# 2.5 V 35 dBm IIP3 75 MHz sixth-order active RC filter

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A differential sixth-order Butterworth Sallen-Key lowpass filter in 0.25 µm SiGe BiCMOS, using a 2.5 V supply, is presented. The filter has a 75 MHz cutoff frequency and an attenuation of more than 20 dB at a stopband frequency of 148 MHz. The third-order intercept point (IIP3) is 35 dBm, providing excellent linearity.

*Introduction:* A differential sixth-order Butterworth Sallen-Key lowpass filter is used as a reconstruction filter for new generation power line transmitters [1]. 0.25 µm SiGe BiCMOS was chosen for a high-performance broadband powerline front-end IC design. To avoid the disturbance of other available services, deep notches are needed in a multicarrier scheme, leading to a high linearity requirement. An active RC filter uses operational amplifiers (opamp) in combination with resistors and capacitors to provide a LRC-like behaviour.

*Filter design:* The Sallen-Key filter is a good choice when gain accuracy is important. A unity gain stage is used with a low quality factor $Q$. A high $Q$ response would suffer from additional noise caused by peaking. Advantages of the unity gain operation are the inherent stability of the feedback loops around the unity gain buffer and the low $Q$ sensitivity to resistor and capacitor variations.

A Butterworth response was chosen owing to its small group delay variation and monotonically increasing attenuation with frequency in the stopband. The aim of the filter is to remove unwanted frequencies after DAC. With an input signal bandwidth extending to 60 MHz and a DAC sample rate of 208 Msps, the first aliasing image would be at 148 MHz and must be attenuated by more than 20 dB as required for the application. A disadvantage of a RC filter is that the capacitive and resistive elements suffer from process variations, resulting in different cutoff frequencies. The attenuation at the stopband frequency $f_s$ (148 MHz) is specified as 20 dB, so the minimum order $N$ for a Butterworth approximation fulfils $-20N\log(f_s/f_{BW}) > 20$ dB. According to this equation (with $f_{BW}$ 60 MHz), a filter order of three would be sufficient. However, simulations showed that capacitor and resistor variations with temperature and process corners require a sixth-order filter (with a cutoff frequency of 75 MHz) to meet the specification. Fig. 1*a* shows the proposed sixth-order Sallen-Key lowpass filter. It consists of a cascade of three second-order sections. Lower $Q$ stages are placed ahead of higher $Q$ stages to prevent opamp output saturation due to high gain peaking and to attenuate high-frequency out-of-band signals and input noise. High linearity is obtained, up to high frequencies, by feedback linearisation of the unity gain closed-loop buffers [2].

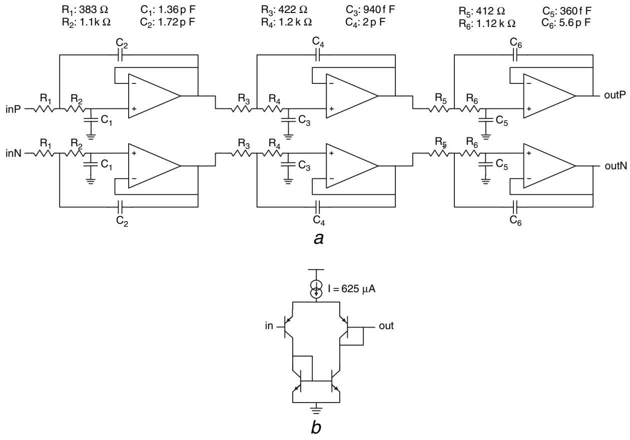

**Fig. 1** *Sixth-order differential Sallen-Key filter*

*a* Schematic diagram
*b* Unity gain buffer

The conventional approach for a Sallen-Key filter has a single-ended output. However, a fully differential implementation was chosen, because a differential design can halve the signal swing and lower the IM3 (third-order intermodulation) distortion by 12 dB. A straightforward way to implement a differential filter is to use two matched single-ended active filters. Fig. 1*b* shows the unity gain buffer. The unity gain buffer, with an open loop gain bandwidth product of 11.64 GHz, is a collector-coupled differential pair with an inverted input terminal and output terminal short circuit [3]. Thanks to the use of a closed-loop gain stage, a low gain error is achieved. The mismatch between both paths is low enough to be able to take advantage of differential signalling. The DC-offset caused by mismatch would be no problem for the application because AC coupling is used and because the desired frequencies are above 1.6 MHz [1]. An additional advantage of this single-ended opamp is that it needs no common-mode feedback circuit. The optimum output common-mode voltage is 900 mV and it provides the best linearity (highest open-loop gain). Choosing the R and C values requires a trade-off between noise, linearity and power consumption. The resistors in the filter will generate thermal noise, so one would like to minimise the resistance where noise voltage is important (all resistors are smaller than 1.2 kΩ). However, for the same cutoff frequency, if the resistance is decreased the capacitance has to increase. There are a number of disadvantages in increasing the capacitances. First, the area will increase. Second, the capacitors C$_2$, C$_4$ and C$_6$ will load down the amplifiers. This decreases the slew rate of the amplifier, and the increased current to drive the capacitor will increase the distortion and the power dissipation. Consequently, the selection of the R and C values was an iterative process using Cadence to simulate the circuit performance and FilterPro [4] to calculate different sets of R and C values. The implemented values can be found in Fig. 1*a*. The noise of the filter is very low and mostly determined by the resistors.

