A Band-Reject ir-UWB LNA with 20 dB WLAN Suppression in 0.13 μm CMOS

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Abstract*—Custom designed for the IEEE802.15.4a standard, a 2-stage pseudo-differential low-noise amplifier (LNA) with a notch $\geq$ 20 dB in the IEEE802.11a WLAN band is presented for impulse-radio ultra-wideband (ir-UWB). This band-reject LNA is power-to-current (PI) configured employing reactive dual-loop negative feedback, which reduces the noise figure and allows for orthogonal impedance and noise matching over the prescribed bandwidth (i.e., 3.25-10.25 GHz). The LNA is fabricated in 0.13 μm CMOS and presents a maximum power gain of 17 dB, a -9 dBm IIP3 and a 2.5 dB noise figure at 6 GHz, when matched to 50 Ω (single-ended). Noise figure variation across the pass-band(s) is limited to $\leq$ 0.75 dB. Employing a current-reuse technique limits the total power consumption to $\leq$ 15 mW from a 1.2 V supply. The LNA occupies a die area of 1.4x1.2 mm^2.

I. Introduction

In 2002, the Federal Communications Commission (FCC) granted unrestricted access to the 3.1-10.6 GHz band for ultra-wideband (UWB) wireless communication at a low EIRP of -41.3 dBm/MHz. This technology has attracted much attention as it promises high data-rate, short-range connectivity in low-cost silicon CMOS technology [1], [2]. Envisioning a lucrative market for future wireless products, the industry put forth the IEEE802.15.4a standard, thereby allocating the 3.25-10.25 GHz bands (optional and mandatory) for UWB communications (see Table I).

TABLE I
LNA TARGET SPECIFICATIONS FOR 802.15.4a

Bandwidth (GHz)[1]	Sub-channels	S_{21} (dB)	Z_{in} (Ω)[2]
Ch-I: 3.25-4.75	3	14-17	100
Ch-II: 6.25-8.25	4	14-17	50
Ch-III: 8.25-10.25	4	10-14	50

[1]500 MHz sub-channels; [2]Single-ended

UWB systems transmitting at low spectral densities overlap and share bandwidth resources with existing narrowband systems that have relatively high transmission power levels (as high as 70 dB). Issues of UWB coexistence and the suppression of narrowband interference (NBI) are challenges that remain unresolved, since proposed solutions neither meet the low complexity requirements nor are effective in suppressing strong narrowband signals. Under certain circumstances, situations may arise where the presence of a strong interferer (e.g., IEEE802.11a WLAN), saturates an UWB front-end.

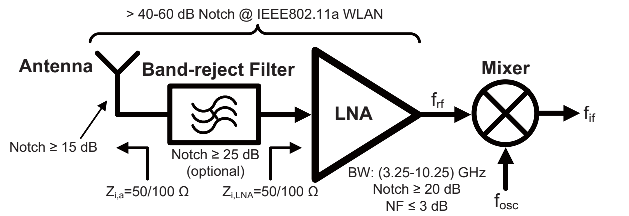

Fig. 1. *Proposed block diagram of an UWB receiver with high narrowband immunity (802.11a WLAN). Single-ended LNA is matched to 50 Ω*

Moreover, recent studies reveal that for UWB receivers, the bit-error-rate (BER) performance degrades due to the effect of narrowband interference (NBI) [3]. Therefore, not only with respect to hardware constraints but also to relax the signal-to-interference plus noise ratio (SINR), it becomes essential to suppress NBI within the front-end.

Fig. 1 illustrates one solution to mitigate the effect of WLAN (i.e., inband NBI), where 40-60 dB suppression at the NBI is required and must be appropriately distributed over the front-end. To meet this stringent requirement, in [4], a 'sail-boat' antenna is proposed that provides a stop-band notch of at least 15 dB in the WLAN band. Furthermore, in [5] a tailor made filter response for a band-reject filter with a notch depth $\geq$ 25 dB is presented.

In this paper, a low-power, 2-stage pseudo-differential power-to-current (PI) LNA with a notch $\geq$ 20 dB in the WLAN band is realized to meet the 802.15.4a specifications. This LNA employs reactive dual-loop negative feedback and is fabricated in standard 0.13 μm CMOS technology. A differential structure is chosen as it is least sensitive to noise and interference coupled through supply lines and substrate. Moreover, differential topologies offer excellent common-mode rejection and suppress 2^{nd}-order inter-modulation (ΔIM) products. The proposed structure also accommodates differentially fed antennas, without the need for an input balun. Adaptability is introduced by matching the LNA to 100 Ω for the lower band and 50 Ω for the upper two bands.

