

# A 50-300-MHz Low power and High Linear Active RF Tracking Filter for Digital TV Tuner ICs

Y. Sun, C. J. Jeong, I. Y. Lee, J. S. Lee, S. G. Lee  
Korea Advanced Institute of Science and Technology

**Abstract**—A low power and highly linear CMOS active tracking bandpass filter is presented to overcome a local oscillator harmonic mixing problem for Digital TV tuner ICs. A transistor linearization technique based on a method of dynamic source degenerated differential pair is adopted to improve the linearity performance. The newly proposed low power high quality factor (Q) biquad and the linearized transistor with negative resistance load (NRL) enables a low power and high Q RF tracking filter design. The total chip area is 0.25 mm X 0.9 mm. The fabricated tracking filter based on the 0.13  $\mu$ m CMOS process shows 48~300 MHz tracking range with 10~50 MHz bandwidth, more than 38 dB 3rd order harmonic rejection, 6 dB unwanted signal rejection@N+6 channel offset, and a maximum IIP3 of 6 dBm at 5 dB gain while drawing 6.4 mA from a 1.2 V supply.

## I. INTRODUCTION

Today's digital TV (DTV) standards, such as advanced TV systems committee-terrestrial (ATSC-T), Open Cable, digital video broadcasting terrestrial (DVB-T), and DVB-C cover a wide range of operating frequencies, from 48 to 860MHz. The tuner, as a key element of DTV, converts received RF signals into digital signals, which can be further processed for the sound and picture. To develop a broadband DTV tuner, there are many challenging technical issues including harmonic mixing, image rejection, dynamic range, and linearity [1]. Unlike narrowband receivers, with broadband tuners, when receiving lower-band channels (48~288 MHz), the harmonics of the LO signal down convert the higher-band channels (288~860 MHz). Therefore, harmonic rejection is an important feature of DTV tuners to secure the down conversion of the lower-band channel signals. Moreover, TV broadcasting environments with multiple strong interferers are another challenge in terms of selectivity and linearity requirements. Those strong adjacent channel signals can saturate the tuner RF front-end or degrade receiver sensitivity by the down conversion of the LO phase noise into the desired channel. For decades, the problems of linearity, harmonic rejection and wide range signal strength have been resolved by the adoption of an external tracking filter in front of the LNA. Such external tracking filters are implemented with coils and varactors, which are bulky, require high tuning voltage and manual tuning, and furthermore, the tuner has to be shielded from outside electromagnetic signals, i.e., CAN type tuners. Therefore, the bulky size, poor temperature characteristics, and manufacturing difficulty have been the long lasting problems of CAN type tuner [2]. Lately, motivated by the need for a smaller size tuner, industries have started to develop more integrated tuner solution, i.e., a silicon tuner, to overcome the deficiencies of the CAN type tuner. A silicon

tuner can offer the advantages such of smaller size, ease of manufacture, and superior thermal stability. With a silicon tuner, the issues that have been resolved by the off-chip tracking filter still remains, but this time, these issues need to be implemented on-chip. The on-chip tracking filter can be implemented as passive or active. Fig.1 shows a typical silicon tuner architecture in which the tracking filter is located after the LNA but before the mixer.

With most of the previously reported silicon tuners, RF tracking filters are based on the LC type, which still requires bulky inductors, capacitors and varactors with high tuning voltage [3], [4]. An active RF tracking filter can be an alternative solution that can provides the advantages of small size, low cost, and on-chip integration. However, the key issues with using an active RF tracking filter for a DTV tuner are poor linearity, high noise figure (NF), and large power consumption. The previously reported on-chip active RF tracking filters cover a tuning range of up to 300MHz with large bandwidth (low Q), but consume a large amount of power [5] [6], and most of them are based on low pass filter type (LPF) which means that the filter provides only the harmonic rejection not the channel selection. This paper presents the very low power integrated RF tracking bandpass filter with high linearity, wide frequency tuning range, and good harmonic and unwanted signal rejection ratio. Section II describes the design details of the proposed Gm-C type RF tracking bandpass filter and Section III discusses the measurement results. Section IV concludes.

