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DESIGN OF 2.4–2.5 GHZ LOW-NOISE AMPLIFIER WITH DIGITAL GAIN CONTROL IN 28 NM FD-SOI TECHNOLOGY

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Abstract: this paper presents a 2.4-2.5 GHz Low Noise Amplifier (LNA) with Digital Gain Control (DGC) implemented in 28-nm FD-SOI CMOS technology. The LNA achieves NF of 1.7 dB at maximum gain. At minimum gain it provides IIP3 of −0.02 dBm, and P1dB of −2.8 dBm. A 3-bit DGC varies the power gain from 7.5 dB to 17 dB, while LNA consumes 15.3 mW at 1.8 V supply across all gain settings. At maximum gain S11/S22/S12 are −20.3/−27.9/−26.5 dB at 2.45 GHz. The design achieves high gain, low NF, high linearity and a 9.5 dB gain tuning range.

Keywords: Low Noise Amplifier (LNA); Digital Gain Control; CMOS; FD-SOI; ISM; WLAN.

I. INTRODUCTION

The 2.4 GHz ISM band is a key frequency range for modern wireless communications, supporting Wi‑Fi, Bluetooth, ZigBee, and a wide range of IoT devices. The Low Noise Amplifier (LNA) is the first active stage in a receiver, and it is responsible for providing high gain, low noise figure (NF), good linearity, and stable impedance matching, under tight power constraints [1]. A weak signal requires high gain and low NF to maintain sensitivity, whereas a strong signal may saturate the receiver, causing distortions. This trade‑off motivates the use of adaptive gain control. A digitally controlled LNA can adjust its gain based on the input power, improving linearity when needed without compromising noise performance under weak signal conditions [2]. The design uses a cascode topology with LC load and operates from a 1.8 V supply.

II. CIRCUIT DESIGN

An inductive load is chosen for its low DC voltage drop and high gain. However, classical common-source LNA design often suffers from the Miller effect, caused by the parasitic gate-drain capacitance, which becomes significant at high frequencies. In combination with the inductor, this parasitic capacitance can introduce negative resistance [2], degrading input matching and overall stability (S-parameters). A cascode transistor suppresses this effect and increases the reverse isolation [3]. To achieve high gain with low noise, a cascode LNA with an LC resonant load is implemented. The proposed design of the LNA is presented in Figure 1.

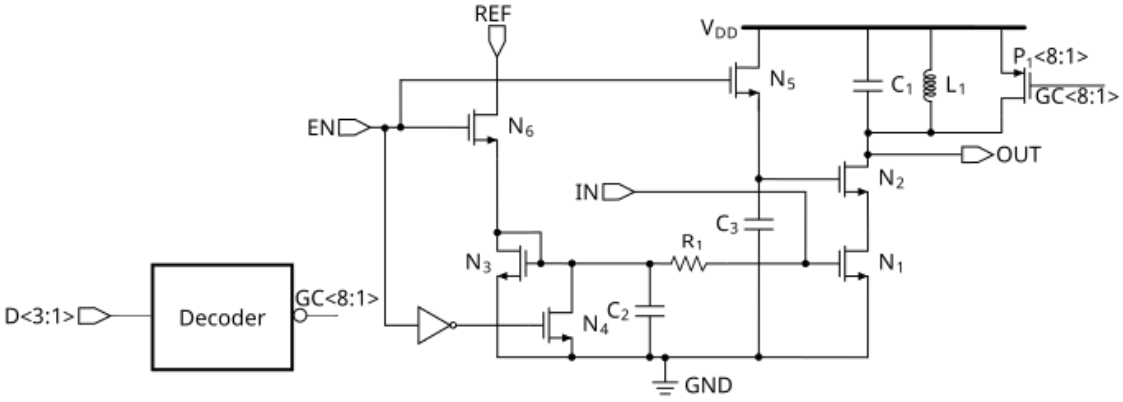


Figure 1. Proposed design of CS Cascode LNA with LC load

The WLAN application of the LNA determines the necessity of handling a wide range of input signals: from the thermal noise floor to levels near the supply voltage. To prevent saturation without sacrificing sensitivity, the LNA gain must be adjustable. In the following design, the gain switching is realized by a 3-bit Digital Gain Control system (Decoder), which configures the load impedance by enabling or disabling parallel p-channel MOSFET branches connected to the LC tank. When all branches are disabled, LNA operates with the highest load and provides the highest gain. Enabling additional branches lowers the tank impedance, reducing the gain and improving linearity. This feature is essential when the input power varies widely, requiring the system to adjust gain and linearity dynamically.

