A Current Mode Low-Noise Gm-C Filter with a Cut-Off Frequency of 5 GHz in Telecommunication System

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Abstract: The high linearity low-noise filter is an indispensable key circuit in the communication system. Based on the structure of current-reuse source-degradation operational transconductance amplifier (OTA), a 5 GHz current-mode low-noise Gm-C filter suitable for high-speed communication systems is proposed. Thanks to the proposed current mode structure and the OTA's high-power efficiency and high linearity, the filter obtains good noise and high linearity performance with very low power consumption. The filter is designed in standard 65 nm CMOS technology and occupies a core area of 0.06 mm^2. The simulation results show that the operating bandwidth is 5 GHz, the IIP3 is 35 dBm, and the power consumption is only 3.2 mW.

Key words: Gm-C filter; lowpass filter; current mode filter

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0 Introduction

Modern wireless telecommunication systems evolve towards broadband features with high filtering requirements for in-band and out-band blockers. Normally, out-band blockers are filtered out by off-chip surface acoustic wave (SAW) filters. The in-band blockers need to be filtered by an integrated filter when the RF signal is down converted to the baseband[1]. In direct conversion receivers with very wide baseband, the baseband signal is directly filtered and processed without the second down-conversion[2]. Typically, the frequency of this signal can be up to several Giga hertz. An on-chip filter with high speed and good performance is needed to process a small power signal among many interferers. Both high SNR and high IIP3 are required for the filter in this application scenario. To meet such requirements, a new current mode Gm-C filter structure is proposed in this paper, achieving low noise and high linearity performance based on a current reused source degeneration operational transconductance amplifier (OTA).

This paper is organized as follows. Section 1 explains the traditional voltage mode Gm-C filter. Section 2 presents and explains the design details of the proposed current mode Gm-C filter. Then, a comparison analysis between the proposed filter and the traditional filter is undertaken in Section 3. Besides, the simulated results and the performance comparison with other state-of-the-art results are also presented. Finally, a summary is concluded.

1 Traditional Voltage Mode Gm-C Biquad

In a typical direct conversion receiver's structure, a filter can be inserted after the down mixer to filter out the unwanted signals. It is widely accepted that Gm-C filters are the best choices for high-speed systems[3-12]. Fig.1 shows a traditional voltage mode Gm-C biquad, which consists of at least four

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OTAs[13]. As shown in Fig.1, the first OTA, which is also called Gm1, is used to convert the input voltage signal to a current signal. The second OTA, called Gm2, is utilized to realize low resistance by connecting its input and output. The transfer function of the traditional Gm-C biquad is expressed as follows

$$H(s)=\frac{\dfrac{g_{m1}g_{m3}}{C_1C_2}}{s^2+s\dfrac{g_{m2}}{C_1}+\dfrac{g_{m3}g_{m4}}{C_1C_2}}=\frac{\dfrac{g_m^2}{C_1C_2}}{s^2+s\dfrac{g_m}{C_1}+\dfrac{g_m^2}{C_1C_2}} \quad (1)$$

where $g_{m1,2,3,4}=g_m$.

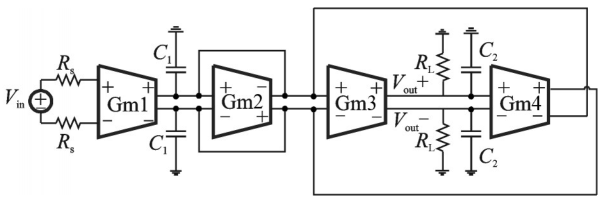

Fig.1 A traditional Gm-C biquad

For analysis convenience, the Gm-C biquad can be simplified in Fig.2. As discussed before, Gm1 cell generates a current signal from a voltage signal. With the help of capacitor C_1, Gm2 cell defines the first pole. Gm3, Gm4 and the output capacitor C_2 compose a gyrator, which can be considered as an inductor $L=C_2/g_{m3}g_{m4}$. Consequently, Gm2 cell, C_1 and L generate two poles. As a result, a second order lowpass filter is realized. $\overline{\mathrm{d}v_{\mathrm{eq}}^2}$ is the equivalent input noise of the filter. With simulations and calculations, it is found that this voltage mode filter has a high noise figure (NF) and limited linearity. Among its components, Gm1 generates very large part of the noise and the none linearity.