## II. ACTIVE RF TRACKING FILTER DESIGN

### A. Filter Type

On-chip active filters can be implemented as active RC, MOSFET-C, Gm-C, or switched capacitor filter types [7]. It is well known that the active RC, MOSFET-C, and switched capacitor filters can provide high linearity due to negative feedback. However, their operating frequency bands are limited due to the limited gain-bandwidth product of the operational amplifier. High frequency operation is possible at the cost of huge power consumption. The Gm-C filters are known to show superior high frequency performance while consuming a small amount of power, and to show good tenability, but linearity is poor due to the open loop operation nature. However, there have been many efforts to improve the linearity of the Gm-C filter to a level comparable to that of active RC filters. Therefore, the Gm-C type filter has been adopted in the proposed RF tracking filter design.

### B. Proposed High Quality Factor (Q) Biquad

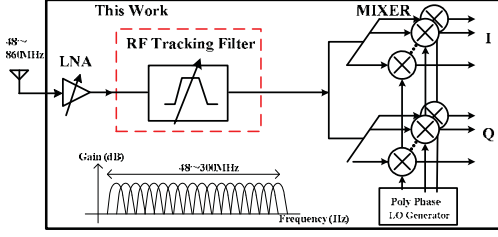


Fig. 1. A Typical block diagram of RF front-end for silicon DTV tuner.

The biquad based filter architecture is chosen to build the tracking filter considering the tenability and the simplicity in analysis and control. Fig. 2 shows the conventional biquadratic structure of a typical Gm-C bandpass filter. Transconductors  $G_{m1-4}$  along with  $C_1$  and  $C_2$  determine the filter's center frequency  $\omega_0$  and Q. The transfer function of the tracking filter is

$$\frac{V_2}{V_1} = -\frac{sC_2G_{m1}}{s^2 + s\omega_0/Q + \omega_0^2}, \quad (1)$$

where the center frequency and Q are

$$\omega_0 = \sqrt{\frac{G_{m3}G_{m4}}{C_1C_2}}, \quad Q = \frac{1}{G_{m2}} \sqrt{\frac{G_{m3}G_{m4}C_1}{C_2}}, \quad (2)$$

and bandwidth is

$$B = \omega_0 / Q = G_{m2} / C_1, \quad (3)$$

In order to provide good harmonic rejection and unwanted signal rejection, the Q factor of the biquad should be high. From (2), it is possible to achieve high Q by adopting large value  $G_{m3}$  and  $G_{m4}$ . However, this method consumes large power, and, moreover, if we want to keep the same center frequency, the capacitor value should also increase, further increasing the chip size. Another method to achieve high Q is to reduce the value of  $G_{m2}$ . To achieve accurate analysis, the parasitic capacitance and finite output resistance of the transconductor are included, as shown follows

$$sC_1 \rightarrow s(C_1 + 3C_o + 2C_i) + 3g_o = sC_{1eff} + 3g_o, \quad (4)$$

$$sC_2 \rightarrow s(C_2 + C_o + C_i) + g_o = sC_{2eff} + g_o$$

where  $C_i$ ,  $C_o$  are effective input and output capacitors which include the parasitic capacitance, and  $g_o$  is the output conductance of the  $G_m$  cell. Including these effects, the more accurate transfer function is shown in (5).

$$\frac{V_2}{V_1} = -\frac{(sC_{2eff} + g_o)G_{m1}}{s^2C_{1eff}C_{2eff} + s[G_{m2}C_{2eff} + C_{1eff}g_o + 3C_{2eff}g_o] + G_{m3}G_{m4} + 3g_o^2 + G_{m2}g_o}, \quad (5)$$

where the updated center frequency and Q are

$$\omega_0 = \sqrt{\frac{G_{m3}G_{m4} + 3g_o^2 + G_{m2}g_o}{C_{1eff}C_{2eff}}}, \quad (6)$$

$$Q = \frac{\sqrt{(G_{m3}G_{m4} + 3g_o^2 + G_{m2}g_o)C_{1eff}C_{2eff}}}{G_{m2}C_{2eff} + C_{1eff}g_o + 3C_{2eff}g_o}$$