The paper is organized as follows. The principle of dual-loop negative feedback and a detailed description of the LNA is presented followed by measurement results and a comparison of this work with recently published amplifiers.

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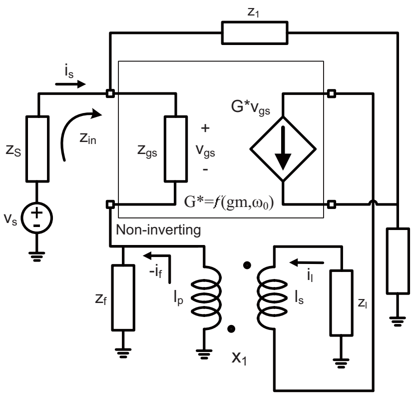

Fig. 2. *Principle of a dual-loop negative feedback PI LNA*

II. Dual-Loop Reactive Feedback LNA

Negative feedback is often the leading candidate for broadband amplification as it promises numerous benefits, such as insensitivity towards process and supply variations, stabilization of gain, lower distortion, larger bandwidth (at the expense of available gain) and orthogonal noise and impedance matching [6], [7].

A. General Principle

For maximum power transfer, two negative feedback loops (i.e., series (V-I) and series-shunt (I-I)) are employed to achieve broadband impedance matching at the input terminal of the amplifier (see Fig. 2). Source degeneration and a resistive divider are used to form the V-I and I-I loops, respectively.

As the open-loop transfer function of the amplifier is non-inverting, a transformer (x_1) is used as an inverter in the series feedback loop to guarantee negative feedback. Various transformer non-idealities associated with on-chip transformers, particularly substrate loss, winding resistance, interwinding capacitances and leakage inductance, have been partially neglected to simplify the following analysis.

From the individual loop equations (for V-I and I-I), the input impedance (Z_{in}) can be expressed as,

$$\begin{aligned} Z_{in} &= \left(\frac{i_l}{i_s}\right)\left(\frac{v_s}{i_l}\right) = \frac{v_s}{i_s} \\ &= z_f\left(\frac{z_1+z_2}{z_2}\right) \;//\; z_2\left(\frac{z_1+z_2}{z_2}\right) = z_f\left(\frac{z_1+z_2}{z_f+z_2}\right) \end{aligned} \quad (1)$$

where z_f is the series feedback impedance and z_1 and z_2 are the current divider impedances for the series-shunt feedback. Likewise, the power gain (G_p) and noise figure (NF) are also derived from the values of the feedback elements.

Under matched conditions ($Z_{in} = z_s^*$) and with z_l the load impedance, the power gain of the amplifier is found as

$$G_p = \frac{p_l}{p_{in}} = \left(\left|\frac{v_s/2}{z_f}\right|^2 \mathrm{Re}\{z_l\}\right) \Big/ \frac{|v_s/2|^2}{\mathrm{Re}\{z_s\}} = \frac{\mathrm{Re}\{z_s\}\mathrm{Re}\{z_l\}}{|z_f|^2} \quad (2)$$

which reduces to $G_p = r_s r_l / r_f^2$ for real valued impedances.

The impedances in the feedback loops directly contribute to the overall noise transfer. Upon shifting and combining all the noise sources, we obtain the following expression for the total noise voltage power spectral density.

$$\begin{aligned} S_{v_{n,eq}}(f) &= 4kT\mathrm{Re}\{z_{a,s}\} + 4kT\frac{\mathrm{Re}\{z_f\}}{|\alpha_s|^2} \\ &+ S_{v_n}(f)\frac{1}{|\alpha_s|^2} + S_{i_n}(f)\left|z_s + \frac{z_f}{\alpha_s}\right|^2 + 4kT\frac{|z_s|^2}{\mathrm{Re}\{z_1+z_2\}} \end{aligned} \quad (3)$$

where $\alpha_s = (z_1+z_2)/(z_1+z_2+z_s)$, S_{v_n} and S_{i_n} are the equivalent power spectral density of the voltage and current noise sources of the first stage of the amplifier and $z_{a,s}$ is the radiation resistance of the antenna.

It is critical that the first stage be optimized for minimum noise contribution and maximum gain. The transistor geometry (e.g., aspect ratio, W/L) and the biasing conditions (e.g., drain current, i_d and transconductance, g_m) directly influence the noise figure of the amplifier.

