A 14.7mW Blocker-Tolerant Wideband Receiver Using a Transformer-Based N-Path Passive-LNA and a 2nd-Order TIA Achieving 110MHz RF-BW and 13dBm OB-IIP3

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2024 IEEE Asian Solid-State Circuits Conference (A-SSCC) | 979-8-3503-7632-6/24/$31.00 ©2024 IEEE | DOI: 10.1109/A-SSCC60305.2024.10849137

To underpin high-speed wireless communication in the sub-6GHz bands, especially for the 5G New Radio (NR) and towards the 6G standards, RF receivers (RXs) are evolved to support a wide signal bandwidth (BW) (e.g. 100MHz in 5G-NR), cover a wide RF spectrum, and become more resilience to out-of-band (OB) blockers. In [1], the mixer-first RX (Fig. 1, upper) supports a wide range of RF and has a high linearity (27dBm OB-IIP3) by delaying the signal amplification to baseband (BB). This topology yet sacrifices the NF (5.5dB) and power consumption (60mW) due to no RF gain. In [2], the LNTA-based RX (Fig. 1, upper) attains a better tradeoff between NF (2.2dB) and power consumption (40mW) with an RF gain, but at the expense of linearity (5dBm OB-IIP3) and active area (0.8mm^2). In [3], the gain-boosted N-path mixer-first RX (Fig. 1, lower) exhibits 2.9dB NF and 8dBm OB-IIP3 with only 11mW power consumption. Yet, the RF passband BW is limited to ~4MHz, hindering its applications on the standards such as 5G-NR. In addition, the RF coverage of the RXs [1]-[3] is limited by the input capacitance.

Herein we describe a blocker-tolerant wideband receiver featuring a transformer-based N-path passive-LNA (Fig. 1, lower). Unlike the differential passive-LNA in [4] that supports only a 20MHz BW and entails a wideband external balun, our solution targets >100MHz BW and benefits from a single-ended RF input to avoid any external components. Also, to improve the passband BW and also the OB rejection, a 2nd-order TIA with complex conjugate poles is employed. It features not only passive gain and high-Q bandpass filtering at RF, but also high linearity and wide passband BW at low power budget. Besides, the inductive characteristic of L_1 can absorb the parasitic capacitance at the RF input port, widening the RF coverage. Fabricated in 28nm CMOS process, our RX operates over 2-to-3GHz RF range with a 110MHz RF BW, exhibits 12.2-to-13.5dB voltage gain, 3.4-to-3.8dB NF and 13dBm OB-IIP3. The power consumption is merely 12.6 to 14.7mW and the core area is 0.55mm^2.

The schematic of our RX is shown in Fig. 2, in which the signal is injected to a fully-passive RF front-end (transformer and N-path network, SW_{NP} and C_{NP}). After down-converted by SW_{NP}, the BB signals are extracted by SW_B and amplified by the 2nd-order TIA. SW_{NP} and SW_B in each path are driven by two 25%-duty-cycle non-overlap LOs, which are 180° out of phase. The center frequency is defined by f_{LO}. To improve both the linearity and NF, a step-up transformer with an impedance ratio of ~7 is employed to provide passive voltage gain, in which the two spiral coils L_1 (0.86nH) and L_2 (6.02nH) are vertically coupled and the coupling factor k is 0.88. The N-path SC network is parallelized with the transformer. At in-band, the signals are coupled to $V_{o,RF}$ since the N-path network presents a high impedance at f_{LO}, while the OB blockers are coupled and passed the N-path network to $V_{o,RF}$ with inverse polarity, resulting partial OB cancellation. Thus, the transformer-based N-path LNA provides high-Q bandpass filtering at both $V_{i,RF}$ and $V_{o,RF}$. Capacitor C_T around transformer is used to offset the center-frequency shifting, which is designed with 3-bit resolution. Thanks to the Miller effect, small SW_{NP} (1.2μm/30nm) and C_{NP} (2pF) are employed.

Unlike [3] that employs a series resistor to extract BB signal between SW_{NP} and C_{NP}, we propose a small switch SW_B (0.6μm/30nm) to enhance the Q factor of the transformer-based N-path loop. The capacitor C_{B1} (2pF) aids enhancing the OB rejection. To extend the passband BW, we employ a 2nd-order BB TIA, which contains an inverted-based transconductance amplifier, G_{mB}, feedback resistor R_F and two shunt capacitors C_{B2} and C_{B3} at $V_{B2,I\pm}$ and $V_{B3,I\pm}$, respectively. The TIA can provide complex-conjugate poles and its natural frequency is $(g_{mB}/(R_F \cdot C_{B2} \cdot C_{B3}))^{0.5}$. Finally, at BB output ($V_{B3,I\pm}$) we obtain a lowpass response with 50MHz BB-BW.

