CMOS RF First-Order All-Pass Filter

Seyed Rasoul Aghazadeh*, Herminio Martinez*, Alireza Saberkari† and Eduard Alarcon*
*Department of Electronics Engineering, Technical University of Catalonia (UPC)−BarcelonaTech, Barcelona, Spain
†Department of Electronics Engineering, University of Guilan, Rasht, Iran

***Abstract*—In this paper, a wide-band first-order voltage-mode all-pass filter is presented. Due to a simple structure and appropriate performance of the proposed all-pass filter, this filter achieves a flat group delay of over 60 ps with a pole/zero pair located at 4.5 GHz. The proposed circuit demonstrates a high linearity and consumes merely 16 mW power from a 1.8-V supply. Simulation results indicate an input-referred 1-dB compression point P_{1dB} of 4.1 dBm and the wide-band operation capability of the first-order all-pass filter. Furthermore, the proposed all-pass filter is capable of converting into a second-order all-pass filter adding only a grounded capacitor. To demonstrate the performance of the proposed all-pass filter, simulation results are conducted by using Virtuoso Cadence in a TSMC 180-nm CMOS process.**

***Index Terms*—All-pass filter, delay, CMOS, wide-band, linearity.**

I. Introduction

All-pass filters or phase shifters have a variety of applications in signal processing and communication systems. In these circuits, the amplitude of the input signal is constant over the desired frequency band, while creating a frequency dependent delay. There are both current-mode and voltage-mode all-pass filters based on, e.g., the second generation current conveyors (CCIIs) [1]−[3], differential voltage current conveyors (DVCCs) [4]−[6], digitally programmable DVCCs (DPDVCCs) [7], differential difference current conveyors (DDCCs) [8], [9], current controlled current conveyors (CCCIIs) [10]−[12], operational transresistance amplifiers (OTRAs) [13]−[15], and dual-X current conveyor transconductance amplifier (DXCCTA) [16], as active elements in the literature. A number of these all-pass filters, however, suffer from excessive number of active and/or passive elements [1]−[3], [5], [7], [9]−[15], the use of floating capacitors which is not desirable for IC implementation [17]. Furthermore, most of these circuits operate up to multi-KHz frequency [1]−[3], [5]−[8], [12]−[15], [17] and the others around multi-GHz frequency [4], [9]−[11], [16].

On the other hand, there are some voltage-mode all-pass filters reported over the last two decades, which operate in radio frequencies (RFs) and have different applications [18]−[22]. In some applications, e.g. beam-forming, delay stages as delay cells are normally realized by cascading first-order all-pass filters in order to reach a desired delay [22]. However, there are just few RF first-order voltage-mode all-pass filters in the literature [22], [23], since it is hard to design an all-pass filter which has a flat group delay over a wide frequency range.

A broadband RF first-order voltage-mode all-pass filter is introduced in this work. The proposed all-pass filter is comprised of one transistor, three resistors, and one grounded inductor. This circuit demonstrates a high linearity and a large delay in a single delay cell through a wide frequency band. In addition, the proposed filter is considerably flexible, since it can achieve a higher order by adding just one grounded capacitor.

The structure of this paper is as follows. Section II describes the structure of proposed all-pass filter and provides theoretical analyses. In Section III, simulation results are presented. An increase in the order of the all-pass filter is provided in Section IV. Ultimately, conclusions are drawn In Section V.

II. Proposed First-Order All-Pass Filter

Fig. 1 shows the proposed first-order all-pass filter. In this filter, M_1 is a common-source configuration to convert the input voltage signal into current. At the output node, the drain current of M_1 and the current of feedback resistor R_1 are subtracted to realize an all-pass function. Then, the current will be converted to voltage by the load resistor, R_L. Resistor R_2 is realized by the diode-connected transistor of M_2, which is self-biased.

