UNIVERSITÀ
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Final Report

High bandwidth Base-band filter design

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First Design: *High linear output buffer for Mixer first receiver*

Figure1 shows an inverter-based amplifier used as a buffer after the baseband filter in a mixer first receiver. By keeping low the overdrive voltage for Mn transistors and using High V_{TH} for Mcm transistors, all the transistors work in the saturation region. So, in the differential mode, a high gain of $(gm_p+gm_n).(ro_p||ro_n)$ is achieved where ro_p and ro_n are the output impedance of Mp and Mn respectively. For a common mode input signal, Mcm offers a low output impedance of $1/gm_c$ and low common-mode voltage gain gm_p/gm_c. The circuit is supposed to sink 12 mA current (Ibias) and provide sufficient linearity.

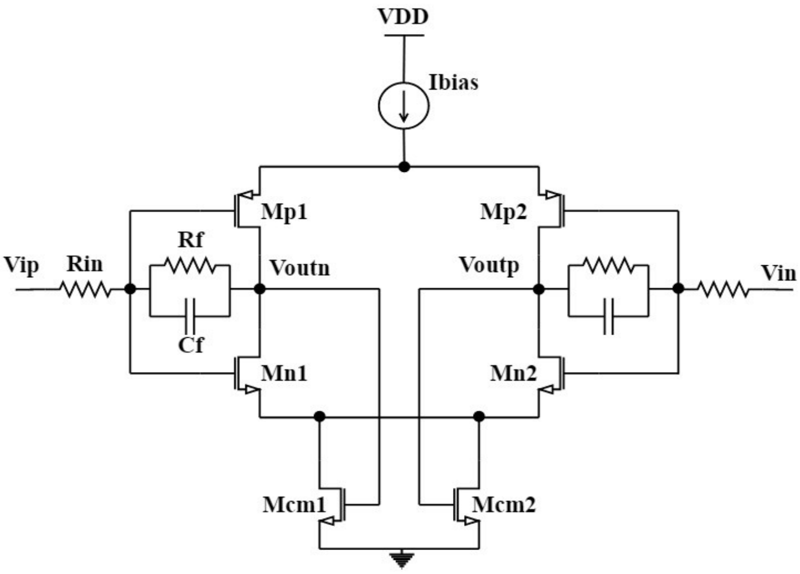

Figure1: Output buffer of a mixer first receiver

The post-layout design shows 120 MHz bandwidth with IIP3 more than 34 dBm for in-band (f1, f2=50 and 90 MHz) and out-of-band (f1, f2=500 and 990 MHz) tones. Figure2 shows the small contribution of noise at the buffer input.