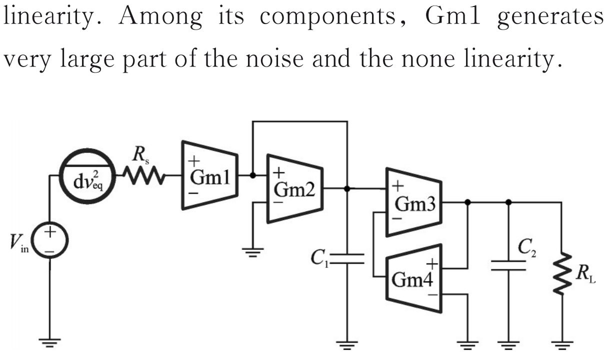

Fig.2 Simplified model of the traditional Gm-C biquad

2 A Current Mode Gm-C Biquad

To reduce noise and improve the linearity of a Gm-C filter, several current mode filters were proposed[14-19]. Among them, Ref.[16] introduced a high linearity current mode noise shaping filter. But its bandwidth was only 2.8 MHz, which is not feasible for the wideband applications. The filter presented in Ref.[19] had a bandwidth of 1 GHz but a limited IIP3. To solve above issues, a high speed, low noise and high linearity current mode Gm-C biquad is proposed in this paper, as shown in Fig.3.

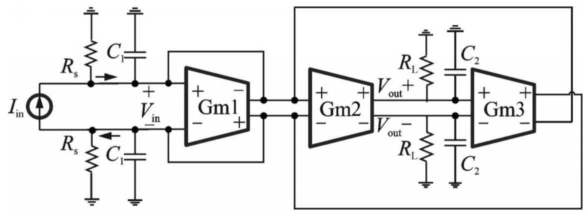

Fig.3 The proposed current mode biquad

The proposed biquad makes use of a high linearity complementary OTA shown in Fig.4 as its unit Gm cell. In the OTA structure, both NMOS pair and PMOS pair have been utilized for the input transistors, employing the same bias current. The current reuse technique has greatly increased the power efficiency of the circuit. The transistors M_{P} and M_{N} are added to act as the source degeneration resistors, improving the linearity of the OTA with an ability of transconductance adjustment. Besides, M_{N} is made by two identical transistors with the middle node V_{N} using for the common mode voltage in the common-mode feedback (CMFB) circuit. In this way, extra sensing resistors, are not needed for the common mode voltage. Moreover, since the OTA's common-mode output voltage is susceptible

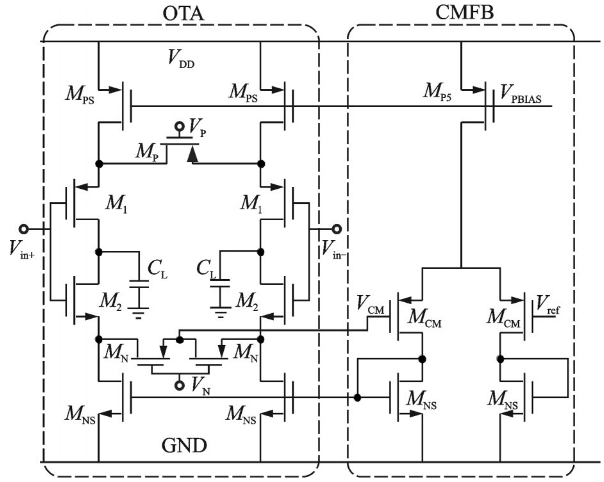

Fig.4 OTA structure including a CMFB

to the common-mode input signal disturbances and current source mismatches, the CMFB circuit shown in the right part of Fig.4 is utilized to stabilize it.

As shown in Fig.3, the proposed current mode biquad consists of three OTAs, four capacitors and two R_L. The structure gets rid of the first voltage to current transformation OTA in the traditional Gm-C filter. In this way, the nonlinearity components coming from the first OTA in Fig.1 can be reduced. Besides, the input interferers can be filtered with the help of input capacitor C_1 before they enter the nonlinear device. As a result, the proposed filter can achieve a very good IIP3 performance.

The transfer function of the proposed biquad is given by

$$\frac{V_{\text{out}}}{I_{\text{in}}}=\frac{\dfrac{g_m}{C_1C_2}}{s^2+s\dfrac{g_m}{C_1}+\dfrac{g_m^2}{C_1C_2}} \tag{2}$$

where $g_{m1,2,3}=g_m$.

Clearly, a second order low-pass function can still be realized by the structure, except that its input signal is in current domain. With calculation, the cut-off frequency of the current mode biquad is

$$\omega_0=\pm g_m/\sqrt{C_1C_2} \tag{3}$$

and the quality factor is

$$Q=\sqrt{C_1/C_2} \tag{4}$$

where ω_0 is decided by the values of g_m and the capacitors C_1 and C_2. Since large sizes of M_1 and M_2 generate large g_m but also large parasitic capacitance, an optimized value of g_m is chosen to be 1.7 ms in order to achieve a bandwidth of 5 GHz. Meanwhile, C_1 and C_2 are designed as 60 fF and 200 fF, leaving a certain margin for the layout of parasitic capacitance. Since the direct current (DC) gain of the OTA should be larger than 30 dB in a low Q filter[4], the OTA gain is set to be 35 dB in this parper. Normally, the CMFB circuit needs sense resistors R to provide the common mode voltage. However, large sense resistors not only occupy large layout area, but also increase parasitic capacitance and degrade the OTA speed performance. As explained before, because of using the middle node of the active resistance M_N, the large sense resistor R can be avoided in the design.