B. Design with Current-Reuse Technique

The power-to-current dual-loop LNA employs broadband reactive feedback to target the 3.25-10.25 GHz bandwidth with high NBI suppression at the WLAN band. To minimize the power consumption, the bias current is recycled though all the stages.

In Fig. 3 the proposed power-to-current LNA employs a cascade of two common-source stages (M_1 and M_2), two reactive networks formed using a current-current transformer (x_1 for V-I loop) and an RC divider network (for I-I loop) followed by an output current buffer (M_3). The current buffer allows for a high impedance output node. To obtain a suitable noise figure while sustaining sufficient gain for the LNA, the first stage is biased between optimum noise and f_T points.

This LNA employs a current reuse technique (i.e., dc current is recycled via l_b) with an additional on-chip unbalanced-unbalanced (*UN-UN*) auto-transformer at the output for impedance transformation and to bias M_3. Minimal dc voltage

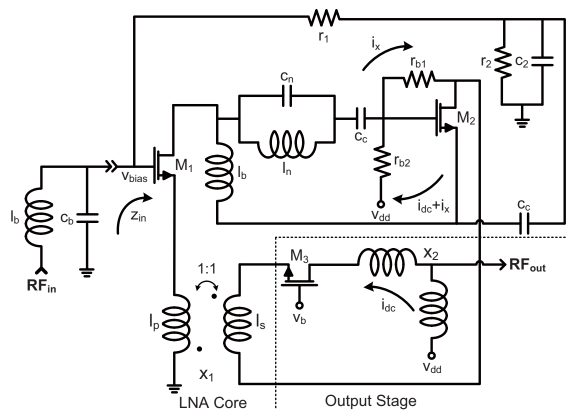

Fig. 3. *Schematic of the 2-stage dual-loop negative feedback PI-LNA (half-circuit)*

drops across l_b and the secondary winding of x_1 allow all three stages to operate from a 1.2 V supply (v_{dd}). However, because of limited headroom, the gate potential of M_2 is higher than its drain voltage and M_3 is biased to one v_{th} higher than v_{dd} or 1.5 V (v_b).

For narrowband interference (NBI) rejection as well as out-of-band suppression, a high Q resonant tank (l_n and c_n) is strategically placed between M_1 and M_2, such that at its resonance frequency (f_0), the first and the second stages are decoupled, thereby producing a null in the pass-band.

The reactive V-I feedback loop works as follows: the output current flowing through M_3 is sensed by the secondary winding (l_s) of the inverting transformer and converted into a corresponding voltage at the input through the primary winding (l_p) of x_1. Similarly, for the I-I loop, the output current at the source of M_2 is resistively divided using an RC network and the resulting current is fed to the input of M_1. To broaden the bandwidth and boost the gain at higher frequencies, a zero is placed at the cut-off frequency. This is realized by placing capacitor c_2 in parallel to r_2.

Frequency tuning of the notch can be achieved by replacing c_n by varactors or a bank of capacitors. LNA parameters such as S_{11}, NF, etc. and the notch depth are influenced by the quality factor of the LC-tank. The finite Q leads to a higher NF and marginally lower the power gain around the resonant frequency. It also causes the impedance in the lower band to be higher than that in upper band.

III. Measurement Results

The results for the power gain and noise figure are illustrated in Fig. 4 and Fig. 5, respectively. The power gain of the LNA peaks at about 17 dB and the noise figure remains lower than 2.5 dB throughout the operational band. As the transformer produces less mutual flux linkage and mutual inductance at the lower end of the spectrum, the noise figure sensitivity is greater. The quality factor of the transformer is simulated to be about 10. Because of the finite Q of the resonant tank, the measured notch depth at 5.25 GHz (Δ 150 MHz) is 20 dB (Δ 6 dB). The reverse isolation (S_{12}) remains below -35 dB within the required bandwidth. Note that the solid lines and the dashed lines are measurements and simulations, respectively.