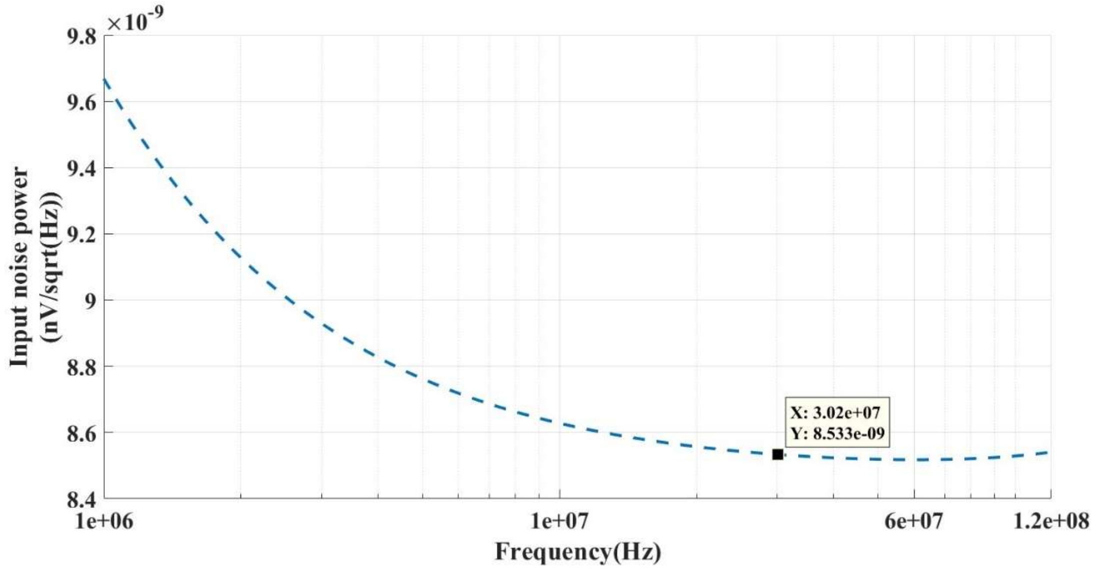

Figure2: Input noise power of buffer

Second Design: *High linear, low power first order base-band filter*

Figure 3 shows a saw-less current mode receiver. The output current of LNTA which is down-converted to base-band using a passive mixer is converted into voltage using TIA by doing first-order filtering on the signal. The TIA structure is a closed-loop system composed of an Operational *Trans-Conductance Amplifier (OTA) with a capacitive feedback load.* TIA design aims to achieve a high gain in the desired signal bandwidth to suppress the noise coming from the following stages and provide a high out-of-band attenuation to reject large interferers. So, the TIA's input impedance, noise, and linearity can limit the overall receiver chain performance. Low input impedance is necessary to keep the voltage swing sufficiently small at the output of the mixer and reduce the modulation on the mixer's switch when large blockers appear.

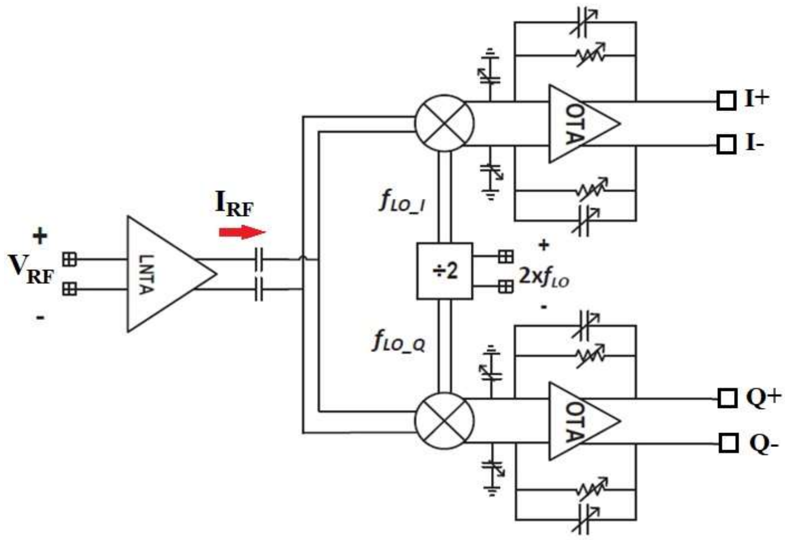

Figure3: current-mode receiver

The conventional approach to bring down the input impedance and improve linearity is putting a big shunt capacitor, *C*in (in the order of hundreds of pF) at the TIA virtual ground node as shown in Figure 4. A big capacitor at the TIA input can serve several purposes:

- Bypassing the clock harmonics signal in mixer's output.
- By lowering signal swing in TIA's input, it can improve the linearity (IIP2 and IIP3) of mixer with strong OOB interferers.
- Improving the TIA out-of-band (OOB) IIP3 by filtering the high-frequency down-converted interferers.

In addition to increasing the chip area, such a big capacitor can also inject more noise to the TIA's output. By inserting input-referred OTA noise voltage in Figure 5, the noise transfer function (NTF) to the TIA output follows equation bellow:

$$|NTF| = \left(1 + \frac{R_f}{R_{mix}}\right)^2 \left|\frac{1 + s(R_f || R_{mix})C_{in}}{1 + sR_fC_f}\right|^2$$

where, *Rmix* shows the mixer output impedance.

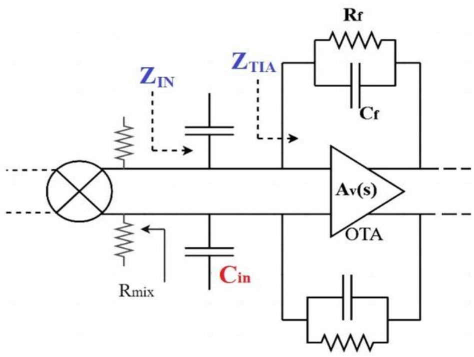

Figure4: Using big input capacitor (Cin) to decrease input impedance

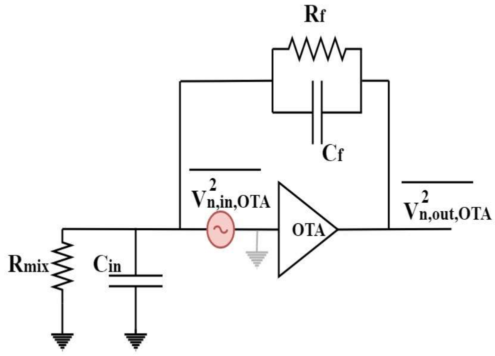

Figure5: OTA's Noise model in TIA

High Bandwidth OTA Design:

As aforementioned, the conventional approach to improve the linearity of the mixer and TIA was putting a big capacitor, for example 100 pF at the TIA's input which can limit the bandwidth dramatically. So, to extend the bandwidth and improve the linearity of the circuit by decreasing *Cin* simultaneously, an OTA with sufficiently high gain in the desired bandwidth is needed to provide a low input impedance, Z_{TIA} and input swing voltage.