Equation (6) proves that even with an ideal transconductor ( $g_o=0$ ), Q could not go to infinite. In order to develop a biquad very suitable for RF tracking filter, the biquad should be low

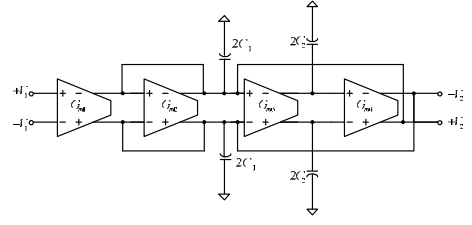


Fig. 2. Conventional biquadratic structure of a typical gm-c band pass filter.

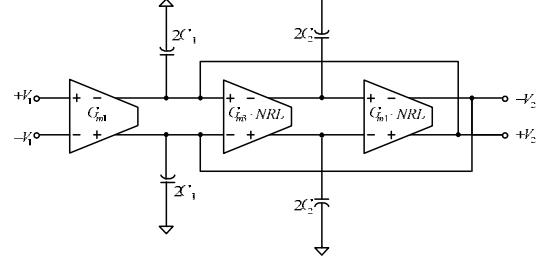


Fig. 3. Proposed low power and high Q biquad used for RF tracking filter.

power, high Q and high linear. With an emphasis on these aspects, we propose a new simple low power and high Q biquad for the RF tracking bandpass filter. The proposed low power and high Q Gm-C biquad is shown in Fig. 3. By removing the  $G_{m2}$  stage and adopting the negative resistance load (NRL) in the Gm-cell design, we both remove  $G_{m2}$  and reduce  $g_o$  value in (6). Therefore, a high Q and low power biquad for RF tracking filter design is achieved. The quantitative analysis is provided in this paper. The  $sC_1'$  and  $sC_2'$  of proposed biquad are

$$sC_1' \rightarrow s(C_1 + 2C_o + C_i) + 2g_o = sC_{1eff}' + 2g_o, \quad (7)$$

$$sC_2' \rightarrow s(C_2 + C_o + C_i) + g_o = sC_{2eff}' + g_o$$

where the center frequency and Q are

$$\omega_0 = \sqrt{\frac{G_{m3}G_{m4} + 2g_o^2}{C_{1eff}'C_{2eff}'}}}, \quad Q = \frac{\sqrt{(G_{m3}G_{m4} + 2g_o^2)C_{3eff}C_{4eff}}}{C_{1eff}'g_o + 2C_{2eff}'g_o}. \quad (8)$$

From (8), also note that,  $C_{1eff}'$  and  $C_{2eff}'$  are smaller than  $C_{1eff}$  and  $C_{2eff}$  respectively. We can find that the Q factor of the proposed biquad is higher than the conventional one. With an ideal transconductor, the Q factor of the proposed biquad architecture can be infinite. Moreover, the center frequency is also slightly higher without increase of the  $G_m$  value. As shown in Fig. 3, there is only one internal node in the biquad architecture, which means that the first and last stages can share the common-mode stability and gain enhancement circuit, thus further simplifying the architecture and also reducing the power. The proposed biquad is very suitable for RF tracking filter design in the aspect of low power and high Q.

Cascaded sections of the two biquads are used to realize a fourth order Butterworth RF tracking filter. Center frequency tuning is achieved with the integrated programmable capacitor bank,  $C_1$ ,  $C_2$ , which can also compensates for the variation of process, supply voltage, and temperature. In contrast with integrated varactors, an integrated capacitor bank enables a higher tuning range and better linearity performance. The

proposed RF tracking filter shows the potential to the whole frequency band tracking filter design.