The proposed LNA is implemented in a 28‑nm FD‑SOI (Fully Depleted Silicon‑On‑Insulator) CMOS process. In FD‑SOI, the fully depleted floating body further improves transconductance (gm) and reduces parasitic capacitances, which directly contribute to a lower noise figure and higher gain compared to bulk CMOS technologies. A direct comparison of LNAs designed in 40 nm bulk CMOS and 28 nm FD‑SOI under the same methodology showed that the FD‑SOI implementation achieves comparable noise figure while consuming 20% less power [4].

III. SIMULATIOM RESULTS

The RF core uses FD‑SOI devices, while the gain‑control switches and digital decoder are implemented in bulk CMOS. Figure 2 presents the simulated S-parameters (S11, S22, S12, S21) and NF of the proposed LNA at maximum gain setting.

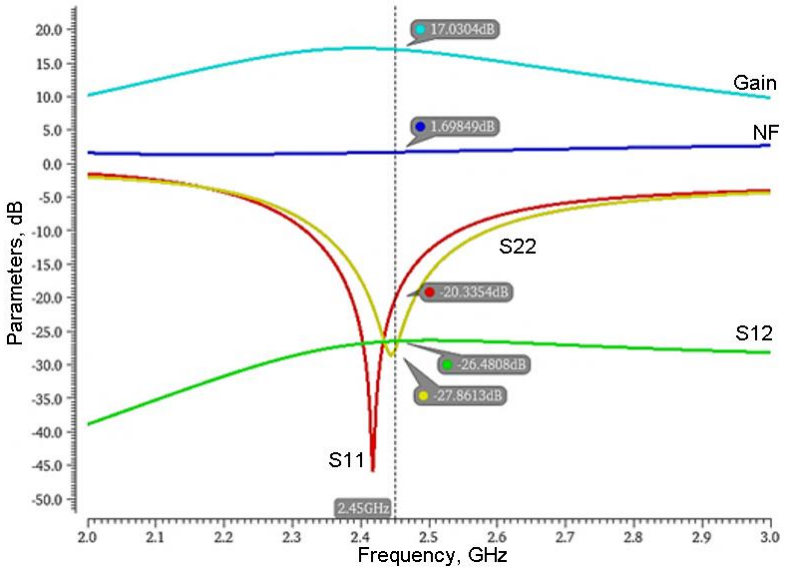


Figure 2. Simulated S-parameters and noise figure at maximum gain

According to the results the LNA achieves gain of 17 dB, NF of 1.7 dB, and S-parameters S11 of −20.3 dB, S22 of −27.9 dB, and S12 of −26.5 dB at 2.45 GHz. At the band edges (2.4 GHz and 2.5 GHz), the gain is 17.2 dB and 16.6 dB, while the NF is 1.6 dB and 1.79 dB, respectively. The input and output return losses remain stable across the whole band from 2.4 and 2.5 GHz, with S11 of −25 dB and −12.9 dB, S22 of −17.3 dB and −16.5 dB, and S12 of −26.9 dB and −26.4 dB respectively.

Table 1 summarizes the LNA performance across all gain states (gain code 0 means minimum gain and code 7 maximum gain).

Table 1. LNA parameters vs. Gain settings at 2.45 GHz

Gval	Gain (dB)	NF (dB)	S11 (dB)	S22 (dB)	S12 (dB)	IIP3 (dBm)
0	7.5	1.91	−15.8	−3	−34.8	−0.02
1	8	1.89	−16.3	−3.4	−34.4	−0.9
2	8.8	1.87	−16.9	−3.9	−33.7	−2
3	9.7	1.85	−17.8	−4.7	−32.9	−3.3
4	10.9	1.82	−19.1	−5.9	−31.9	−5
5	12.4	1.75	−21.1	−7.9	−30.6	−7
6	14.3	1.74	−23.6	−12.2	−28.9	−8.9
7	17	1.7	−20.3	−27.8	−26.5	−10.1