3 Comparison of Simulation Results Between the Proposed Current Mode Gm-C Biquad and the Traditional Gm-C Biquad

In order to compare the noise performances of the traditional voltage mode and the proposed current mode filters, source resistors are added at the inputs of the two Gm-C biquads to represent the output impedance of their previous stage, as shown in Fig.2 and Fig.5. In this way, these two filters have the same representations for their source resistances. As described in Section 2, the input equivalent noise of the voltage mode filter is represented by $\overline{dv_{\text{eq}}^2}$. In contrast, the current mode filter is actually driven by a current source, its input equivalent noise is represented by $\overline{di_{\text{eq}}^2}$ and $\overline{dv_{\text{eq}}^2}$. Then the calculation of the two filters' NF can be simplified as Eqs.(5,6) [20].

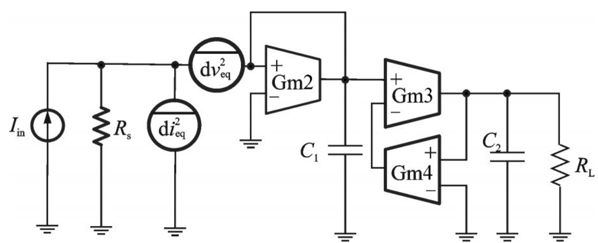

Fig.5 Noise model of current mode biquad including source resistors

$$\text{NF}_{\text{voltage mode}}=10\lg\left(1+\frac{\overline{dv_{\text{eq}}^2}}{4kTR_s df}\right) \tag{5}$$

$$\text{NF}_{\text{current mode}}=10\lg\left(1+\frac{\overline{dv_{\text{eq}}^2}+R_s^2\cdot\overline{di_{\text{eq}}^2}}{4kTR_s df}\right) \tag{6}$$

where k is the Boltzmann's constant, T the absolute temperature, and f the frequency. Apparently, the NF of the voltage mode Gm-C filter is reverse proportional to its source resistance R_s. As a result, it will decrease when R_s increases. Differently, the NF of the current mode Gm-C filter has an optimum value when R_s is small. Consequently, the filter with a low source resistance should choose the current mode structure to improve its noise performance. Besides, from Eqs.(5, 6), it can be seen that the NF is not influenced by the gain of two filters, meaning that the load impedance R_L will not affect their NFs.

For a fair performance comparison, the same OTA with a fixed g_m value for high-speed applications, shown in Fig.4, is used in the traditional voltage mode and the proposed current mode filters with their source impedance R_s setting to 150 Ω. The DC voltage gain of the filters is defined as $A_{DC}=V_{out}/V_{in}$, which is also influenced by R_L. Both filters have been designed with the same A_{DC} by using of suitable R_L, which will not affect the noise performance as explained before. Fig.6 shows the simulated transfer functions of the proposed current mode and traditional voltage mode filters. Clearly, these two filters have very similar lowpass transfer functions. As indicated, both filters have an DC gain of around 2.5 dB with a similar bandwidth of 5 GHz. Fig.7 shows the NF performances of the filters. Obviously, in the frequency range from DC to 5 GHz, the NF of the proposed current mode structure is about 5 dB less than that of the traditional structure. In a wideband communication system, a high-speed filter is always needed after a down mixer in a receiver or after a high-speed digital to analog converter (DAC) in a transmitter. In both cases, the previous stage of the lowpass filter has a relatively low output impedance ranging from 50 Ω to 300 Ω[21-22]. Therefore, a current mode filter is preferable compared with the traditional structure in these scenarios.

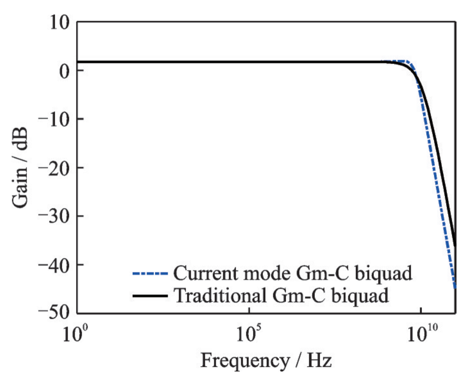

Fig.6 Simulated transfer functions of the traditional Gm-C biquad and the proposed current mode Gm-C biquad

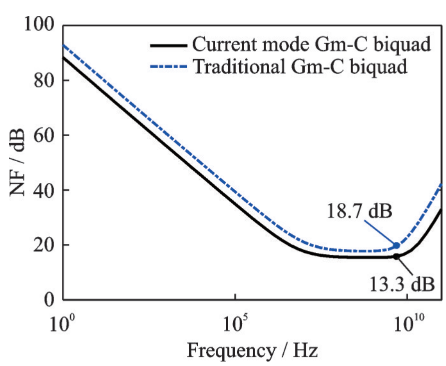

Fig.7 NF of two biquads

Fig.8 shows the simulated IIP3 of the two structures with a 2 GHz and 2.1 GHz two-tone test. Clearly, the proposed current mode biquad has an IIP3 value of 35 dBm, which is 6.7 dB better than the traditional voltage mode biquad.

