prototype low-pass and band-pass filter designed in a TSMC 0.25 µm process are discussed. Simulation results for the low-pass filter designed for a cutoff frequency of 6 GHz show a THD of –40 dB for 400 mV input peak-peak sinusoidal input. The band-pass filter has a resonant frequency programmable from 4 GHz to 5.18 GHz, a programmable Q from 4 to 89 and mid-band THD of –40 dB for a 200 mV peak-peak sinusoidal input signal.

I. INTRODUCTION

Integrated analog filters can be classified into two categories: continuous-time filters and discrete–time filters. Continuous-time filters are capable of operating at higher frequency than the discrete-time filter but this is often at the expense of deterioration in linearity and noise performance. There are, however, many applications in the areas of communications and video circuits in which the distortion and noise performance requirements are relaxed. [1]-[3].

In the continuous-time filter domain, g_m-C filters offer a speed advantage over active R-C and MOSFET-C filters[4],[5]. The speed of the g_m-C filtesr is limited by the size and frequency response of the transconductance elements and the capacitance. If the capacitance can be reduced, the filters can operate at higher frequencies.

It is well known that CMOS voltage controlled oscillators are capable of operating at very high frequencies. For example, using the TSMC 0.25µm CMOS process, it is possible to achieve CMOS VCOs with oscillation frequencies of 4 GHz or higher.

Reported continuous-time CMOS monolithic filters are invariably limited to operating frequency that are much lower than the reported oscillation frequencies of VCOs designed in the same process. By introducing additional loss in the delay stage of a VCO to move the poles into the left half-plane and appropriately introducing signal inputs into the resultant structure, monolithic filters that have operation frequencies comparable to the oscillation frequency of the VCO can be derived.

In Section II, the VCO-derived filter structure is developed. In Section III, it shows the design of the components which are used in the VCO-derived filters. The simulation results are shown in Section IV.

II. VCO-DERIVED FILTER DESIGN

A ring voltage controlled oscillator is generally realized by cascading an odd number of open-loop inverting amplifiers (often termed delay stages when used in VCOs) in a feedback loop or a "ring". An even number of delay stages can also be used provided that an odd number of amplifiers in the ring are noninverting. The amplifiers have signal propagation delay approximately half of the period of the oscillation frequency. These delay stages are often simply integrators which invariably have some loss either introduced intentionally or attributable to the non-zero output conductance of the MOS transistors. In some VCO's, feedback or control mechanisms are used to control this loss which affects both the waveshape and frequency of the VCO output signal. The small-signal pole locations of the VCO are dependent on the amount of loss in the delay stages with a requirement that at least one complex-conjugate pole-pair be in the right half-plane to sustain oscillation of the VCO. If too much loss is added in the delay stages, oscillation will cease and the VCO will behave as a filter if signal inputs are added appropriately.

The delay stages (integrators) generally have dominantly a first-order small signal transfer function with a pole in the left half-plane. In the filter terminology, the delay stages are generally termed lossy integrators. In this paper, we will use the word "integrator" and "lossy intergrator" in both VCO and filter cases. The lossy integrator behaves like a first-order low-pass filter with the transfer function given by

$$\frac{V_o}{V_i} = \frac{I_o}{s+p} \tag{1}$$

where I_o is unity gain frequency, and pole p is the loss term.

It can be shown that an n-stage VCO constructed with identical lossy integrators has poles on a circular constellation located at

$$s = (-1)^{1/n} I_0 - p \tag{2}$$

The location of the pole constellation of the system can be controlled by modifying the amount of integrator loss. Increasing the loss pushes the pole constellation leftward in the s-plane while reducing the loss will move the constellation rightward. Thus by appropriately controlling the loss, the poles can be placed in the LHP ensuring a stable system. Fig. 1 illustrates a 3-stage VCO's pole constellation with and without additional loss.