The gain varies from 7.5 dB to 17 dB, providing a tuning range of 9.5 dB. S-parameters improve with gain increasing due to better impedance matching. The NF varies from 1.7 dB to 1.91 dB across all gain settings,

showing little dependence on gain. IIP3 improves to −0.02 dBm at minimum gain, compared to −10.1 dBm at maximum gain. The P1dB parameter is −2.8 dBm at minimum gain and −16 dBm at maximum gain. The bias current of 8.5 mA and power consumption of 15.3 mW remain constant in all gain settings under nominal conditions.

The stability parameters K and B1 are analyzed at maximum and minimum gains in the frequency range 0–5 GHz and are presented in Figure 3. According to the graph, the LNA remains stable in the entire frequency range from 0 to 5 GHz.

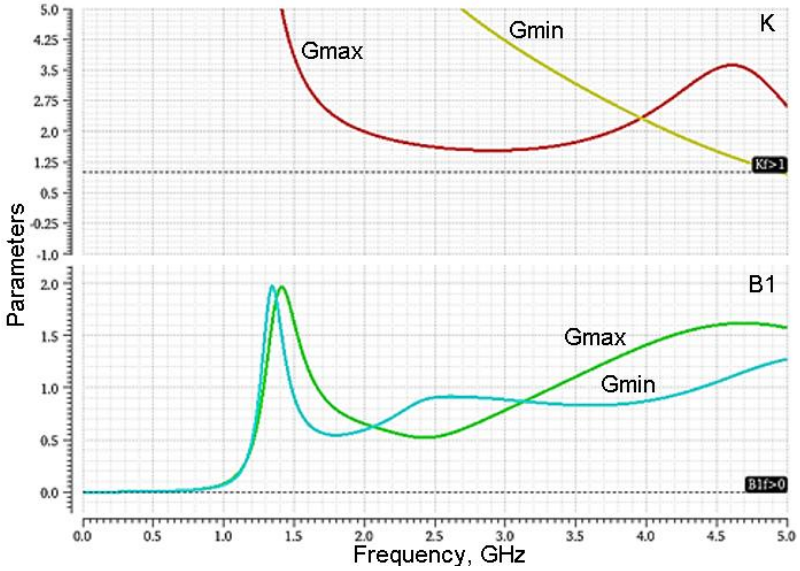


Figure 3. Stability parameters of Low-Noise Amplifier

Although Kf < 1 above 5 GHz suggests a region of conditional stability, this does not lead to oscillations in practice. The onset of oscillation requires a loop gain of at least unity, whereas at these high frequencies the LNA's S21 is negative. The Figure 3 shows that the LNA is stable across the entire frequency range where its forward gain is positive (up to 5 GHz). Above 5 GHz, although Kf < 1, the gain becomes negative, making oscillations impossible.

IV. COMPARISON

The comparison LNAs at central frequency 2.4 GHz is presented in Table 2.

Table 2. Comparison of state-of-the-art LNA performances

Ref.	This work		[5] 2021		[6] 2024		[7] 2022		[8] 2016		[9] 2024
	G_{max}	G_{min}	G_{max}	G_{min}	G_{max}	G_{min}	G_{max}	G_{min}	G_{max}	G_{min}	
Tech. (nm)	28		28		65		65		130		22
Band width [GHz]	2.4–2.5		2–5		2.4		1.8–2.7		2.4		2.4/5/10
Gain (dB)	17	7.5	22.9	16.8	28.2	17.1	20.5	−11	10.1	4.6	16.9
NF (dB)	1.7	1.91	3.6	6.6	2.56	5.18	1.15	14	2.5	4.5	2.8
S11 (dB)	−20	−16	-		-		−10		−30		-
S22 (dB)	−28	−3	-		-		-		−50		-
S12 (dB)	−27	−35	-		-		-		-		-
IIP3 (dBm)	−10	0.02	−17	−16	−15	−9.9	−11	8.6	−8.1	−9.5	−6.5