A multi-stage OTA is needed to boost the effective transconductance (Gm) of the OTA and provide high gain and bandwidth TIA. The stability is the main challenge for designing the multi-stage OTAs. The traditional approach to compensate a multi stages amplifier is miller technique which provides stability by bringing down the dominant pole and pushing non-dominant poles to higher frequency to improve phase margin of the system. In this approach to extend the bandwidth, we need very high *Gm* stages which increase our power consumption a lot. Another interesting approach is adding some zeroes (by RC network) to different nodes of the circuit to compensate the phase behaviour and make the circuit stable, but the maximum achievable bandwidth is limited with parasitic capacitors.

To extend the bandwidth and decrease the parasitic capacitors effect of multi stages OTA, the parallel approach was proposed as shown in Figure6. In the low frequency range, only the main path conducts the signal, so there are three stages with three effective poles. By going to the middle-frequency range, one feed-forward path will be active and bypasses two first stages in main path, so only two stages in this frequency range are working effectively, it is like a zero was added to the system. Finally, at higher frequency closed to unity gain bandwidth, the second auxiliary path bypasses all other branches, so there is only one stage active that ensures the system stability.

Proposed structure: using local feedback (LFB)

With several branches in parallel together, the power consumption of this structure is the main issue. Figure7 explains the idea to save the power. The system has three stages in main path and two stages in local feedback path (LFB). By sharing the first stage between the main path and LFB path, we boost the FFW circuit's *Gm* instead of using only one power-hungry stage there.

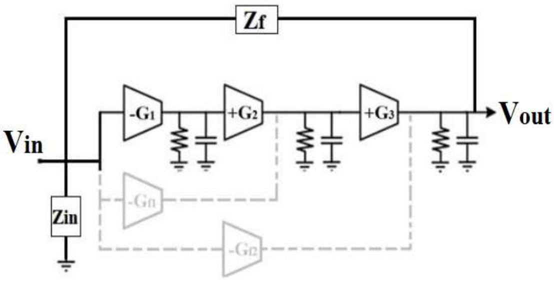

Figure6: Parallel approach to compensate multi stages OTA for high bandwidth application

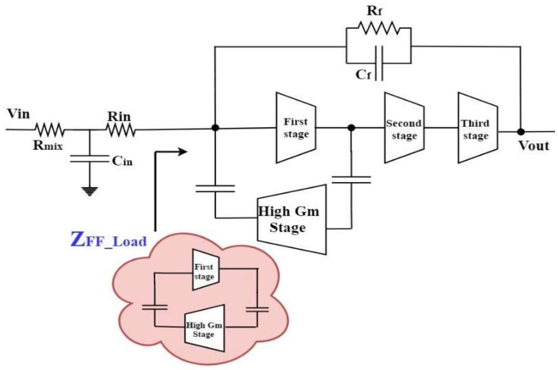

Figure7: LFB approach to enhance frequency response

As mentioned, in the low frequency, the main path is active, and in the high frequency, the LFB one is dominant. Since the unity-gain bandwidth of the system determines by the LFB path, we need to have a noticeable *Gm* in this path, so we are looking for a high *Gm* stage there. The first stage is a P-N cascode structure used to boost the gain and gm. By doubling the gm in P-N structure, the power consumption and also the noise contribution of the first stage will be decreased. The second stage has doublets pole-zero which improves the bandwidth and phase behaviour. The output stage is a push-pull circuit that benefits the common-mode circuit to set the output node to $VDD/2$. The ac coupled high-Gm stage has three stacked P-N stages can multiply circuit transconductance by a factor of six. Figure8 shows different stages' circuit.