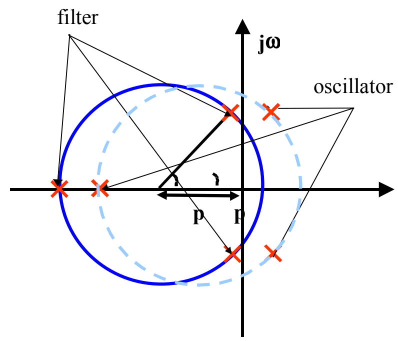

Fig. 1. The poles location of the 3-stage oscillator (without additional loss) and filter (with additional loss)

Based on this concept, a VCO-derived low-pass filter can be designed by moving the pole constellation by the proper amount to the left and adding an external input to one of the lossy integrators. Fig. 2 shows the block diagram of the 3-stage VCO-derived low-pass filter. Where Vc is the control voltage, V_{i+} , V_{i-} are the inputs and V_{o+}, Vo- are the outputs.

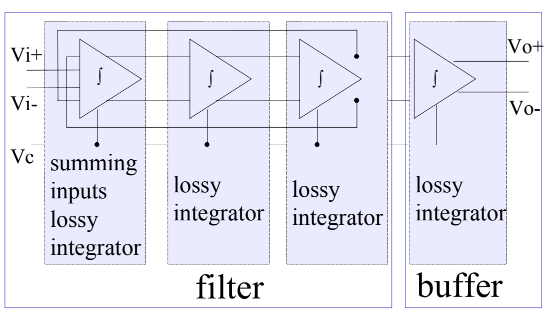

Fig. 2. The diagram of the 3-stage VCO-derived low-pass filter

The transfer function of this low pass filter is

$$\frac{X_o}{X_i} = -\frac{I_0^3}{(s+p)^3 + I_0^3} \tag{3}$$

This can be expressed as

$$\frac{X_o}{X_i} = -\frac{I_0^3}{\left(s^2 + \frac{\omega_0}{Q} s + \omega_0^2\right)(s + p_3)} \tag{4}$$

For high Q poles, the transfer function can be approximated by the second-order function

$$\frac{X_o}{X_i} \cong -\frac{I_0^2}{\left(s^2 + \frac{\omega_0}{Q} s + \omega_0^2\right)} \tag{5}$$

A band-pass filter can be created by adding a zero near the origin. One way to achieve this is by making the last integrator stage lossless and obtaining the filter's output from the second to last stage. The block diagram of a 3-stage band-pass filter is shown in Fig. 3.

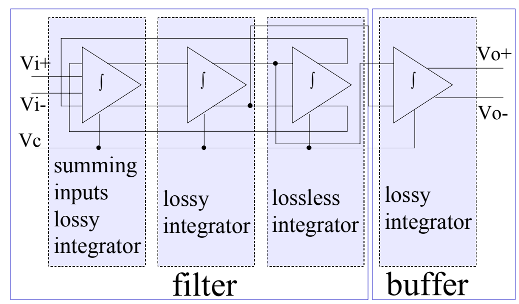

Fig. 3. The diagram of a 3-stage VCO-derived band-pass filter

The band-pass filter transfer function can be approximated by the second-order function

$$\frac{X_o}{X_i} \cong -\frac{I_0^2 s}{\left(s^2 + \frac{\omega_0}{Q} s + \omega_0^2\right)} \tag{6}$$

III. Components Design

To implement a low-pass VCO-derived filter, a lossy integrator with and without summing inputs is required. The band-pass filter implementation also requires a lossless integrator. To achieve low noise and distortion, the fully differential structures are used. These integrators will be discussed next.

A. *Lossless integrator*

A lossless or low lossy integrator is required to implement the band-pass filter in order to provide a zero at the origin. A widely usage VCO delay stage that is actually a low loss integrator is shown in Fig. 4.

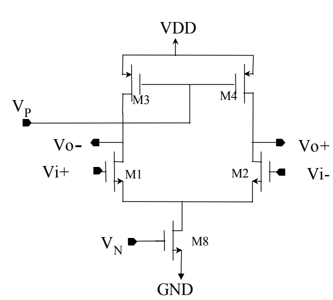

Fig.4. The schematic of low loss integrator

B. Lossy integrator

The widely used VCO delay stage that behaves as a lossy integrator is shown in Fig. 5. Compared to the low loss integrator, a pair of diode connected active loads appear in parallel with the PMOS current source. The controlled voltages which are used in a VCO to control the frequency of oscillation V_n and V_P control the unity-gain frequency and the loss of the integrator. In low-pass filter, in order to increase the cutoff frequency of the filter, M3 and M4 are removed to decrease the output node capacitance.