*Experimental results:* Fig. 2 shows the measured AC characteristic of the filter. The 3 dB bandwidth of the filter is 75 MHz and the attenuation for the stopband frequency of 148 MHz is 26 dB. The attenuation in the passband (0.7 dB) is due to losses in the test setup (de-embedding the filter gives a passband attenuation of 0.16 dB). In Fig. 3 the IM3 is shown for different input signals in function of the frequency. For example, for two differential input tones of −2 dBm (4 dBm input power) spaced at 10 kHz around 60 MHz, the IM3 distortion is about −58.17 dBc. Fig. 4 shows the measured two-tone third-order input referred intercept point (IIP3), which is 35 dBm, providing very high linearity. The input referred noise is −144.63 dBm/Hz or 13.122 nV/sqrt(Hz) at 10 MHz. This is well below the typical power line noise floor of −130 dBm/Hz. The circuit uses a die area of 0.169 mm$^2$. The power consumption of the filter is 15 mW at 2.5 V supply. Table 1 summarises the measured performance of the filter, which is compared with [5–7]. The presented filter provides a higher bandwidth with a higher filter order, a significantly, higher IIP3, a smaller area and low noise compared to [5–7].

The power consumption is higher than [5–7]; however, this is a less stringent requirement for a power line front-end (and the bandwidth is 3–14 times higher). By using some extra power, the linearity has been increased significantly, this is the main issue for multicarrier power line communications.

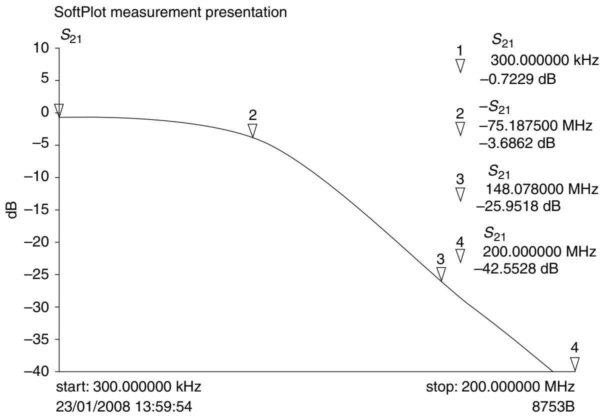

**Fig. 2** *AC characteristic*

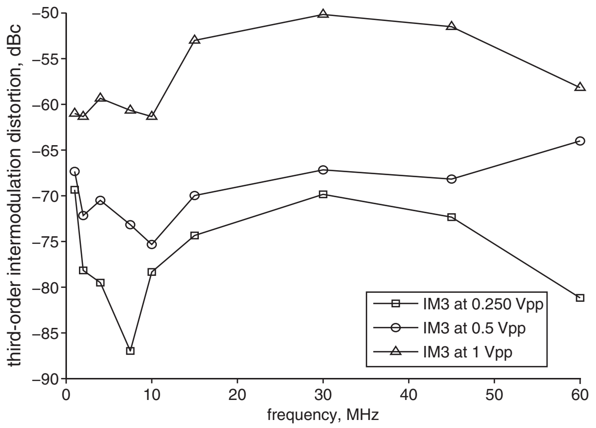

**Fig. 3** *Third-order intermodulation distortion*

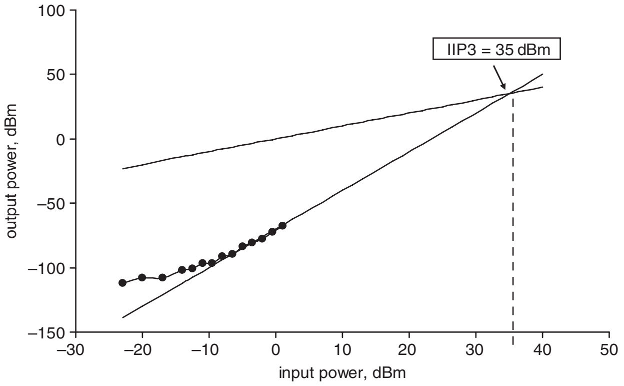

**Fig. 4** *Two-tone test at 60 MHz*

**Table 1:** Comparison of filter implementation

| Reference | [5] | [6] | [7] | This work |
|---|---|---|---|---|
| Technology | 0.12 μm CMOS | 0.18 μm CMOS | 0.13 μm CMOS | 0.25 μm SiGe BiCMOS |
| Filter order | 5 | 4 | 5 | 6 |
| Area (mm$^2$) | 0.25 | 0.52 | 0.20 | 0.169 |
| Supply (V) | 1 | 1.8 | 1.5 | 2.5 |
| Power consumption (mW) | 6.1 | 4.1 | 11.3 | 15 |
| DC-gain (dB) | 0 | − 3.5 | 2 | 0 |
| BW (MHz) | 5 | 10 | 19.7/8.9 | 75 |
| IIP3 (dBm) | 20 | 17.5 | 18.3 | 35 |
| Noise (nV/sqrt(Hz)) | x | 7.5 | 30 | 13.2 |

*Conclusions:* A 70 MHz sixth-order Butterworth active RC filter is presented. A very high linearity (IIP3 35 dBm, IM3 below −50 dBc for 1 Vpp up to 60 MHz) and low noise (13 nV/sqrt(Hz)) has been achieved. Compared to previous publications, the presented filter consumes a lower area and achieves a much higher linearity, notwithstanding a higher bandwidth and higher filter order.

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