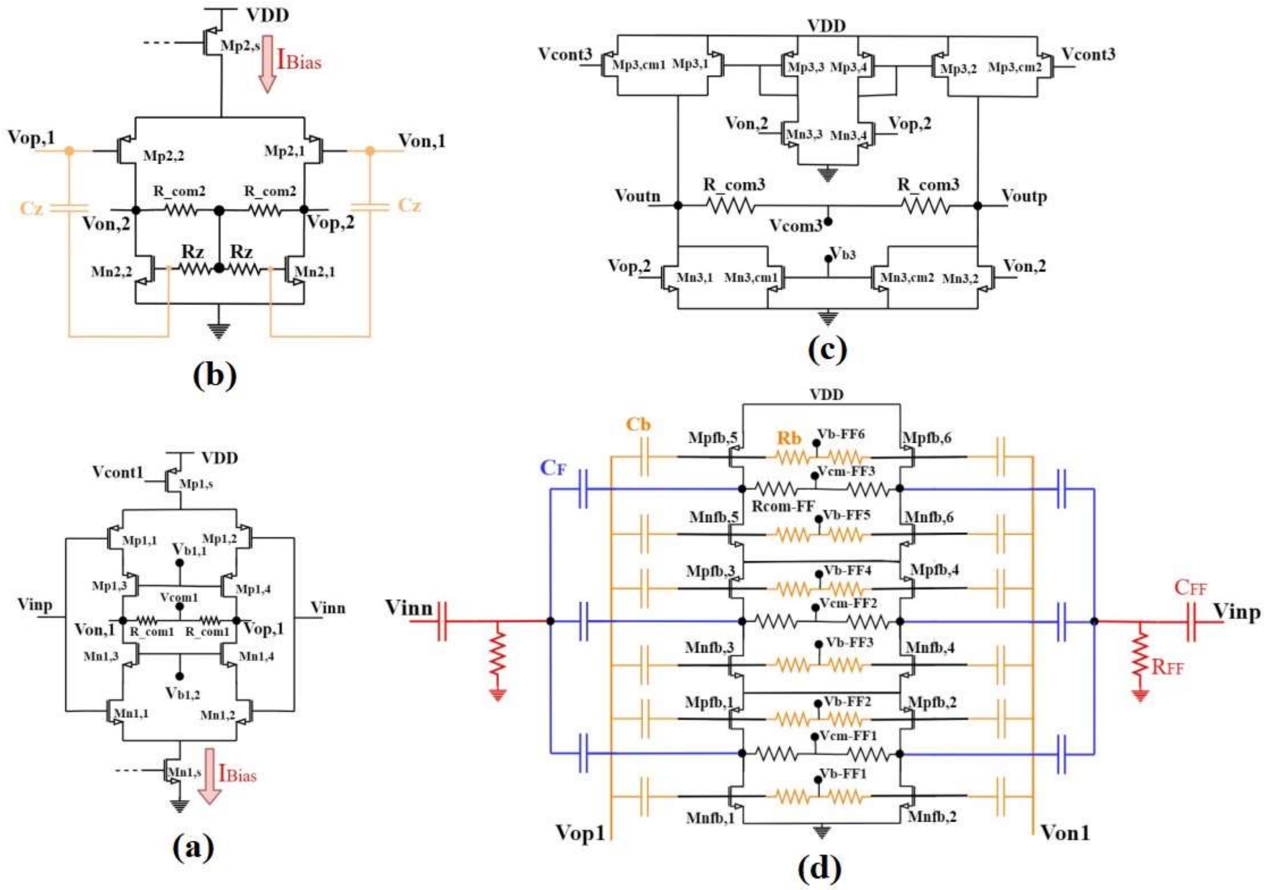

Figure8: (a)First stage, (b)second stage, (c)third stage, (d) high Gm stage

Post-Layout results:

The TIA was fabricated by tsmc 28 nm protocols. The whole occupied area is around 0.018 mm^2 thanks to decreasing input capacitor to 8 pF. TIA has 80 MHz bandwidth with less than 4 mw power consumption in V_{DD}=1.8 v. Figures 9 and 10 show the G-loop response and input referred IP3 of TIA respectively.