The steep filtering shape from $V_{i,RF}$ to $V_{B3,I\pm}$ can be tuned by changing R_B and $C_{B2,3}$, respectively. When R_B is tuned from 7 to 3kΩ, the passband BW widens from 61 to 110MHz while the voltage gain drops by 6.5dB in Fig.3 (upper). When $CB_{2,3}$ is tuned from 5 to 9pF, the passband BW shrinks from 110 to 59MHz while the OB rejection is improved by 10.8dB at 110MHz offset. In Fig.3 (lower), our transformer offers an intrinsic lowpass filtering response, i.e., 25dB rejection at 9GHz, which effectively suppresses the harmonic-folding effect existed in N-path filters, especially the 3rd- and 5th-order terms. The simulated 3rd- and 5th-order harmonic folding rejection ratio ($HFRR_3$ and $HFRR_5$) are >19dB in Fig.3 (lower).

Our RX was fabricated in 28nm CMOS process (Fig. 7). The static power consumption due to G_{mB} is 8.4mW. The dynamic power is due to 4-phase 25%-duty-cycle LO generator, with ~2.1mW/GHz power efficiency for a -161.8dBc/Hz phase noise at 100MHz offset. Fig. 4 (upper) presents the gain response and S_{11} in the 2-to-3GHz RF range, in which the passband gain is 12.2 to 13.5dB with 110MHz BW and S_{11} is<-10dB. The OB rejection is 34dB at ~2xBW offset. In Fig. 4 (lower), the group delay variation of out RX is <6.5ns. The NF is 3.4 to 3.8dB for a 2-to-3GHz RF range (Fig. 5, upper). The blocker NF reaches 8.6dB at 2.5GHz when injecting a 0dBm CW signal at Δf=4xBW, which can be improved by enhancing the OB rejection, and reducing the reciprocal mixing of the phase noise in the LO generator. In Fig. 5 (lower), the OB-IIP3 and OB-IIP2 are 13 and 57dBm, respectively, at Δf=5xBW offset, and the B_{-1dB} is -4.5dBm. Note that with high-order filtering at RF and BB, more low-power BB gain stages can be added after the TIA to increase the RX gain, while keeping low NF and high OB linearity.

The comparison table is shown in Fig. 6. When compared to the prior art [2]-[6], our RX features both wide passband BW and large OB rejection with small power consumption, meanwhile with comparable NF and linearity. Compared to the gain-boosted N-path RX and LNTA-based RX in [2, 3], our RX achieves a >10x wider passband BW and >5dB higher OB-IIP3. Although the N-path RX with two zeros in [5] shows wider passband BW and gain, our filter has ~7.8x less power consumption and a single supply. Although the N-path filter/RX in [4, 6] achieves better linearity, our filter has a >5x wider passband BW than [4] and >2.8dB lower NF than [6].

Acknowledgements:

This work is funded by the National Natural Science Foundation of China (NSFC) - 62104263, the GuangDong Basic and Applied Basic Research Foundation - 2022A1515012295, and the Macau Science and Technology Development Fund - 004/2023/SKL.

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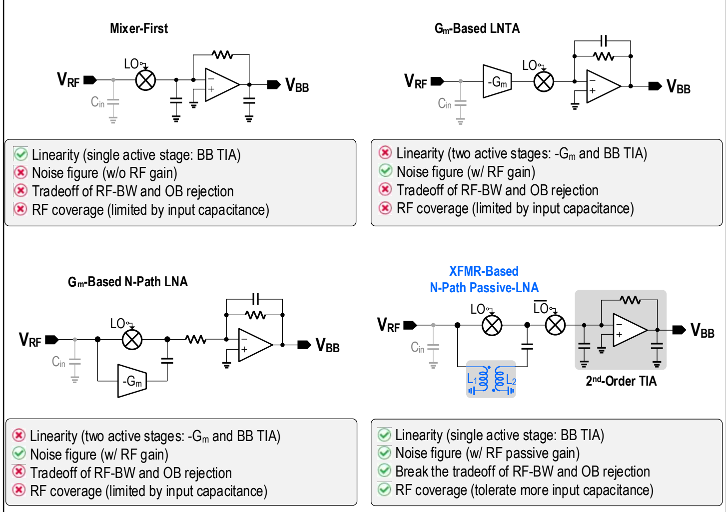

Fig. 1. Overview of wideband RX architecture: mixer-first [1], LNTA-based [2]; gain-boosted N-path mixer-first [3] and this work with a transformer-based N-path passive-LNA and a 2nd-order TIA.