An all-pass filter can be accurately approximated to a first-order all-pass filter, which its ideal transfer function is expressed by

$$H(s) = e^{-s\tau} = \frac{1 - s(\tau/2)}{1 + s(\tau/2)} \tag{1}$$

where τ is time delay. If we assume that $g_{m1,2} \gg g_{ds}$ and neglect the parasitics of the transistors, the transfer function of the proposed first-order voltage-mode all-pass filter in Fig. 1 is given by

$$\frac{V_{out}}{V_{in}}(s) = -\frac{R_L(g_{m1}R_1-1)}{R_L+R_1} \cdot \frac{1-sL\left(\frac{g_{m1}+g_{m2}-g_{m1}g_{m2}R_1}{g_{m1}R_1-1}\right)}{1+sL(g_{m1}+g_{m2})} \tag{2}$$

where g_{m1} and g_{m2} are the transconductances of M_1 and M_2, respectively. The nominator and denominator in (2) have to be the same to realize an all-pass structure. Therefore, if we satisfy the following conditions:

$$g_{m1}R_1 = 2 \tag{3a}$$

$$R_L \gg R_1 \tag{3b}$$

$$g_{m1} + g_{m2} \gg g_{m1}g_{m2}R_1 \tag{3c}$$

then, the transfer function can be rewritten as

$$\frac{V_{out}}{V_{in}}(s) \cong -\frac{1 - sL(g_{m1} + g_{m2})}{1 + sL(g_{m1} + g_{m2})}. \tag{4}$$

The voltage gain of the filter is -1 at low frequencies, as the inductor L shorts the source terminal of M_1 to ground. At high frequencies, the inductor L can be regarded as an open-circuit and, therefore, we have a voltage gain equal to -1 again. The

pole/zero frequencies, phase, and group delay responses of the first-order all-pass filter are given, respectively, by

$$\omega_p = -\omega_z = -\frac{1}{L(g_{m1}+g_{m2})} \tag{5}$$

$$\varphi(\omega) = -2\ tan^{-1}\left[\omega L(g_{m1}+g_{m2})\right] \tag{6}$$

and

$$\tau_g(\omega) = -\frac{\partial\varphi(\omega)}{\partial\omega} = 2L(g_{m1}+g_{m2})\cdot \frac{1}{1+\left[\omega L(g_{m1}+g_{m2})\right]^2} \tag{7}$$

where ω is the angular frequency. From (7), it should be noted that the group delay is equal to $2Lg_{m1}$ at low frequencies and g_{m2} (i.e., $R_2 = 1/g_{m2}$) will be ignored, since the L shorts the source of M_1 to ground at DC.

At high frequencies, the resistor R_2 in Fig. 1 will be just seen at the source of M_1 and considered as a source degeneration resistor, contributing to the linearity of the circuit.

Note that, we can not ignore the effects of parasitic capacitors C_{gs} and C_{gd} on the all-pass filter in Fig. 1. Therefore, we need to find the closest parasitic pole to the dominant poles/zeros. The parasitic pole stemmed from the C_{gd} is approximately equal to $1/R_1C_{gd}$. From (3), the value of resistor R_1 has to be small. Hence, this parasitic pole will be far beyond the dominant poles/zeros. Further analysis indicates that the nearest parasitic pole to the dominant poles/zeros is stemmed from the C_{gs}. Considering the C_{gs}, which affect the pole/zero frequencies and DC-gain, and assuming $g_{m1,2} \gg g_{ds}$, the transfer function of the first-order all-pass filter can be determined by

$$\frac{V_{out}}{V_{in}}(s) = -\frac{R_L}{R_L+R_1}\cdot \frac{\left[(g_{m1}R_1-1) - sL(g_{m1}+g_{m2}-g_{m1}g_{m2}R_1) - s^2LC_{gs}\right]}{\left[1+sL(g_{m1}+g_{m2}) + s^2LC_{gs}\right]}. \tag{8}$$

Consequently, it can be observed that the additional parasitic pole is located at

$$\omega_{p2} \cong \frac{L(g_{m1}+g_{m2}) + \sqrt{L^2(g_{m1}+g_{m2})^2 - 4LC_{gs}}}{2LC_{gs}}. \tag{9}$$

III. Simulation Results

The proposed first-order all-pass filter is simulated in a 180-nm TSMC CMOS process and results are obtained using Virtuoso Cadence. The proposed circuit in Fig. 1 is expected to achieve pole/zero frequencies located at 4.5GHz and simulated with $g_{m1} = 31.5$mA/V, $g_{m2} = 7.4$mA/V, $R_L = 3$KΩ, $R_1 = 65\Omega$, and $L = 0.85$nH. The power consumption is 16mW from a supply voltage of 1.8-V.

Fig. 2 indicates the gain and phase responses of the first-order all-pass filter. The gain of the proposed filter is about -1dB, due to the fact that the DC gain of the all-pass filter is less than unity (refer to (2)), and also due to the parasitic effects of the transistors. The group delay response of the proposed all-pass filter is shown in Fig. 3, proving a flat group delay of over 60ps within a bandwidth of about 4.5GHz. This simulated group delay value is close to the theoretical one in (7), with an error of around 12%.