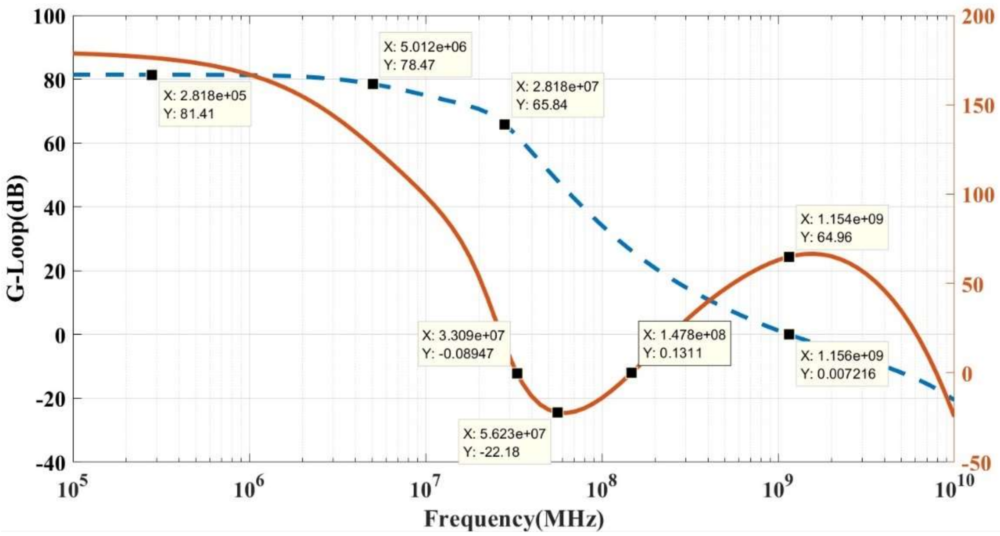

Figure9: G-loop response of TIA

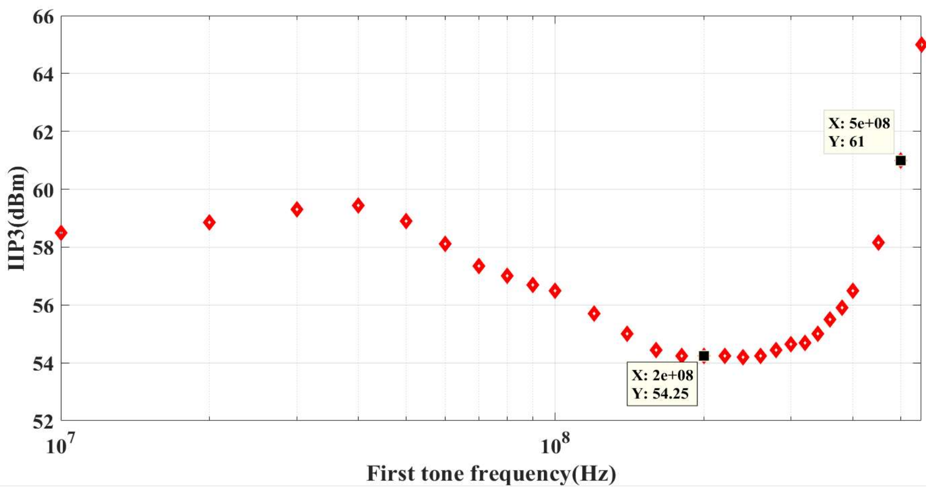

Figure10: Linearity behaviour of TIA

G-loop shows the phase goes under zero degree in some frequency range and it seems that the system is unstable. By looking at unity gain bandwidth frequency at 1.15 GHz, the phase margin is around 65 degree, so the system experiences a conditional stability situation that helps to system linearity with noticeable in-band (IB) and out-of-band (OOB) IIP3 more than 54 dBm. To give a number to circuit quality, the figure of merit (FOM) for TIA defined as below is around 188 dBJ^{-1}.

$$FOM=2/3(OOB\ IIP3 - Noise) + 10\log(N.BW/Pw)$$

Where N is the filter's order.

Third Design: *High bandwidth Rauch filter for 5G application*

Figure11 shows a current mode receiver for 5G application with two modes for base-band filters. The low frequency mode filter is a third order base-band filter composed of a Rauch filter plus a TIA as shown in Figure12. The filter has the maximum bandwidth 200 MHz which can be set to 25 MHz and gain variation possibility by changing TIA gain.