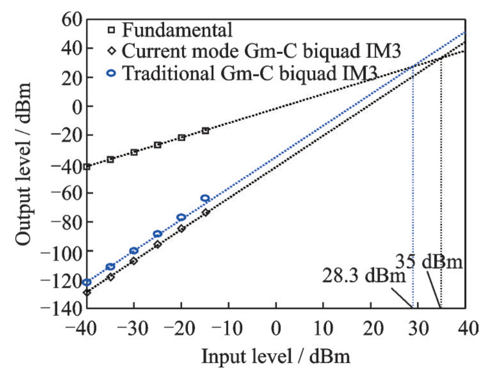

Fig.8 Comparison of IIP3 of current mode and traditional biquad

Besides, the current mode biquad only consumes 3.2 mW while the traditional one consumes 4.3 mW. The layout of the current mode biquad is shown in Fig.9 with a core area of 0.06 mm^2. Table 1 summarizes the simulated results of this paper and compares it with other state-of-the-art results in recent years. The figure of merit (FoM) used in Table 1 is shown in Eq.(7). Thanks to the proposed current mode Gm-C structure, this paper has the highest speed of 5 GHz, the smallest core area and the best FoM value with very good linearity and noise performances. Accordingly, the proposed current mode Gm-C filter is very suitable for broadband applications with high area-efficiency.

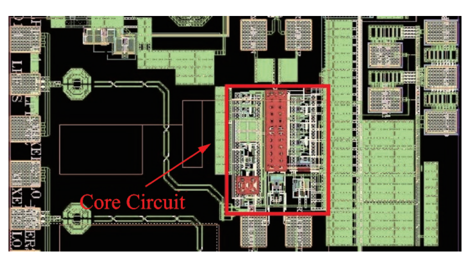

Fig.9 Layout of the filter

Table 1 Performance comparison with other Gm-C filters

Reference	[12]	[13]	[19]	[20]	Ours
Process CMOS/nm	90	40	65	28	65
Topology	Gm-C	Active RC	Current mode	Current mode	Current mode
Order	2	4	4	2	2
SFDR/dB	0	46	70.43		60
f_C/GHz	1.114	1.6	0.002 8	1	5
Gain/dB	2.37	10	−1	−1.8	2.5
IIP3/dBm		11.3	35.6	16	35
NF/dB					13.3@5 GHz
Area/mm^2		0.12	0.5	0.374	0.06
V_{DD}/V	0.6	1.1	2.5	1.5	2.5
Power/mW	1.55	17.6	1.26	0.36	3.2
FoM/pJ	0.69	0.013	0.03		0.000 3

$$\mathrm{FoM}=\frac{\mathrm{power}}{N_{\mathrm{poles}}\times f_{\mathrm{C}}\times \mathrm{SFDR}} \tag{7}$$

where N_{poles} is the number of the poles and f_{C} the cut-off frequency. SFDR denotes spurious free dynamic range.

4 Conclusions

A 5 GHz wideband current mode second order filter is presented. By using of a current reused source degeneration OTA, the proposed filter can achieve much better noise and higher linearity performance with a lower power consumption compared with the traditional voltage mode filter. This paper is designed in standard 65 nm CMOS technology with a simulated IIP3 of 35 dBm and a power consumption of 3.2 mW.

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Author contributions Dr. **WU Xu** designed the work, simulated, made the layout, post-simulation and wrote the manuscript. Prof. **LI Lianming** contributed to the discussion, background of the study and revised the manuscript. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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应用于通信系统中的5 GHz电流模低噪声Gm-C滤波器

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摘要:高线性度低噪声滤波器是通信系统中不可缺少的关键电路。基于电流复用型源极退化运算跨导放大器(Operational transconductance amplifier, OTA)结构,本文提出了一种适用于高速通信系统的5 GHz电流模低噪声Gm-C滤波器。利用电流模滤波器的结构特点和电流复用型源极退化OTA的高能效和高线性度,本文设计的滤波器可在低功耗条件下仍具有良好的噪声和线性度性能。该滤波器采用标准65 nm CMOS工艺,核心面积为0.06 mm^2。仿真结果表明,其工作带宽为5 GHz,IIP3为35 dBm,而功耗仅为3.2 mW。

关键词: Gm-C滤波器;低通滤波器;电流模滤波器