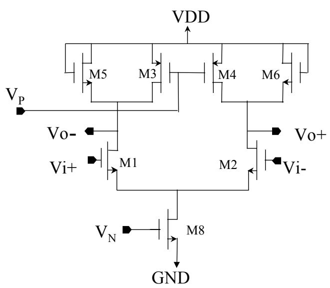

Fig. 5. The schematic of the lossy integrator

C. Lossy integrator with summing inputs

A lossy integrator with summing inputs was constructed by adding an additional input pair to the lossy integrator shown in Fig. 5. The resultant schematic is shown in Fig. 6.

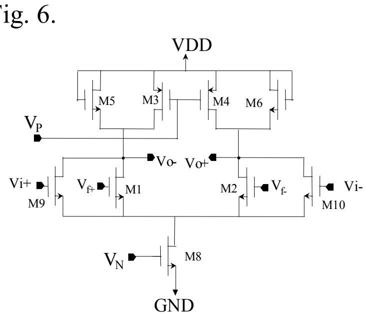

Fig. 6. The schematic of the lossy integrator with summing inputs

Using the integrators shown in this section, it can be shown with a tedious derivation that the Q and ω_o of a low-pass or band-pass filter can be expressed as

$$Q = \frac{\sqrt{1 - 2\cos\theta \cdot \frac{g_{m5}}{g_{m1}} + \left(\frac{g_{m5}}{g_{m1}}\right)^2}}{2\left(\cos\theta - \frac{g_{m5}}{g_{m1}}\right)} \tag{7}$$

$$\omega_o = \frac{g_{m1}}{C_L}\sqrt{1 - 2\cos\theta \cdot \frac{g_{m5}}{g_{m1}} + \left(\frac{g_{m5}}{g_{m1}}\right)^2} \tag{8}$$

where g_{m1} and g_{m5} are the transconductances of M1 and M5 in Fig. 6, respectively, C_L is the total capacitance on the output node of the integrator and where θ is a constant depending on the number of delay stages in the parent VCO which in this example is assumed to be three. For the three-stage oscillator, θ=60°.

IV. Simulation Results

The circuit was designed for the TSMC 0.25µm process and was simulated using the Hspice simulator. The supply voltage was 2.5V. The device sizes for low-pass and band-pass filters are shown in Table 1

TABLE 1
DEVICE SIZES FOR LOW-PASS AND BAND-PASS FILTER (µm)

	low-pass		band-pass		
	lossy	sum.	lossy	low loss	sum.
M1/2	45	45	24	20	24
M3/4	/	/	10	7.5	10
M5/6	30	30	16.5	/	16.5
M8	100	100	100	100	100
M9/10	/	70	/	/	12

A. Low-pass filter

A low-pass filter with a 3 dB bandwidth of 6 GHz was designed. The AC and transient response are shown in Fig. 7 and Fig. 8 respectively. The performance of the designed low-pass filter is summarized in Table 2. The total harmonic distortion (THD) was simulated with an input swing of $400mV_{p-p.}$

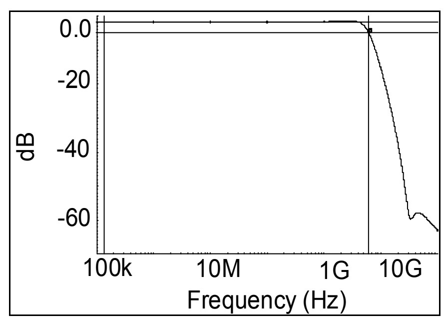

Fig.7. The AC response of the low-pass filter at V_n=1.1V

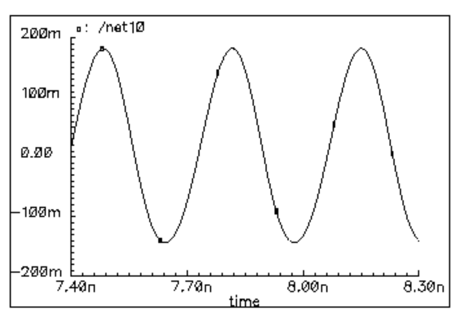

Fig.8. The transient response of the low-pass filter with an input swing of $400mV_{p-p}$ at a frequency of 3GHz.