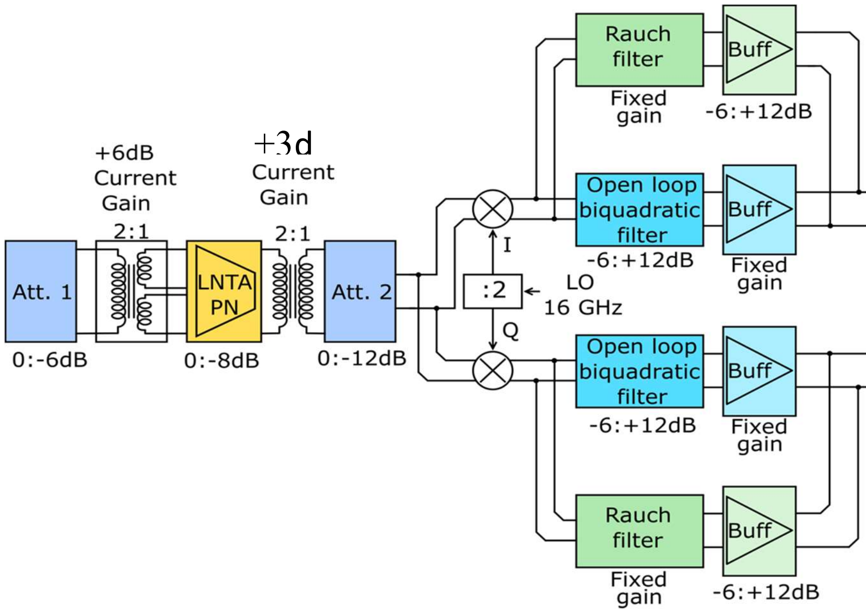

Figure11: Rauch based third order filter in a current mode receiver for 5G

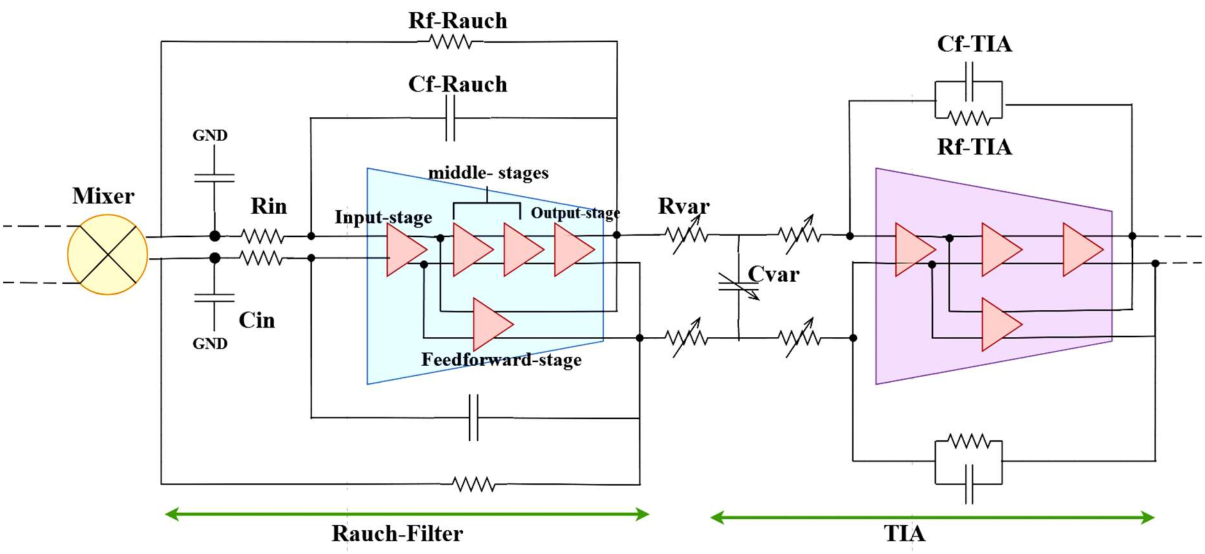

Figure12: The third order base-band filter

The TIA and Rauch filter's cores have OTA with three and four stages respectively in the main and one stage in the feed-forward path. Both use the same concept for high bandwidth design mentioned in previous section. Figure 13 and 14 shows filter bandwidth and gain variation respectively in whole receiver chain.