### B. $G_m$ -cell Design

The Gm-cell is the main building block in Gm-C type filter. Fig. 4 shows the schematic of the Gm-cell used in this work, in which the dynamic source degeneration technique is adopted to improve the linearity [8]. The four cross-connected transistors,  $M_{3-6}$ , operate in linear mode and provide dynamically varying degeneration resistance to the differential pair,  $M_{1-2}$ , leading to nearly constant transconductance to the input signal amplitude variation. As  $v_{in}$  increases from zero, the channel resistance of one of the two degeneration transistors ( $M_3$  or  $M_4$ ,  $M_5$  or  $M_6$ ) is reduced, so that the transconductance stays constant. In order to achieve the optimized linearity, the size ratio between  $M_{1,2}$  and  $M_{3-6}$ , is defined as  $a = (W/L)_{M_{1,2}} / (W/L)_{M_{3-6}}$ . Fig. 5 shows the simulated transconductance (gm) and the gm'' of the Gm-cell as a function of the differential input voltage for various transistor size ratios  $a$ . From Fig. 5,  $a=2$  shows the flattest gm and the smallest gm'' which means that this value gives the best linearity.

In order to achieve high Q biquad which proved foregoing, the negative resistance load (NRL) is adopted in our transconductor design, formed by  $M_7$  to  $M_{10}$ , as shown in Fig. 4. This NRL is very suitable for low supply voltage design, since it does not need stack transistors which would introduce extra internal nodes. Moreover, our design can maintain high frequency performance with no generation of parasitic poles. The operation of this load is such that  $M_9$  and  $M_{10}$  introduce positive feedback between the nodes  $V_{o+}$  and  $V_{o-}$  and a negative resistance is produced that will be used to compensate for the parasitic output resistance of the two differential output nodes.

The common mode feedback circuit, formed by  $M_{cf1-4}$ , is used to stabilize the DC operating point and bias the circuit properly. The circuit has enough phase margins and good linearity after adopting a source degeneration resistor  $R_c$ .

Other advantages to the Gm-cell are shown in Fig. 4. The  $G_m$ -cell exhibits good high-frequency performance as no additional internal nodes are created in the circuit. In addition, the input impedance of the  $G_m$ -cell is highly capacitive, and can easily be incorporated into the integrating capacitors of the filter.

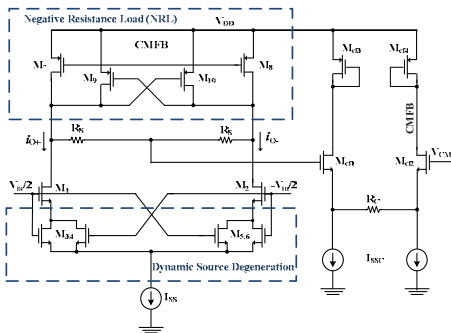


Fig. 4. Schematic of Gm-cell with negative resistance load used in the proposed RF tracking filter.

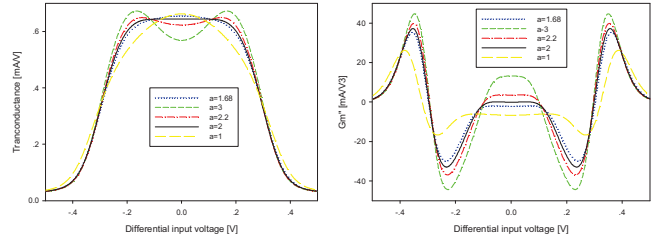


Fig. 5. Simulated (a) gm and (b) gm'' of the Gm-cell as a function of input voltage for various size ratios.