TABLE 2
SIMULATED PERFORMANCE OF THE DESIGNED LOW-PASS FILTE

V_n(v)	ω_0(GHz)	THD (-dB)
1.1	6	40
1.0	5.89	36.4
0.9	5.68	31.5
0.8	5.2	27

B. Band-pass filter

A band-pass filter with a center frequency that is tunable from 4.05 GHz to 5.18 GHz and a Q factor that is adjustable from 4 to 89 was also designed. The performance of the designed band-pass filter is summarized in Table 3. The AC and transient responses of the filter with a Q of 7.34 excited by a 5.18 GHz sinusoid are shown in Fig. 9 and Fig. 10 respectively.

TABLE 3:
SIMULATED PERFORMANCE OF THE DESIGNED BAND-PASS FILTER

V_n (V)	V_p (V)	ω_0 (GHz)	Q	THD(-dB)@ input =200mV_{p-p}
0.9	2	5.04	3.95	51.2
	1.5	5.08	4.29	49.2
	1	5.17	5.49	44.4
	0.5	5.18	7.34	43.5
	0	5.18	8.63	41.1
0.8	2	4.91	4.29	46.3
	1.5	4.92	4.96	48.3
	1	4.93	8.9	43.2
	0.7	4.96	89	N/A
0.7	2	4.29	4.5	42.9
	1.5	4.12	5.36	38.6
	1.3	4.05	9.87	32.6
	1.2	4.21	66.3	33.4

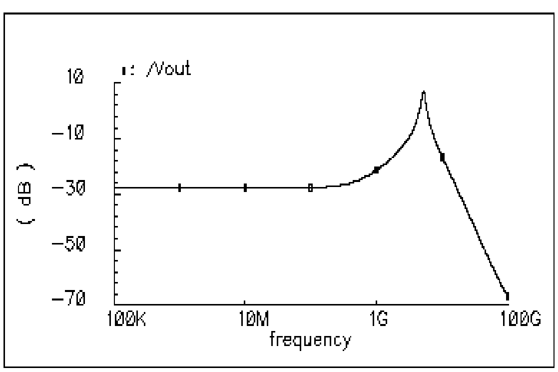

Fig.9. The AC response of the band-pass filter at V_n=0.9V and V_p=0.5V.

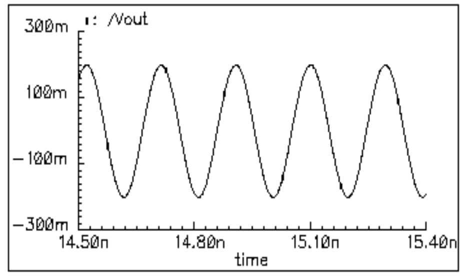

Fig.10. The transient response of the band-pass filter with a 200mV_{p-p}, 5.18GHz input.

V. CONCLUSION

A method of designing monolithic filters derived from CMOS VCOs was introduced. Sample VCO-derived low-pass and band-pass filters were presented. A low-pass filter with a cut-off frequency of 6 GHz was designed in 0.25 µm CMOS TSMC process. It exhibits a THD of –40dB with a 400mV_{p-p}, 3 GHz input signal. A band-pass filter with a center frequency tunable from 4.05 GHz to 5.18 GHz and a Q adjustable from 4 to 89 was also designed. It exhibits a THD of -40 dB with a 200mV_{p-p}, 5.18 GHz input. The VCO-derived filters offer two main advantages over other types of integrated CMOS filters: higher frequency of operation, and a higher and easily adjustable Q. VCO-derived filters offer potential for use in modern communication circuits that require modest distortion performance.

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