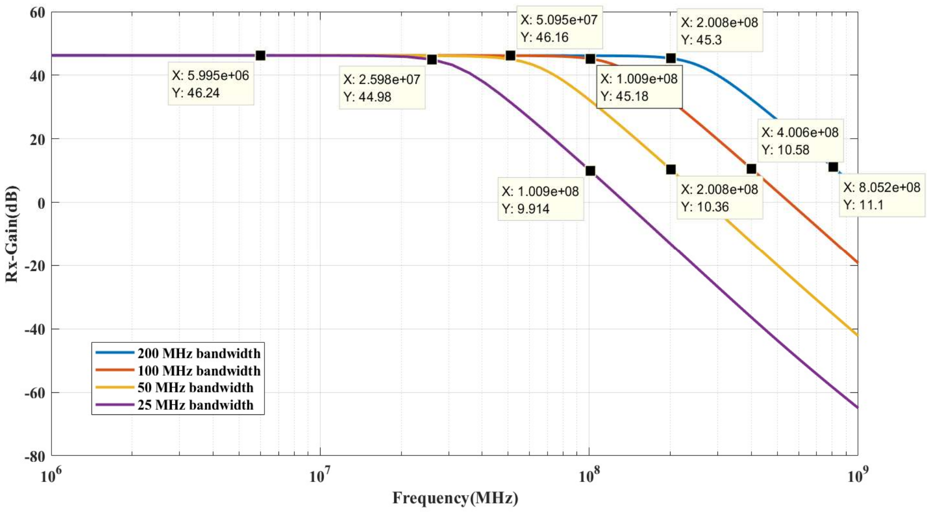

Figure13: Filter's bandwidth variation from 200MHz to 25 MHz in receiver

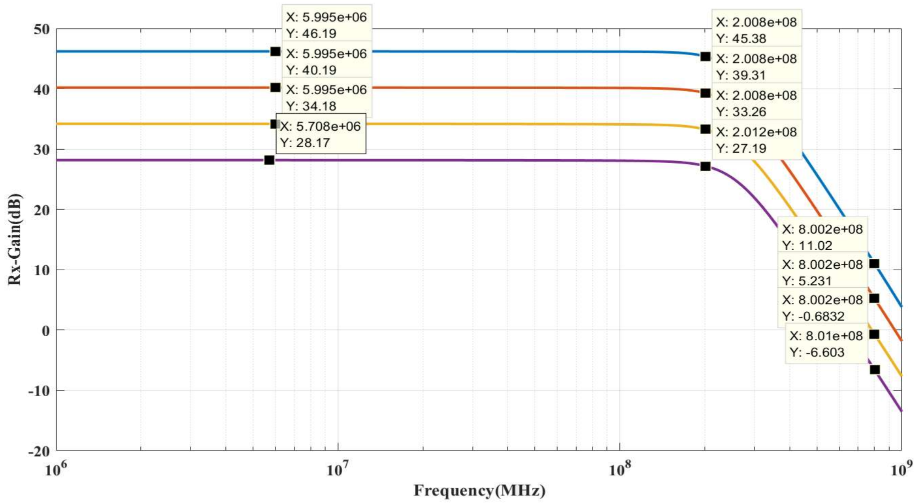

Figure14: Filter's gain variation by 18 dB in receiver

The measurement result:

The circuit fabricated in 28 nm tsmc technology is composed of a Rauch filter and simple output buffer (with 6mA current sinking) as shown in Figure15. The switch provides 13 dB gain variation.

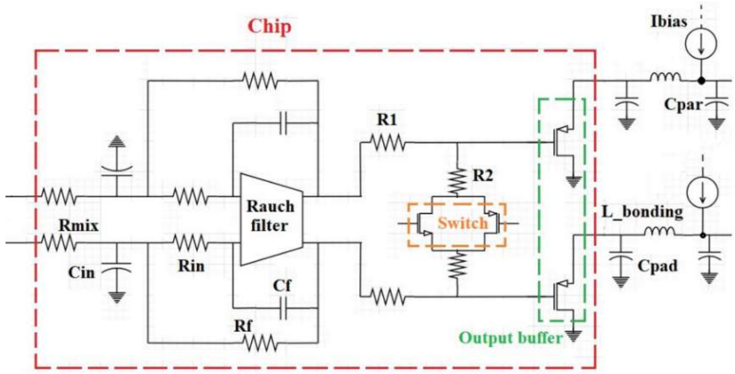

Figure15: The fabricated Rauch filter

The circuit consumes 5.2 mA at 1.5 v supply. Figure16 shows the filter response in measurement and post-layout simulations in high-gain and low-gain mode, the circuit shows around 16.5 dB and 3.6 dB gain respectively.