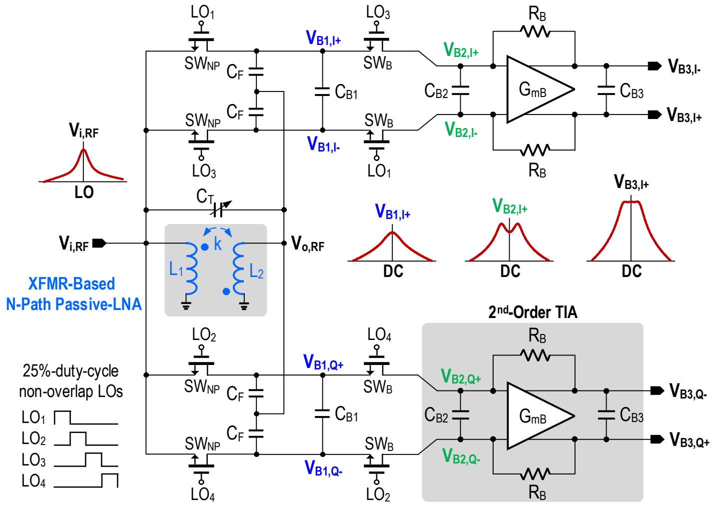

Fig. 2. Proposed blocker-tolerant wideband RX. Passive RF gain is achieved by adding a step-up transformer to drive the bottom plate of the four C_F, while creating an N-path bandpass filter response.

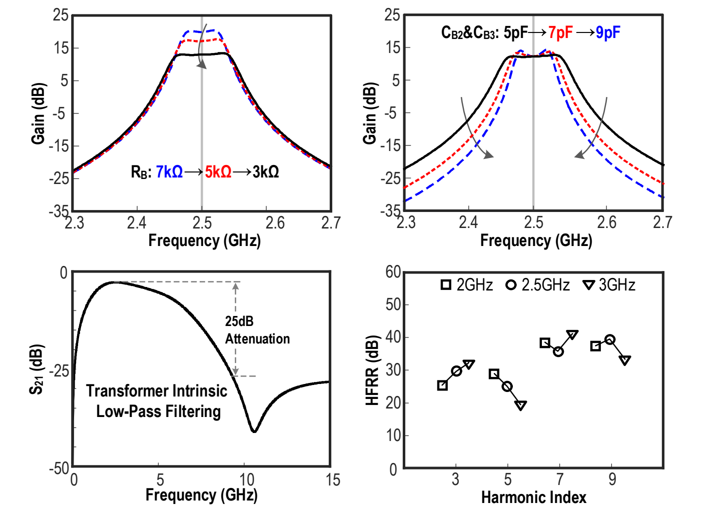

Fig. 3. Simulated gain response with different R_B, C_{B2} and C_{B3} (*upper*), and transformer's intrinsic low-pass filtering and HFRR at different RF (*lower*).

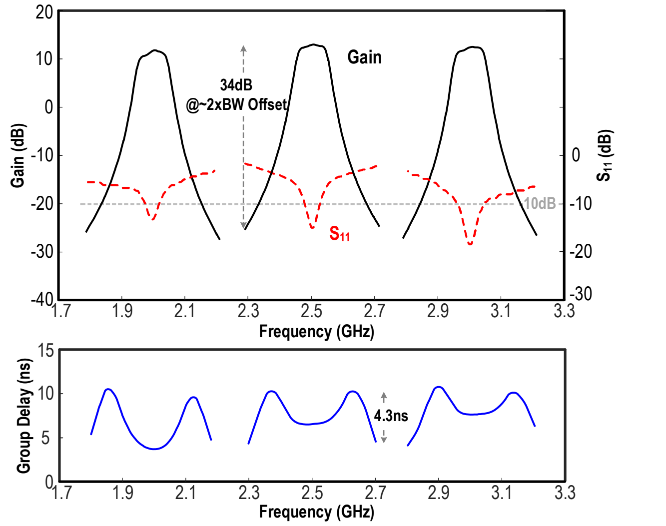

Fig. 4. Measured gain response and S_{11} at 2-to-3GHz RF range (*upper*), and the group delay at different RF (*lower*).