## IV. MEASUREMENT RESULT

The proposed RF tracking filter is fabricated using the 0.13  $\mu\text{m}$  CMOS process. For the measurement, a buffer is added at the output and the filter dissipate 6.4 mA excluding the buffer from a 1.2 V supply. Fig. 6 shows the chip micro-photograph which includes the output buffer for measurement with a size of 0.25 mm x 0.9 mm. Fig. 7 shows the measured frequency characteristic of the filter for various center frequencies. As can be seen in Fig. 7, the proposed RF tracking filter shows tuning range of 48~300MHz. With proposed high Q biquad, the 3-dB bandwidth ranges from 8 to 50MHz. Measured 3rd-order harmonic rejection ratio (HRR) and unwanted signal rejection ratio (URR) @ N+6 channel offset versus center frequency is shown in Fig. 8. More than 35 dB HRR and 6 dB URR are achieved. A two-tone test with 10 MHz separation is applied to obtain the IIP3. Fig. 9 shows the measured IIP3 versus the center frequency for the input signals with 10MHz offset at -23dBm power. As can be seen in Fig. 10, the filter IIP3 varies from 1.9 to 6 dBm. Fig. 11 shows the measured NF over the 48~300 MHz center frequency at the 50ohm source impedance.

To compare the performance of the proposed filter with that of other reported filters, a figure-of-merit (FOM), defined in [15], is adopted. Table I compares the performance of the proposed filter with that of other reported filters. This FOM does some injustice to filters with high quality factor, to band pass filters, and to filters with good blocking performance; this design has all these properties, so the comparison is conservative. However, as can be seen in Table I, the proposed on-chip active RF tracking filter still shows good FOM with lowest power consumption.

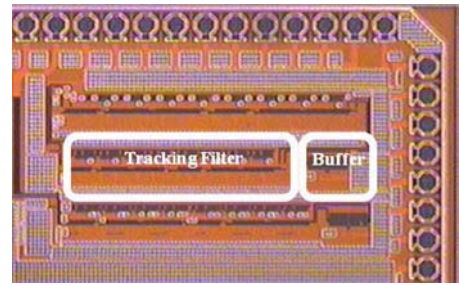


Fig. 6. Chip micro-photograph of the proposed RF tracking filter

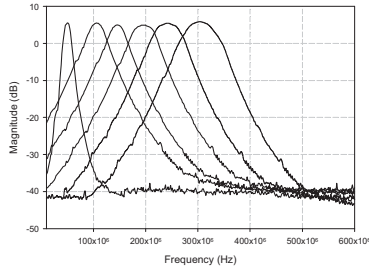


Fig. 7. Measured frequency response of the RF tracking filter.

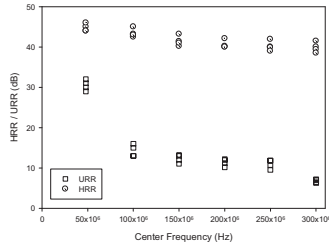


Fig. 8. Measured third order HRR and unwanted signal rejection ratio @ N+6 channel offset versus channel frequency with different chips testing.

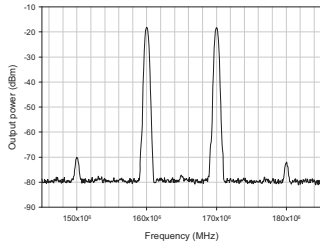


Fig. 9. Measured two tone test spectrum with 160 MHz and 170 MHz input, at 165MHz center frequency, input power is -23dBm.

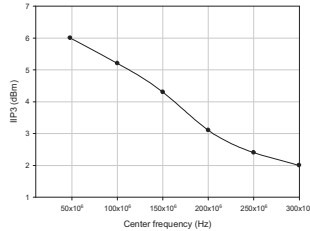


Fig. 10. Measured linearity performance over the frequency range.

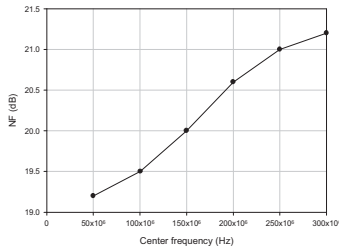


Fig. 11. Measured NF over the frequency range.

