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► To cite this version:

A. Abbasi, N Sulaiman, Rozita Teymourzadeh. Highly linear low-pass $G_m - C$ filter with self-biasing transconductor for digital TV tuner. International Journal of Electronics, In press, 00, pp.1 - 13. hal-01802065

HAL Id: hal-01802065

<https://hal.science/hal-01802065>

Submitted on 28 May 2018

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To appear in the *International Journal of Electronics*
Vol. 00, No. 00, January 2013, 1–13

Highly linear low-pass $G_m - C$ filter with self-biasing transconductor for digital TV tuner

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(Revised on November 2014)

A technique of multiple gated transistors on the basis of self-biasing circuit in this paper is chosen to enhance the linearity of the transconductor, whereas decreasing the bill-of-material (BOM) and complexity of the design. The transconductor is chosen by third-order chebyshev which tracks low-pass filter with low power consumption. The filter cutoff frequency is 50-200 MHz. The hybrid tracking low-pass filter is designed to defeat the problems related to a local oscillator harmonic-mixing for Advanced Television System Committee terrestrial digital TV tuner integrated circuit. **The proposed operational transconductor amplifier (OTA) is designed in 90 nm CMOS technology. The simulation result with two-tone test at 100 MHz center frequency shows that the proposed OTA has 5 dBm Input-referred Third-Order Intercept Point (IIP3) improvement compared with a single-gate OTA in the third-order Chebyshev filter.** The proposed OTA achieves maximum noise figure (NF) of 13 dB and maximum IIP3 of approximately 21.7 dBm at 100 MHz, whereas consuming 18 mA with 1.2 V supply voltage.

Keywords: ATSC, linearity, local oscillator harmonic mixing, multiple gated transistors, tracking filter, transconductor-C filter, self-biasing.

1. Introduction

In recent years, digital television (DTV) has become popular because of the high quality and band-width efficiency with several channels prepared to the users. Thus, DTV obtain more consideration in the market to try to decrease DTV costs. One of the approaches to reach the goal is to decrease the BOM (Greenberg et al. (2013)). A wide VHF/UHF frequency range from 48 MHz to 862 MHz have been utilized by several available cable TV and terrestrial standards like Digital Video Broadcasting (DVB) and Advanced Television System Committee (ATSC) where it can support hundred broadcasting channels. Broadband essence of the TV spectrum causes several serious problems. Local oscillator (LO) harmonic mixing problem is one of the critical challenges; the unfavorable input channel situated at odd-order harmonic frequencies of the square-wave LO signal in the RF path are down-converted and mixed with RF input. Therefore, it degrades the signal-to-noise ratio (SNR) of the tuner system (Cha, Kwon, Choi, Kim, & Lee (2010)).

Several studies discovered to solve the LO harmonic mixing difficulty like a double-conversion with up-and-down conversion architecture and single-conversion

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receiver Hsiao, Meng, & Wei (2012); Stevenson et al. (2007); Syu, Meng, Teng, & Liao (2010); Ying-mei, Yong-kang, Zhi-hang, & Li (2010). However, they are based on external high-quality factor (Q) inductors, off-chip surface acoustic wave (SAW) filters and large number of mixers that are area consumers, bulky and expensive. Recently, a low cost and high integration structure was initiated as an excellent candidate with a harmonic rejection mixer (HRM) and direct-conversion receiver (Chen (2011); Lerstaveesin, Gupta, Kang, & Song (2008); Mohamed & Manoli (2013); Trabelsi, Bouzid, Derbel, & Masmoudi (2008)). As far as, HRM is not able to reject all odd-order harmonics of the LO that digital TV tuner system requires, a tracking filter is needed in order to eliminate undesirable signals with frequencies of LO odd-order harmonics. Furthermore, low noise and highly linear performances are the requirements of this filter to prevent from degrading the SNR of the whole receiver.

