LSM Polyphase g_m-C Filter

Srdjan Milenković, Vančo Litovski, Slobodan Bojanić and
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Abstract – In modern telecommunication systems, receiver sensitivity is of paramount importance. On the other hand, receiver sensitivity is directly related to the receiver noise figure (NF). The lower NF the better receiver sensitivity. For portable devices, power consumption is also very important. This paper presents active polyphase g_m-C filter design approach which can be used as an integrated solution taking care of the above mentioned issues. The filer occupies low space when integrated while consuming low power. At the same time, due to its polyphase nature it suppresses received signal image at the negative frequencies when the receiver runs in low IF mode hence improving SNR i.e. NF. As an example, Bluetooth is used as the target communication standard.

Keywords – Polyphase filters, Bluetooth, LSM, IF, gyrator, transconductance.

I. INTRODUCTION

Integrated intermediate frequency (IF) filters are very attractive from a cost, size, and manufacturing point of view. The major drawbacks, compared to passive filters, are higher power consumption and a lower dynamic range. To minimize power consumption, the lowest possible centre (IF) frequency f_0 should be chosen. With traditional band-pass filters this will cause filter warping because of the non-linear low-pass-to-band-pass frequency transformation $H_{lp}(j\omega) \rightarrow H_{bp}(j\omega + 1/j\omega)$.

Furthermore, a low IF filter will suffer from an in-band image signal. This image is, with a traditional high IF, sufficiently suppressed by filters in front of the mixer, but such filtering is not practical with a low IF [4].

One solution to both frequency warping and in-band image is to use complex (polyphase) band-pass filters. Such filters have a linear frequency transformation and a high image rejection, thus supporting low IF architectures. For example, the specifications for the Bluetooth short-range radio require some 20 dB image rejection, which is easily achievable with an integrated design. Typical cellular systems like UMTS/FDD, requiring 50 dB of in-band blocking, are also well within the reach of the filter described here. The overall behaviour of the filter designed and presented in this paper fulfils the targeted Bluetooth specifications.

CMOS transconductance-C filter design techniques were reported in [2] [4]. In this paper we will design a polyphase filter based on a low pass prototype exhibiting 30 dB stop-band rejection while having excellent passband amplitude characteristic. Similar designs (based on elliptic prototypes) were reported in [4] [1].

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II. THE LSM g_m-C FILTER

LSM polynomial filters [6] [8] are known to have critical monotonic amplitude characteristic in the passband and minimum area under the attenuation characteristic which makes them favourable from many design aspects as compared to their monotonic and non-monotonic counterparts. After the introduction of the rational version of the LSM filters [7] improvements were obtained both in the pass-band (by further reducing the area under the attenuation characteristic in the pass-band) and in the stop-band (by further improving their selectivity).

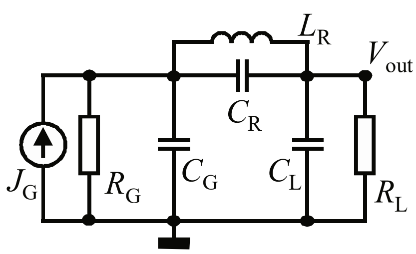

Figure 1. Third order LSM prototype filter

TABLE 1. NORMALIZED ELEMENT VALUES OF THE PROTOTYPE FILTER

Label	Normalized value
R_G	1
C_G	1.3133
C_R	0.1318
L_R	1.4964
C_L	0.8857
R_L	1

Having that in mind we used a third order LSM filter [9] exhibiting maximal stop-band attenuation of 30 dB as a prototype. Its transfer function is normalized so that it exhibits 3 dB at the cut-off frequency ω_c. Its schematic is depicted in Fig. 1 while Table 1 contains the normalized values of the circuit elements for ω_c =1 rad/s.

A g_m-C or Transconductance-C [2] based filter is a structure reminiscent to the active RC filters with the main difference being the absence of resistors; and integrated voltage amplifiers being substituted by operational transconductance amplifiers (OTA) [3]. The benefit is mainly in reduction of the silicon area since in application related to signal processing the OTA does not need large transistors.

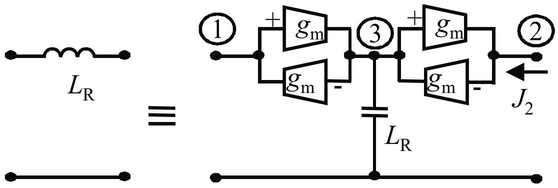

Figure 2. The equivalence used to create a simulated inductance.