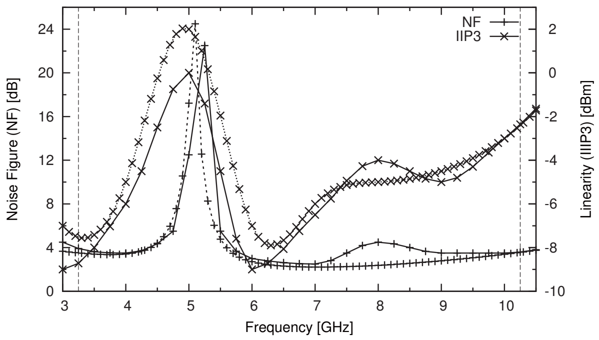

Fig. 5. *Noise figure and third-order input inferred intermodulation point for the ir-UWB LNA*

In broadband amplifier designs, reactive feedback increases linearity without increasing thermal noise. Hence, linearity can be considered an important figure of merit for any LNA. The third-order input inferred intercept point (IIP3) of the amplifier is a useful parameter to predict low-level intermodulation effects. It is often the case that linearity of an amplifier deteriorates as frequency increases. However, with transformer feedback the effects are not as profound. Results for the IIP3 at various frequencies within the band are also shown in Fig. 5. The IIP3 remains relatively constant throughout the band of interest, except at the point of resonance.

The transconductance of the first stage, the transformer parameters (i.e, self-inductances of the windings, turns ratio, coupling coefficient) and the RC divider network, yields the input matching results as seen in Fig. 6. As per commercial standards, if $S_{11} \leq$ -10 dB, the LNA is said to be matched to the source impedance or in our case, 50 Ω. A poorer input match from 7-9 GHz is the likely cause of the 2 dB drop in S_{21}. Note that the lower band is matched to 100 Ω.

A flat group delay or a linear phase response is paramount in broadband amplifier design. An amplifier with non-linear group delay is all but likely to experience phase distortion. The phase and group delay are plotted in Fig. 7. The group delay shows little deviation within the individual channels. At

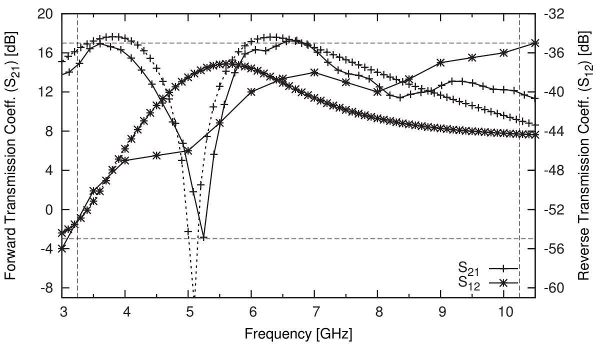

Fig. 4. *Gain and isolation for the dual-loop feedback ir-UWB LNA*

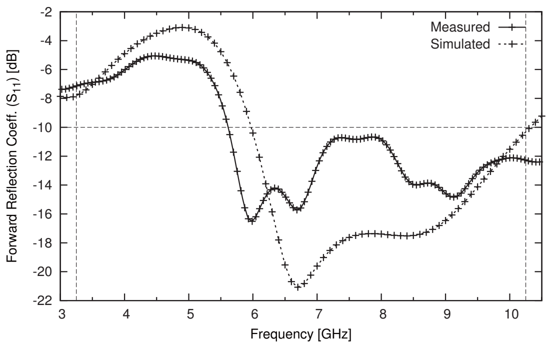

Fig. 6. *Input reflection coefficient for the ir-UWB LNA*

TABLE II
PERFORMANCE SUMMARY

Specification	This work[1]	[1]	[2]	[6]	[7]
Bandwidth (GHz)	3.25-4.75/ 6-8.25/8.25-10.25	2.3-9.3	3.0-10.0	3.1-10.6	1-11.6
Power Gain (dB)	12-17	6.3-9.3	17-21	13.7-16.5	10.8-12
Reverse isolation S_{12} (dB)	≤ -35	≤ -35	N.A.	≤ -30	N.A.
Input return loss S_{11} (dB)	≤ -10[2]	≤ -9	≤ -9	≤ -10	≤ -11
Noise figure (dB)	2.0-4	4-9	2.55-4.25	2.1-2.8	4.7-5.6
Group delay (ps)	100-300[3]	120-200	N.A.	75-130	N.A.
IIP3 @ 6 GHz (dBm)	-9	-6.7	0	-7	-11
Supply voltage (V)	1.2	1.8	3.3	1.2	1.5
P_{diss} (mW)	15	9.2	30	9	10.6
Chip area (mm^2)	1.68	1.10	1.80	0.87	0.66
Technology (CMOS†, SiGe-BJT‡)	0.13 μm†	0.18 μm†	0.18 μm‡	0.13 μm†	0.18 μm†

[1] Pseudo-differential LNA with notch depth @ frequency: ≥ 20 dB @ 5.25 GHz; [2] Matched to 50 Ω from 6-10.25 GHz; [3] Except @ 4.75-6 GHz