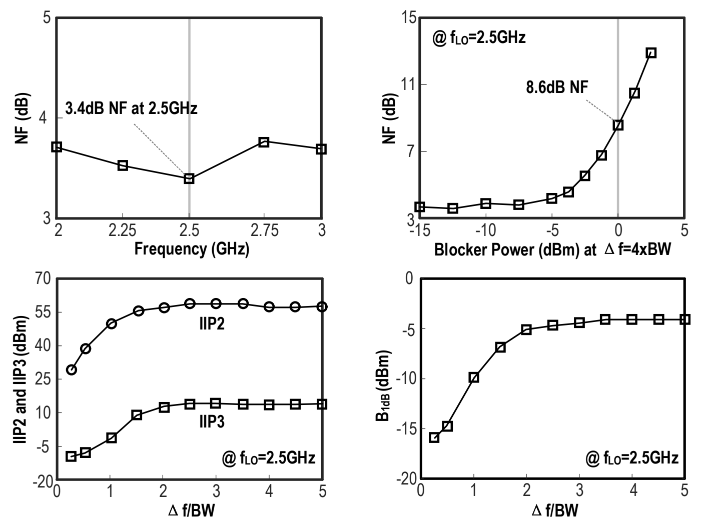

Fig. 5. Measured NF at different RF and blocker-NF at Δf=4xBW (*upper*), IIP_2, IIP_3 and B_{1dB} under different frequency offsets (*lower*).

	This Work	JSSC'15 [2]	ISSCC'15 [3]	ISSCC'21 [5]	JSSC'22 [4]	ASSCC'23 [6]
Topology	**XFMR-Based N-Path RX w/ 2nd-Order TIA**	LNTA-Based RX w/ Noise Cancellation	Gain-Boosted Mixer-First N-path RX	Gain-Boosted N-Path RX w/ Two-Zeros	N-Path pLNA w/ SC-XFMR Network	Gain-Boosted N-Path Filter w/ G_m-C Network
Order of Filter	**4**	2	2	6	2	4
RF Range (GHz)	**2 to 3**	0.1 to 2.8	0.1 to 1.5	0.4 to 3.2	1.7 to 3.6	0.5 to 1.5
RF BW (MHz)	**110**	10	4	160	20	50
Gain (dB)	**12.2 to 13.5**	50	38	36	9.8	10.7 to 12.7
DSB NF (dB)	**3.4 to 3.8**	1.8 to 2.2	1.5 to 2.9	2.7 to 3.6	3.4 to 4.8	5.3 to 6.2
0dBm Blocker NF (dB) @ Offset (MHz)	**8.6 @Δf=4×BW**	14 @ Δf=5×BW	13.5 @ Δf=20×BW	8.4 @Δf=6.25×BW	4.7 @Δf=4×BW	8.3 @Δf=4×BW
B_{-1dB} (dBm) @Δf=5×BW (MHz)	**-4.5**	No data	-6	-5*	1.7	1.5
OB-IIP3 (dBm) @Δf=1×BW (MHz)	**-3.5**	-11*	-11*	-7*	20*	4
OB-IIP3 (dBm) @Δf=5×BW (MHz)	**13**	5*	8*	13	23.5	18.2
OB-IIP2 (dBm)	**57**	50	50	70	64	58
Power (mW)	**12.6 to 14.7**	27 to 40	11	65.6 to 114.8	17.8 to 38.2	11.1 to 15.9
Supply (V)	**1.1**	1.1	0.7, 1.2	1.2, 1.3	1	1.2, 2.5
Active Area (mm^2)	**0.55**	0.8	0.028	0.6	0.84	0.072
Technology	**28nm CMOS**	40nm CMOS	65nm CMOS	40nm CMOS	28nm CMOS	65nm CMOS

Fig. 6. Performance comparison with the recent works. *Estimated from the figure.

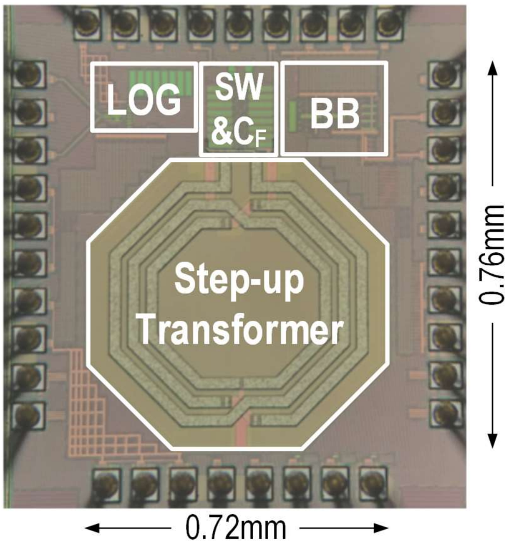

Fig. 7. Die photo of our fabricated wideband RX in 28nm CMOS.