In this study, a highly linear, low noise and low power CMOS tracking filter to overcome the problem of LO harmonic-mixing is implemented in a 90 nm CMOS technology for ATSC terrestrial and cable standard. The third-order chebyshev filter, called hybrid tracking low-pass filter (HTLPF), including of first-order passive RC filter and the second-order Gm-C filter is introduced for low power consumption. The method of multiple gate transistor (MGTR), without external bias circuitry is proposed to reduce BOM, complexity of the design and improve linearity (Abbasi, Rozita Teymourzadeh, & Sulaiman (2014), Kwon & Lee (2011), Jin & Kim (2011); I. S. Kim (2000); T. W. Kim, Kim, & Lee (2004)).

2. Literature of Tracking Filter

High linearity and low noise performance with low power are the critical performances of the tracking filter because the sensitivity of entire system depends on it. There are many publications in this area (Comer, Comer, Casper, & Korth (1999); Gupta, Lerstaveesin, Kang, & Song (2007); Kwon, Kim, & Lee (2009); Sun, Jeong, Lee, Lee, & Lee (2010)). Passive filters are generally desired (Aldeeb & Kalkur (2014)) due to high linearity performance. However, bulky and large inductance raises BOM and extra pins. In the area of active filter design, those issues cited before have been solved. A coupled-resonator topology by Gupta et al. (2007) is employed by fourth-order active tunable filter to overcome the problem of LO harmonics with HRM. However, it does not have good linearity and noise performance. In Sun et al. (2010), source degeneration method is adopted to enhance the performance of linearity for an active band-pass filter. However, it has the problem with linearity and noise performance. Recently, a third-order hybrid tracking low-pass filter adopting MGTR method is introduced with high linearity and good noise performance. In addition, the power efficiency of this filter regarding to other performance is plausible. However, the transconductor used in Kwon & Lee (2011), in Fig. 1, shows that the external bias circuitry increases BOM, complexity of the design and area consumption, especially, with big resistors and extra capacitors.

3. Filter Requirement

A direct-conversion receiver has been introduced with positive specification such as low power dissipation, less BOM and low cost; however, it has the LO harmonic-mixing problem. There are many papers trying to solve the problem of LO harmonics with HRM (Lerstaveesin et al. (2008), Moseley, Ru, Klumperink, & Nauta

[illegible]

A block diagram of TV tuner with a tracking low-pass filter (TLPF) proposed by Kwon & Lee (2011) and an HRM with mismatch calibration suggested by Cha et al. (2008) is indicated in Fig. 2. With these two match circuits, the requirements for RF front-end to remove all LO harmonics more than 60 dB is achieved. Table 1. shows the requirement of TLPF rejection and HRM with mismatch calibration. It should repress signals by over 20 dB and 43 dB at fifth and seventh LO harmonics, respectively.

Table 1. HRM and Filter Specification Cha et al. (2010)

LO harmonics	3rd	5th	7th and 9th
HRM rejection	>60 dB	>40 dB	>17 dB
Filter rejection requirement	None	>20 dB	> 43 dB
Filtering range	48 MHz ~ 172 MHz		

4. Hybrid Tracking Low-Pass Filter

In this section, hybrid tracking low-pass filter with high linearity and low power for ATSC terrestrial digital TV tuner is demonstrated. In Fig. 3, it is inferred that the third-order chebyshev filter consist of the second-order transconductor-C filter and the first-order passive RC. Table 2. shows the values for the transistors and capacitors.

The HTLPPF transfer function is indicated below Kwon & Lee (2011)

$$H_{HTLPPF}(s) = \frac{1}{sR_1C_1 + 1} \frac{\frac{G_{m1}G_{m2}}{C_2C_3}}{s^2 + \frac{G_{m2}}{C_3}s + \frac{G_{m1}G_{m2}}{C_2C_3}} \quad (1)$$

where G_{mi} represents the transconductance of the i-th transconductor, C_i demonstrates the capacitance of the i-th capacitor and R_1 indicates the resistance of the resistor. The third-order chebyshev low-pass filter is adopted due to the requirement in Table 1. to reject all LO harmonic. From two stages of the third-order chebyshev low-pass filter, the RC went after a second-order transconductor-C filter, the real and complex conjugate poles are calculated. Because of utilizing HRM with mismatch calibration circuitry Cha et al. (2008), the requirement for turning range of the cutoff frequency changes from 48 MHz to 172 MHz.