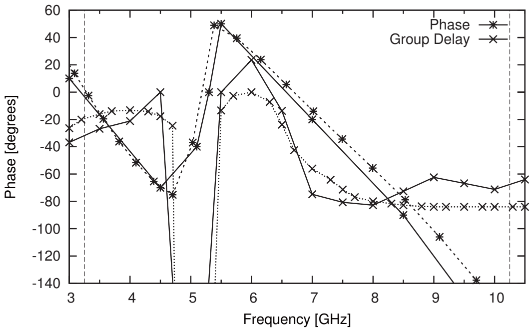

Fig. 7. *LNA group delay and S_{21} phase*

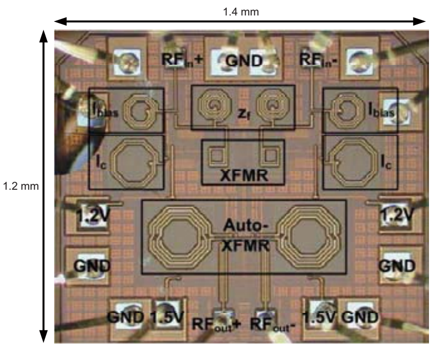

Fig. 8. *Chip microphotograph of the UWB PI-LNA; Die area: 1.68 mm^2(1.4x1.2 mm); Active area: 0.79 mm^2 (1.05x0.75) mm*

the notch, the phase shifts by approximately 130 degrees.

A microphotograph of the fabricated LNA is shown in Fig. 8. The chip area is 1.68 mm^2(1.4x1.2 mm) including the bondpads (active area is approximately 0.79 mm^2).

Table II summarizes the performance of recently published LNAs for UWB communications in standard 0.18, 0.13 μm CMOS and 0.18 μm SiGe HBT technologies. The topology presented here shows similar performance characteristics as compared to those fabricated in standard CMOS technologies, the main difference being the high in-band NBI rejection, which is not incorporated in any such previous design. The low power consumption of the pseudo-differential PI-LNA justifies the effectiveness of the current re-use configuration in conjunction with dual feedback loops.

IV. Conclusions

An IEEE802.15.4a compliant, band-reject power-to-current LNA has been demonstrated in this paper. It employs a current-reuse technique for minimizing the power consumption and dual-loop negative feedback to optimize gain, linearity and noise performance simultaneously. Reactive feedback loops are constructed using an on-chip inverting transformer and an RC network divider. The measured power gain is 17 dB while the noise figure is 2.5 dB with 0.75 dB variation across the band. A notch depth ≥ 20 dB at 5.25 GHz is present in the pass-band. Total power dissipation is 15 mW from a 1.2 V supply.

References

[1] A. Bevilacqua and A.M. Niknejad, "An ultra-wideband CMOS low-noise amplifier for $3.1-10.6$ GHz wireless receivers," *IEEE Journal of Solid-State Circuits*, vol. 39, no. 12, pp. 2259–2268, 2004.

[2] A. Ismail and A.A. Abidi, "A $3.1-10.6$ GHz low-noise amplifier with wideband LC-ladder matching network," *IEEE Journal of Solid-State Circuits*, vol. 39, no. 12, pp. 2269–2277, 2004.

[3] A. Swami, B. Sadler, and J. Turner, "On the co-existence of ultra-wideband and narrowband radio systems," in *Military Communications Conference, MILCOM*, 2001, pp. 16–19.

[4] S. Y. Suh, W. L. Stutzman, W. A. Davis, A. E. Waltho, K. W. Skeba, and J. L. Schiffer, "A UWB antenna with a stop-band notch in the 5 GHz WLAN band," *IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics*, pp. 203–207, 2005.

[5] S. Bagga, Z. Irahhauten, S. A. P. Haddad, W. A. Serdijn, J. R. Long, and J. J. Pekarik, "A UWB transformer-c orthonormal state space band-reject filter in 0.13 μm CMOS," *IEEE European Solid-State Circuits Conference*, 2008.

[6] M. T. Reiha, J. R. Long, and J. J. Pekarik, "A 1.2 V reactive-feedback $3.1-10.6$ GHz ultra-wideband low-noise amplifier in 0.13 μm CMOS," *IEEE Journal of Solid-State Circuits*, pp. 55–58, 2007.

[7] C.T. Fu and C.N. Kuo, "A $3-11$ GHz CMOS UWB LNA using dual feedback for broadband matching," *IEEE Radio Frequency Integrated Circuits Symposium*, pp. 67–70, 2007.