The gain and group delay responses of the first-order all-pass filter for different values of g_{m2}, $(R_2 = 1/g_{m2})$, are shown in Figs. 4 and 5, respectively. It is noticeable that

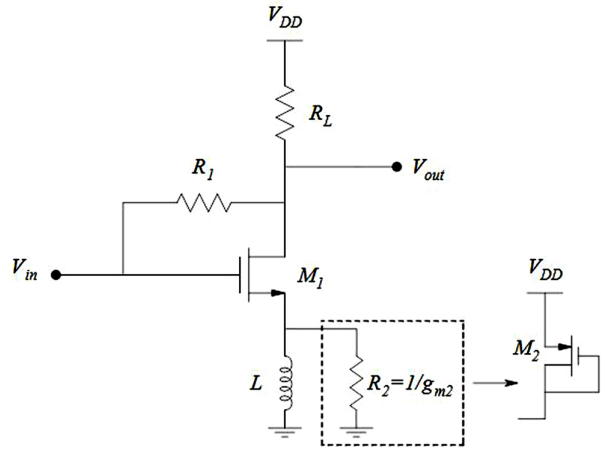

Fig. 1. The proposed first-order voltage-mode all-pass filter.

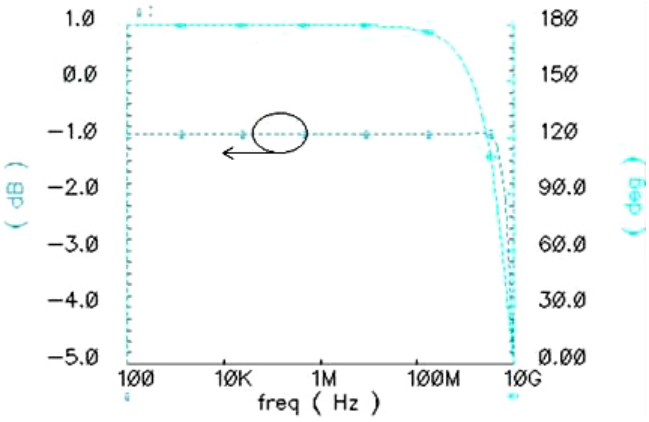

Fig. 2. Gain and phase responses of the proposed first-order all-pass filter.

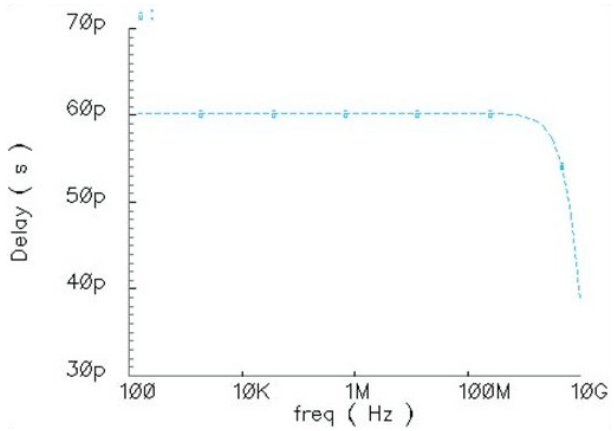

Fig. 3. Group delay response of the proposed first-order all-pass filter.

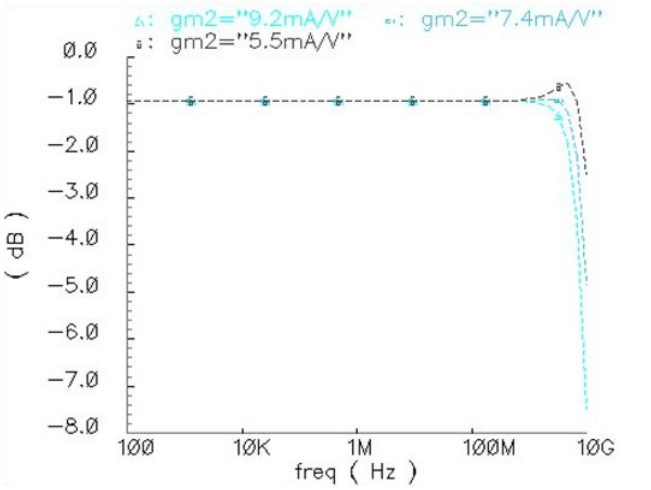

Fig. 4. Gain response of the proposed first-order all-pass filter under different values of g_{m2}, $(R_2 = 1/g_{m2})$.