Table 2. Capacitors and transistors Value

Components	C_1 [pF]	C_2 [pF]	C_3 [pF]	G_{mi} [mS]
50 MHz	10	36	71	16
75 MHz	8	24	47	16
100 MHz	5	19	36	16
150 MHz	4	12	24	16
200 MHz	3	9	18	16
Transistor	MT	ST	LT	CT
Sizes[W/L]	115 μ m /0.18 μ m	13 μ m /0.11 μ m	200 μ m /0.18 μ m	200 μ m /0.09 μ m

Figure 3. Third-order chebyshev hybrid tracking low-pass filter proposed by Kwon & Lee (2011).

4.1 G_m Block

In the $G_m - C$ filter design, G_m block plays a critical role to degrade the linearity performance. In HTLPF, the linearity of the filter related on $G_m - C$ part of the filter because the passive filter is linear enough. The requirement of the linear $G_m - C$ filter is a highly linear G_m block.

In the literature, many linearization techniques have been published to improve IIP3 of RF circuit. Source degeneration is the most popular technique which applies an inductor or a resistor (Monsurrò, Pennisi, Scotti, & Trifiletti (2007)). **However, resistor degrades noise performance and inductor increases area consumption.** (Fayed & Ismail (2005)) **introduce a transconductor linearized by MOSFETs in triode region. However, this method uses extra power because of using MOSFET in triode region.**

The MGTR method is one of the best examples to improve the linearity of the transconductor without any degradation in gain, noise Figure, and power dissipation. The current source i_{DS} of the simple common source defined by using Taylor series expansion B. Kim, Ko, & Lee (2000); T. W. Kim et al. (2004)

$$i_{DS} = I_{dc} + g_m v_{gs} + \frac{g'_m}{2!} v_{gs}^2 + \frac{g''_m}{3!} v_{gs}^3 + \dots \quad (2)$$

here the first and the second derivative is defined, with respect to gate-source voltage v_{gs} , by g'_m and g''_m respectively. It is well known that the third-order intermodulation distortion (IMD3) of system is related to v_{gs}^3 . In MGTR, g''_m that has an critical role in defining the performance of linearity, mostly IMD3 and output-referred third-order intercept point (OIP3) can approach zero by MGTR method.

Fig. 4 shows the proposed transconductor used in HTLPF. MGTR method is used to enhance the linearity performance. The main transistors (MT) have fully differential (FD) structure. The second transistor (ST) has pseudo-differential (PD) structure. The control transistor (CT) control the current flowing in the ST. Regarding to $I = K \frac{W}{L} (V_{GS} - V_{th})^2$, controlling the current is approximately similar to controlling the V_{GS} to shift the g''_m of the ST.

Fig. 5 indicates the characteristics of g_m and g''_m of OTA. Fig. 5(a) indicate the the overall g_m which coming from superposing g_m of MT and ST. Fig. 5(b) which is close to zero are achieved by superposing g''_m of MT and ST. The reason that MT is chosen as a FD and ST is chosen as a PD presented in Kwon & Lee (2011).

Figure 4. Proposed transconductor.

Figure 5. Transconductance (g_m) and its second derivative (g_m'').

4.2 Power Efficiency

Power efficiency of the transconductor, G_m/I_D , plays an critical role in the power efficiency of the filter, where G_m is the overall transconductance and I_D is the current consumption of the transconductor. Generally, from G_m/C cutoff frequency of the system can be calculated, hence, high cutoff frequency is required large G_m with reasonable C. Therefore, more current is required. The MGTR method is an effective way to reach high linearity performance with low power consumption Kwon & Lee (2011).

4.3 Linearity and performance improvement

It is undeniable that many variables can limit the linearity performance, by integration of the first derivative of transconductance (g_m') and harmonic feedbacks by parasitic capacitors of MGTR and inductance components, such as wire bonding (Aparin & Larson (2005); T. W. Kim et al. (2004)). The MGTR method can mostly overcome with this phenomenon. **Equation (3) shows the IIP3 of Common-source MOSFET.**

$$IIP_3(2\omega_a - \omega_b) = 1/(6Re[Z_s(\omega)]|H(\omega)||A_1(\omega)|^3|\varepsilon(\Delta\omega, 2\omega)|) \quad (3)$$

$$\varepsilon(\Delta\omega, 2\omega) = g_3 - g_{OB} \quad (4)$$

$$g_{OB} = \frac{(2g_2^2)}{3} \left[\frac{2}{(g_1 + g(\Delta\omega))} + \frac{1}{(g_1 + g(2\omega))} \right] \quad (5)$$