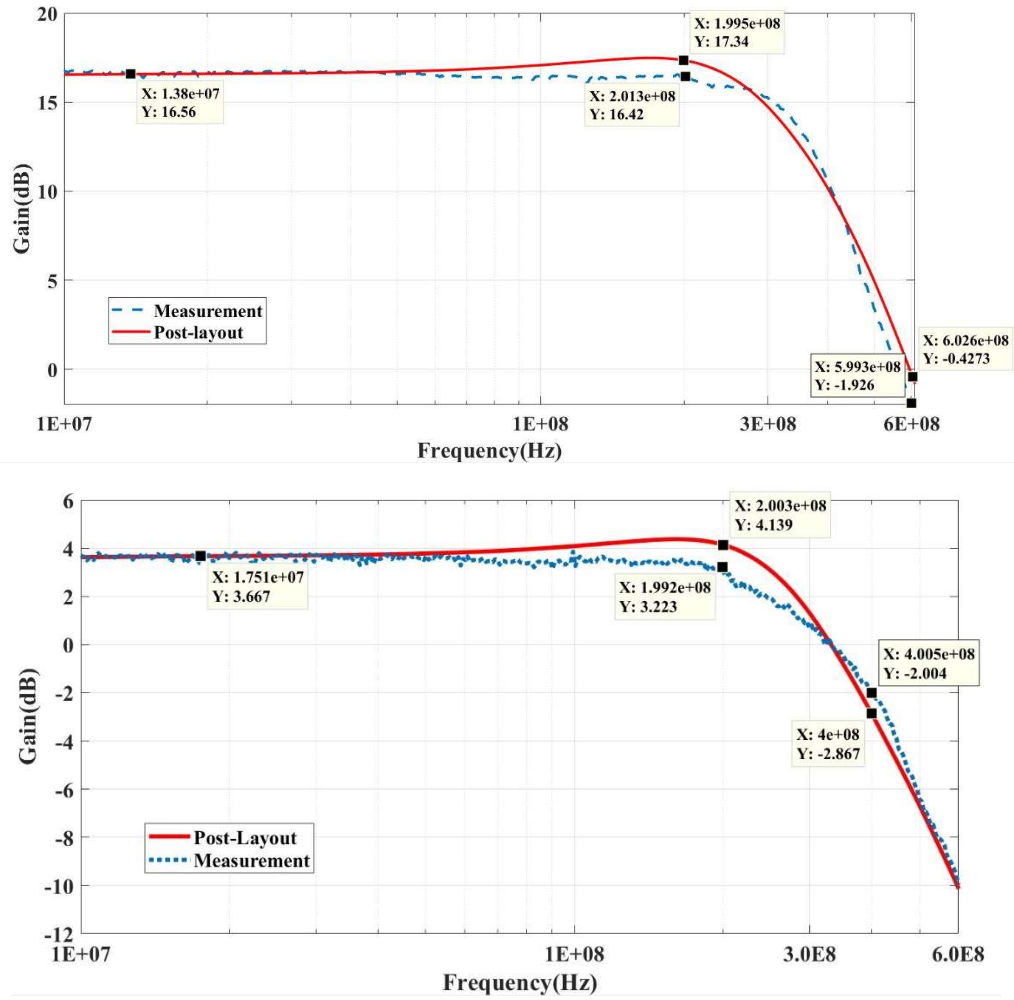

Figure16: Filter frequency response in high-gain and low-gain mode

The output noise measurement almost follows the post-layout simulation perfectly as shown in Figure 17.

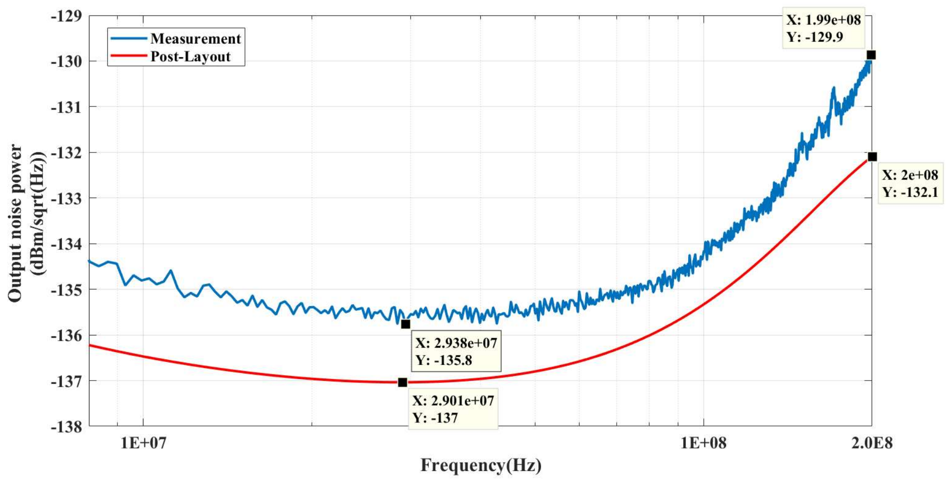

Figure17: Output noise power of Rauch filter

The minimum OIP3 considered in this project for base-band filter is 15 dBm. The measurements at bandwidth edge show +14.3 dBm (with f1, f2 at 180 and 190 MHz) and +17.2 dBm (with f1, f2 at 300 and 430 MHz) in low-gain mode. The 1-dB compression point is around Pin= -4 dBm.

Conclusion:

Base-band filter design with sufficient linearity is a challenging issue in the high bandwidth new generation application. In two filters designed in this report, the goal was increasing the bandwidth and improving the linearity in acceptable power consumption. The post-layout and measurement results met the required specifications for 80 MHz first order and 200 MHz Rauch filter respectively.

Publication:

M. D. Salehi, D. Manstretta, and R. Castello, "A 150-MHz TIA with unconventional OTA stabilization technique via local active feed-back," in 2019 15th Conference on PhD Research in Microelectronics and Electronics (PRIME), July 2019, pp. 5–8

Credits:

University of Pavia courses: 12

Doctoral school, of research institutes, Intensive courses: 12

PhD seminars: 4

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Research seminars: 1.5

Total: 30.5