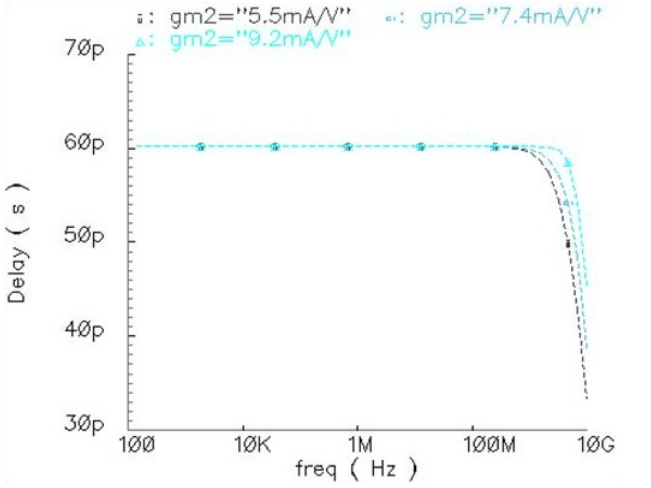

Fig. 5. Group delay response of the proposed first-order all-pass filter under different values of g_{m2}, $(R_2 = 1/g_{m2})$.

flat gain and group delay responses are achieved at high frequencies by varying g_{m2}. Moreover, it can be observed that g_{m2} is proportional to the group delay (refer to (7)), since by increasing g_{m2}, the group delay of the proposed filter is increased as well at high frequencies.

In Fig. 6, the input-referred noise response of the first-order all-pass filter is shown. The input-referred noise value is approximately 1.25nV/sqrt(Hz) throughout the frequency band. The input-referred 1-dB compression point (P_{1dB}) and input-referred third-order intercept point (IIP3) responses of the first-order all-pass filter are shown in Fig. 7. The input-referred P_{1dB} and IIP3 are 4.1dBm and 17.8dBm at 2.5GHz, respectively. This high linearity of the proposed circuit is due to the high drain current of M_2 at the price of higher power consumption.

IV. Increasing The Order Of The All-Pass Filter

The proposed First-order all-pass filter in Fig. 1 can be converted into a second-order all-pass filter by adding just a

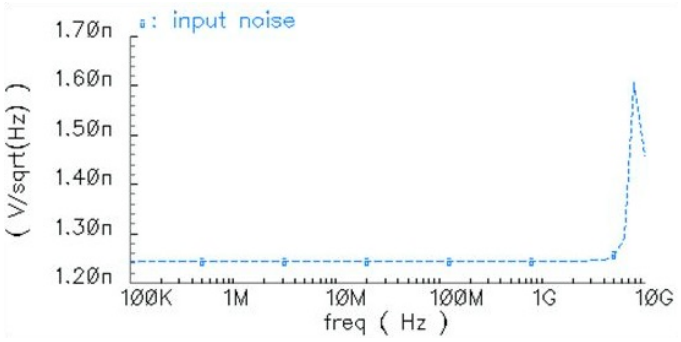

Fig. 6. Input-referred noise response of the proposed first-order all-pass filter.

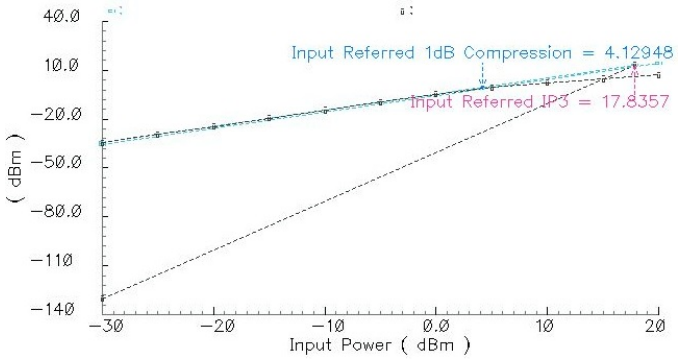

Fig. 7. Input-referred P_{1dB} and input-referred IIP3 responses of the proposed first-order all-pass filter.

capacitor in parallel with the inductor L and resistor R_2 at the source of M_1. Fig. 8 shows the second-order voltage-mode all-pass filter.