Where $H(\omega)$, $A_1(\omega)$ and $Z_s(\omega)$ are the linear part of the equation and determined by requiring gain and noise figure. The value of $\varepsilon(\Delta\omega, 2\omega)$ depends on Z_S and Z_L at sub-harmonic $\Delta\omega$ and second harmonic 2ω frequency. It is known [60] that, $Z_S(\Delta\omega)$ and $Z_L(\Delta\omega)$ have small value and do not affect $\varepsilon(\Delta\omega, 2\omega)$. On the other hand, $Z_S(2\omega)$ and $Z_L(2\omega)$ have the sufficient value to affect $\varepsilon(\Delta\omega, 2\omega)$ and reduce IIP3. In CS MOSFET, the $g(2\omega)$ is approximately given by equation (6) (B. Kim, Ko, & Lee (2001), Kwon et al. (2009)).

$$g(2\omega) \simeq g_m \times \frac{(1 + 2j\omega C_{gs}Z_1 + 2j\omega C_{gd}Z_2)}{(1 + \omega_T C_{gd}Z_2)} \quad (6)$$

Here Z_1 is the impedance looking into the source and Z_2 is the impedance looking into the load. The ω_T is the unit current cutoff angular frequency defined as $\omega_T = g_m/c_{gs}$. It is well-known by Kwon et al. (2009), g_{OB} reduced, finally the effect of $\varepsilon(\delta\omega, 2\omega)$ on the IIP3 decreased. In equation (6), Z_2 is important for increasing the value of $g(2\omega)$. In the OTA the output impedance is large, thus the effect of the combination of g'_m and the second harmonic feedback might be critical. On the other hand, the capacitors in OTA-C structure make the output impedance small. Therefore, Z_2 in OTA-C structure is small. As a result, the linearity performance of $Gm - C$ Filter, employing MGTR, works well.

4.4 Noise distortion evaluation

From each noise source of HTLPF, such as resistor and transconductor, the overall output noise power spectrum density (PSD) of the HTLPF is achieved. R_1 , G_{m1} and G_{m2} are the noise source of the HTLPF. As a result, the overall output noise PSD of the HTLPF is in Kwon & Lee (2011)

$$\begin{aligned} S_{No,HTLPF} &= S_{No,R1} + S_{No,G_{m1}} + S_{No,G_{m2}} \\ &= H_{HTLPF}^2 \cdot S_{Ni,R1} + H^2 N, G_{m1} \cdot S_{Ni, G_{m1}} \\ &\quad + H_{N,G_{m2}}^2 \cdot S_{Ni, G_{m2}} \end{aligned} \quad (7)$$

Here $S_{Ni,G_{mi}}$ and $S_{Ni,R1}$ are transconductor G_{mi} and input-referred noise PSD

of R_1 respectively. Besides, $H_{N,Gmi}(s)$ and $H_{HTLPF}(s)$ are transfer function from noise source of transconductor G_{mi} to output and transfer function of the HTLPF, respectively.

$$H_{N,Gm1}^2 = H_{N,Gm2}^2 = H_{Biquad}(s) = \frac{(g_{m1}g_{m2})/(C_2C_3)}{(s^2 + sg_{m2}/C_3 + (g_{m1}g_{m2})/(C_2C_3))} \quad (8)$$

Due to the fact that the dominating of $g_{m,ST}$ and $g_{m,LT}$ is less, they can ignored in the calculation. Thus, the NF of third-order low-pass filter is given by .