## V. CONCLUSION

In this paper, a low power on-chip active RF tracking filter was proposed and implemented. The low power and high Q factor with good linearity performance are based on the proposed high Q biquad with optimized Gm-cell design. The

TABLE 1  
PERFORMANCE SUMMARY AND COMPARISONS

Ref	This work	[6]	[9]	[10]	Units
Tech.	130nm	180nm	250nm	250nm	nm
Filter type	BPF	LPF	LPF	BPF	-
HRR	40	30	-	-	dB
URR	6~30	No			
Freq range	50~300	50-300	80-200	30-120	MHz
OIP3	11	16.9	18.8	10.1	dBm
N	4	3	7	8	-
NF	20	14	-	-	dB
Power	7.6	72	210	120	mW
FOM	120	152	-	-	-
(FOM*)	(11926)	(3675)	(1264)	(327)	-

NF listed in this table is average values for fair comparison.

$$FOM = OIP3 \cdot f_{MAX} \cdot TR \cdot N / (F - 1)Pdc [6]$$

FOM\* (without NF)

proposed RF tracking filter, implemented with the 0.13  $\mu$ m CMOS process requires no off-chip components. Measurement results show a 50~300 MHz frequency tuning range with narrow bandwidth (8~50 MHz). The average NF, the maximum OIP3, and the power consumption (without buffer) are 20 dB, 11 dBm, and 7.6 mW (from a 1.2 V supply), respectively which shows the lowest power consumption among all published tracking filters.

## ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. R0A-2007-000-10050-0).

## REFERENCES

- [1] Mark Dawkins, Alison Payne Burdett, and Nick Cowley, "A single-chip tuner for DVB-T", IEEE journal of solid-state circuits, vol.38, no. 8, August 2003.
- [2] Alvin Wong, "Silicon TV Tuners Will Replace Can Tuners as Transistors Replaced the Vacuum Tube",
- [3] J.R.Tourret et al., "SiP tuner with integrated LC tracking filter for both cable and terrestrial TV reception," IEEE Journal of Solid-State Circuits, 42, (12), pp. 2809-2821, Dec. 2007.
- [4] Olivier Jamin, Vincent Rameau, Frederic Mercier, Insa Meliane, "On-chip auto-calibrated RF Tracking Filter for Cable Silicon Tuner," in Solid-State Circuits Conference, ESSCIRC 2008. 34th European, Sept.2008 pp.158-161.
- [5] Gupta, S. Lerstaveesin, D. Kang, and B-S. Song, "A 48-to-860MHz CMOS direct-conversion TV tuner," ISSCC 2007, pp. 206-207.
- [6] Kuduck Kwon, H.T Kim, and Kwyro Lee, "A 50-300-MHz Highly Linear and Low-Noise CMOS Filter Adopting Multiple Gated Transistors for Digital TV Tuner ICs," in IEEE Trans. Microwave Theory and Techniques, Feb. 2009, Volume: 57, Issue: 2, pp.306-313.
- [7] R. Schaumann and M. E. Van Valkenburg, Design of Analog Filters. Oxford, U.K.: Oxford Univ. Press, 2001
- [8] V. Prodanov, G. Palaskas, J. Glas, and V. Bocuzzi, "A CMOS AGC-less IF strip for Bluetooth," Proc. IEEE 27th European Solid-State Circuits Conf, pp. 488-491, Sep. 2001.
- [9] S.Dosho, T. Morie, and H. Fujiyama, "A 200-MHz seventh-order equiripple continuous-time filter by design of nonlinearity suppression in 0.25- $\mu$ m CMOS process," IEEE J. Solid-State Circuits, vol. 37, no. 5, pp. 559-565, May 2002.
- [10] G. Bollati, S. Marchese, M. Demicheli, and R. Castello, "An eighthorder CMOS low-pass filter with 30-120 MHz tuning range and programmable boost," IEEE J. Solid-State Circuits, vol. 36, no. 7, pp. 1056-1066, Jul. 2001.