One of the implementation of OTA in filtering circuits is to use gyrators [5] in order to simulate inductors. The analogy depicted in Fig. 2 [10] was used in order to simulate the floating inductor. It comes from the following development (based on the assumption of ideal OTA).

$$j\omega L_R V_3 + g_m V_1 - g_m V_2 = 0$$
$$J_2 = -g_m V_3 \quad (1)$$

After substitution one obtains

$$g_m(V_1 - V_2) = -j\omega L_R J_2 / g_m \quad (2)$$

and

$$(V_1 - V_2)/(-J_2) = j\omega L_R / g_m^2 \quad (3a)$$

For g_m=1 S, one gets

$$(V_1 - V_2)/(-J_2) = j\omega L_R \,. \quad (3b)$$

After substitution of the simulated inductor of Fig. 2 into the circuit of Fig. 1, simulation was performed using LTSPICE [11]. The resulting frequency characteristic is depicted in Fig. 3.

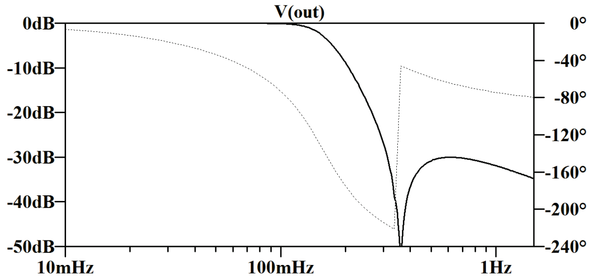

Figure 3. Frequency response of the LSM filter with L_R substituted according to Fig. 2.

III. THE POLYPHASE SOLUTION

The polyphase filter that is presented here has two inputs in-phase (I) and quadrature (Q) and two quadrature outputs (I and Q). Two transfer functions therefore characterize the filter. A low-IF receiver requires a polyphase filter with a passband from positive to positive frequencies, with an attenuation from negative to negative frequencies and with no signal transfer from positive to negative frequencies and vice versa. The transfer functions and the circuit synthesis of such a filter can be found by performing a linear frequency transformation on a low-pass filter characteristic. Equ. 4 gives this for a first order low-pass filter.

$$H_{lp}(j\omega) = \frac{1}{1 + j\omega/\omega_c} \Rightarrow$$
$$H_{bp}(j\omega) = \frac{1}{1 + j(\omega - \omega_0)/\omega_c} \quad (4)$$

where ω_c is the cut-off frequency of the low-pass prototype filter (here considered normalized to unity) while ω_0 is the central frequency of the newly created band-pass filter.

It is usual the transformation given by (4) to be implemented directly to the circuit schematic by creating an equivalent circuit of the capacitor. Namely, i-mplementation of the transformation will lead to the following

$$I_{lp}(j\omega) = j\omega C \cdot V_{lp} \Rightarrow$$
$$I_{bp}(j\omega) = j\omega C \cdot V_{bp} - j\omega_0 C \cdot V_{bp} \quad (5)$$

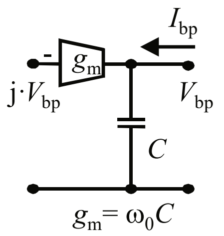

Figure 4. Implementation of the frequency transformation

Note that this transformation is shifting the poles and zeros of the prototype transfer function upwards for a value ω_0 which is usually larger than their imaginary part. In that way the resulting transfer function will have poles and zeros in the top half of the complex frequency plane. That makes $B_{bp}(j\omega)$ different for positive and negative frequencies.

The transformation depicted in Fig. 4 is to be implemented three times in order to create a polyphase filter based on the third order prototype: Twice for the original capacitors and once for the capacitor used within the simulated inductor circuit. The resulting schematic is depicted in Fig. 5. The currents J_{gi} and J_{gq} should be shifted in phase by 90°. In the subsequent simulation their amplitudes are set to 2 A.

Fig. 6 depicts the amplitude characteristic of the circuit of Fig. 5 where the amplitude (in dB) of V_{outi} is shown for positive and negative frequencies. ω_c=1 rad/s was used.