The ideal transfer function of a second-order all-pass filter is approximately expressed by

$$H(s) = \frac{s^2 - \frac{\omega_n}{Q}s + \omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2} \tag{10}$$

where ω_n is the natural frequency of the all-pass filter and Q is the quality factor, which determine the position of poles and zeros in the complex plane. If the parasitics of the transistors are neglected and $g_{m1,2} \gg g_{ds}$, the transfer function of the second-order all-pass filter is defined as

$$\frac{V_{out}}{V_{in}}(s) = -\frac{R_L(g_{m1}R_1 - 1)}{R_L + R_1} \cdot \frac{s^2 - \frac{1}{C}\left(\frac{g_{m1}+g_{m2}-g_{m1}g_{m2}R_1}{g_{m1}R_1 - 1}\right)s + \frac{1}{LC}}{s^2 + \frac{1}{C}(g_{m1}+g_{m2})s + \frac{1}{LC}} \tag{11}$$

where g_{m1} and g_{m2} are the transconductances of M_1 and M_2, respectively. An all-pass realization will be achieved for this circuit if the conditions in (3) are satisfied. Therefore, the transfer function can be rewritten as

$$\frac{V_{out}}{V_{in}}(s) \cong -\frac{s^2 - \frac{1}{C}(g_{m1} + g_{m2})s + \frac{1}{LC}}{s^2 + \frac{1}{C}(g_{m1} + g_{m2})s + \frac{1}{LC}}. \tag{12}$$

Thus, the natural frequency and the quality factor of the

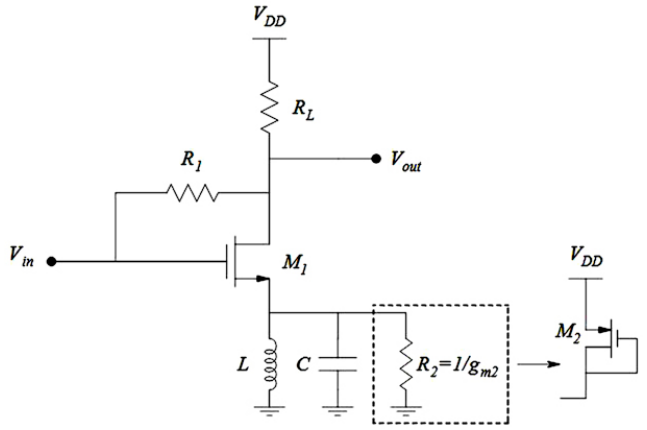

Fig. 8. The second-order voltage-mode all-pass filter achieved by adding a grounded capacitor to the circuit in Fig. 1.

second-order all-pass filter are determined, respectively, by

$$\omega_n = \frac{1}{\sqrt{LC}} \tag{13}$$

$$Q = \frac{1}{g_{m1}+g_{m2}}\sqrt{\frac{C}{L}}. \tag{14}$$

The pole/zero frequencies, phase, and group delay responses of the second-order all-pass filter are expressed, respectively, by

$$|\omega_{p1,2}| = |\omega_{z1,2}| = \frac{L(g_{m1}+g_{m2}) \pm \sqrt{L^2(g_{m1}+g_{m2})^2 - 4LC}}{2LC} \tag{15}$$

$$\varphi(\omega) = -2\ tan^{-1}\left[L(g_{m1}+g_{m2}) \cdot \frac{\omega}{1-LC\omega^2}\right] \tag{16}$$

and

$$\tau_g(\omega) = -\frac{\partial\varphi(\omega)}{\partial\omega} = 2L(g_{m1}+g_{m2}) \cdot \frac{1+LC\omega^2}{(1-LC\omega^2)^2 + ((g_{m1}+g_{m2})L\omega)^2}. \tag{17}$$

Similar to the first-order all-pass filter, the group delay of the second-order all-pass filter is $2Lg_{m1}$ at low frequencies.

V. Conclusion

This paper presents a wide-band first-order voltage-mode all-pass filter. The proposed first-order all-pass filter achieves a flat group delay of approximately 60ps with pole/zero frequencies located at 4.5GHz, while consuming only 16mW power. This all-pass filter is highly linear, and has the input-referred 1-dB compression point P_{1dB} of around 4dBm and the input-referred intercept point IIP3 of 17.8dBm at 2.5GHz. The proposed circuit can reach a higher order, which demonstrates a considerable flexibility.

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