The NF of HTLPF can be expressed to

$$NF_{HTLPF} \cong 1 + \frac{R_1}{R_s} (1 + \omega_0^2 R_1^2 C_1^2) \left(1 + \frac{1}{Q_{Biquad}^2} \right) \frac{2\gamma}{g_{m,MT} R_s} \quad (9)$$

where $\omega_0 = \sqrt{G_{m1}G_{m2}/C_2C_3}$, $Q_{Biquad} = \omega_0 C_3/G_{m2}$, $g_{m,MT}$ is transconductance of the MT in Fig. 4, and γ presents a noise parameter. The noise effect of ST and CT are ignored because of negligible contribution and operating in subthreshold region. Table 3. shows the specification of hybrid tracking filter.

Table 3. Spacification of Hybrid Tracking Filter

Technology	90 nm technology
Filter type	Third-order chebyshev low-pass filter
Supply voltage	1.2 V
Current consumption	18 mA
Tuning range of cutoff frequency	50 MHz ~ 200 MHz
Attenuation	48 dB @ higher order harmonics 39 dB @ 5th order harmonic 26 dB @ 3rd order harmonic
Output referred third-order intercept point	21.7 dBm
NF	13 dB

5. Design verification and Measurement

The proposed transconductor with **self-biased** MGTR method adopted with third-order chebyshev low-pass filter, to solve the LO harmonics, was tested with Advance Design System in 90 nm technology and compared with single-gate transconductor without STs and CTs transistors shown in Fig. 6. It consumes 21.6 mW with a 1.2 V supply voltage. The calculated frequency response of the filter is illustrated in Fig. 7. Thus, From 50 MHz to 200 MHz frequency response achieved. 26 dB, 39 dB and 48 dB rejection are attained for three, five, and seven times greater than the cutoff frequency of the HTLPF. Therefore, it can support the requirements shown in Table 1. As a result, by using both HRM with mismatch calibration and HTLPF, over 60 dB rejection can be achieved for all odd-order LO harmonics.

Fig. 8 indicates the calculated NF of HTLPF based on $50\ \Omega$ reference is approximately 13 dB in different cutoff frequencies. Fig. 9 plots the linearity performance of the HTLPF with MGTR and single gate transistor. The two-tone, 100 and 105 MHz are created, mixed and used for input of the HTLPF. Fig. 9(c) draws the output versus input power to show the IIP3 of 21.7 dBm in 100 MHz cutoff frequency with 5 dBm improvement compare with Fig. 9(a). Fig. 9(d) shows the IMD3 and third-order LO harmonic rejection that reject IMD3 22 dB more than Fig. 9(b). Table 3. indicates the summary of overall performance of the HTLPF. Table 4. shows the comparison between this work and previous works.

Figure 6. Single-gate transconductor without MGTR.

Figure 7. Frequency response.

Figure 8. Noise figure of different cutoff frequency of filter.

Figure 9. Linearity measurements of third-order chebyshev filter with MGTR and single-transistor transconductor.

Table 4. Comparison with Previous Works

		Kwon & Lee (2011)	Li, Huang, & Hong (2010)	Mobarak, Onabajo, Silva- Martinez, & Sanchez- Sinencio (2010)	Darvishi, Van der Zee, Klumperink, & Nauta (2012)	Proposed Research Work
Technology		0.18 μ m CMOS	0.13 μ m CMOS	0.13 μ m CMOS	65 nm CMOS	90 nm CMOS
Cutoff [MHz]	freq	50-200	70-280	200	300-1200	50-200
IIP3 [dBm]		17.3	7	14	9	21.7
NF [dB]		15	-	-	9.5	13
Filter (N)	order	3	5	2	4	3
single (S) or Differential (D)		S	D	D	S	S
Pdc [mW]		23.4	21	5.2	17.6	21.6

6. Conclusion

To address the LO harmonic mixing problem, which is major problem for ATSC terrestrial digital TV standard, a very linear third-order chebyshev HTLPF is designed with 90 nm CMOS technology. By adopting RC filter with second-order transconductor-C filter, a third-order chebyshev filter is created. The MGTR method with internal biasing circuit is employed to enhance the linearity of the HTLPF. 13 dB NF with 21.7 dBm IIP3, while consuming 18 mA from 1.2 V supply voltage, can be achieved from HTLPF by self-biased MGTR linearization technique. The cutoff frequency of the filter can be tuned from 50 to 200 MHz. By adopting HTLPF with HRM with mismatch calibration circuit, over 60 dB LO harmonic rejection is attained.

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