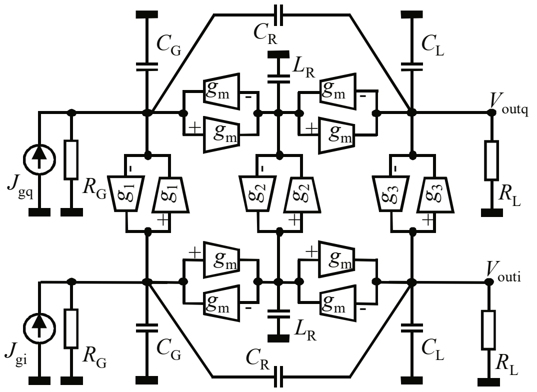

Figure 5. Third order LSM polyphase filter

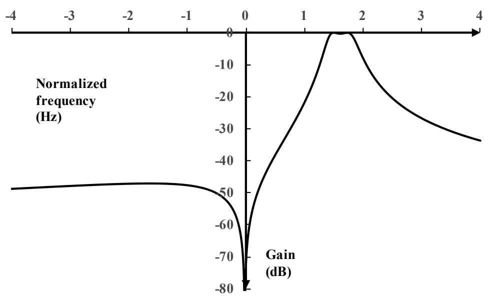

Figure 6. Amplitude characteristic of the LSM polyphase filter ($20 \cdot \log(|V_{outi}|)$ is depicted. ω_0=10·ω_c was used

IV. Some additional considerations

One may be interested on the migration of the poles and zeros due to the transformation given by (4) and (5).

Table 2. Normalized poles and zeros of the prototype LSM filter

Poles	-0.382025	0.917745
	-0.93057	0
	-0.382025	-0.917745
Zeros	0	2.250931
	0	-2.250931

To illustrate Table 2 contains the poles and zeros of the prototype LSM filter. As usual these are complex conjugate and located symmetrically to the real axis. If ω_0= 10 rad/s is used for the transformation the poles and zeros are to be shifted upwards as depicted in Fig. 7. Since no conjugates are present any more, the resulting transfer function has complex coefficients.

For example, the numerator polynomial of the third order LSM transfer function after transformation will become:

$$s^2 - 2js\omega_0 - (\omega_0^2 - \omega_p^2)\,, \qquad (6)$$

where ω_p is the frequency of the attenuation pole (here $\omega_p = 2.250931$.

This makes no use of all existing procedures [12] for filter synthesis so that, to our best knowledge, the only possible synthesis approach is the one described above.

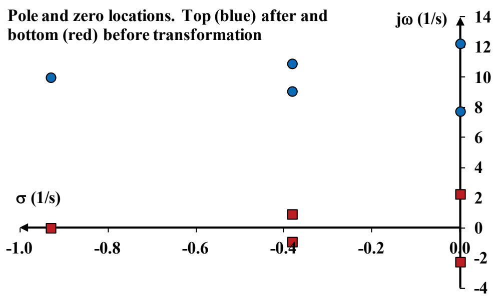

Figure 7. Pole and zero locations before (bottom) and after (top) implementation of the transformation

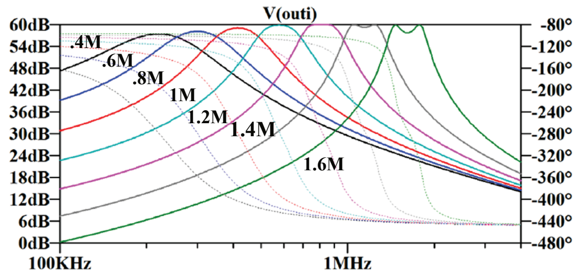

Figure 8. Influence of the ω_0/ω_c ratio to the shape of the passband gain characteristic.

It was noticed during the development of the simulation software that the transformation used here is not to be accepted as completely linear. Namely, due to the non-linear dependence of the amplitude characteristics on the circuit parameters (or transfer function's poles and zeros) distortion may be observed in the passband of the resulting polyphase filter. This phenomenon is illustrated in Fig. 8 where denormalized LSM filter was transformed several times with rising f_0 from 0.4MHz to 1.6MHz while f_c was kept to be 100 kHz. As it can be seen, at low f_0 the passband gain is distorted so that is more like Butterworth's response while at high frequencies with the rise of f_0 a dip grows in the middle of the passband. In the extreme case when $f_0 >> f_c$ one gets a transmission zero in the middle of the passband.

V. Conclusion

Polyphase g_m-C filter has been successfully designed by transforming low pass prototype into polyphase g_m-C filter architecture. The solution offers 30dB stop band attenuation and even better image rejection of 50dB. It has been observed that the performance of the polyphase filter after components denormalization depends on f_0/f_c ratio. However, there is an optimum f_0/f_c ratio around 10 where the resulting polyphase filter preserves frequency response within acceptable tolerances.

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