P1dB (dBm)	−16	−2.8	-		-		-		-	-
Pdc (mW)	15.3		2	0.35	0.56	0.07	16.8	1.33	0.64	13.2
AGC	3-bit Digital		Analog		Digital		Digital		Digital	-
FoM	0.67		1.43		46.5		1.85		3.18	0.92

In case of variable-gain LNAs, the parameters in maximum and minimum gain modes are proposed. In the technical specification, the parameters are mentioned for maximum and minimum gain modes or just for the maximum mode. The comparison includes projects: 28 nm wideband LNA analog current tunning (back-gate) [5], fixed-frequency 2.4 GHz LNA with digital-controlled gain [6], narrowband LNA with digital regulation [7], 130 nm fixed-frequency 2.4 GHz LNA with digital AGC [8] and fixed-gain wideband LNA with the smallest 22 nm technology [9].

The figure of merit (FoM) is calculated according to the following formula, which is commonly used for LNA performance evaluation [1]:

$$FoM = \frac{Gain[\text{linear}] \times IIP3[\text{mW}]}{(NF-1)[\text{linear}] \times P_{DC}[\text{mW}]}. \quad (1)$$

The proposed LNA achieves a competitive gain of 17 dB and NF of 1.7 dB at maximum gain. The S-parameters (S11 = −20.3 dB, S22 = −27.8 dB, and S12 = −26.5 dB) meet the technical specifications and demonstrate stable impedance matching in maximum-gain mode over the entire operating band (Figure 2). The minimum-gain IIP3 of −0.02 dBm is the highest among the compared LNA designs.

The FoM of the proposed LNA (0.67) is lower than of some prior works, mostly due to high power consumption (15.3 mW). However, this design demonstrates the highest linearity in minimum gain mode (IIP3 of −0.02 dBm and P1dB of −2.8 dBm). A 3-bit digital gain-control system provides a 9.5 dB gain range and a constant bias current of 8.5 mA.

VI. CONCLUSOINS

A 2.4–2.5 GHz Low Noise Amplifier with 3-bit digital gain control has been designed and simulated in a 28-nm FD-SOI CMOS technology. The IIP3 improves from −10.1 dBm at maximum gain to –0.02 dBm at minimum gain, demonstrating the effectiveness of gain control under varying input signals.

The LNA's S-parameters (S11 = −20.3 dB and S22 = −27.8 dB and S12 = −26.5 dB at 2.45 GHz) represent the stable impedance matching. At minimum gain, input matching remains stable S11 = −15.8 dB. The decrease of S22 to −3.04 dB due to load switching is acceptable, because in the receiver the LNA follows the active mixer with high input impedance.

The analysis of B1 and K-factors shows the unconditional stability of the LNA across the frequency range 0–5 GHz. The out-of-band instability (above 5 GHz) doesn't affect the LNA performance, because of the negative gain.

Compared to state-of-the-art 2.4 GHz LNAs, the proposed design offers a low noise figure, high gain, the highest linearity, wide gain tuning range, and constant current biasing in all gain modes. The proposed LNA meets the WLAN requirements for high linearity and wide gain tuning range.

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СХЕМОТЕХНИЧЕСКОЕ ПРОЕКТИРОВАНИЕ МАЛОШУМЯЩЕГО УСИЛИТЕЛЯ ДЛЯ ДИАПАЗОНА 2,4–2,5 ГГЦ С ЦИФРОВОЙ РЕГУЛИРОВКОЙ УСИЛЕНИЯ ПО 28 НМ КНИ ТЕХНОЛОГИИ

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Аннотация: представлено схемотехническое решение малошумящего усилителя (МШУ), работающего в диапазоне 2,4–2,5 ГГц, с цифровой регулировкой усиления, разработанное по 28 нм КнИ технологии. Уровень шума (NF) достигает 1,7 дБ в режиме максимального усиления. 3-битная схема цифровой регулировки усиления обеспечивает изменение коэффициента усиления в диапазоне от 7,5 дБ до 17 дБ при потреблении МШУ 15,3 мВт при напряжении питания 1,8 В для всех режимов усиления. При минимальном усилении параметры линейности IIP3 и P1dB достигают значений −0,02 дБм и −2,8 дБм соответственно. S-параметры S11/S22/S12 принимают значения −20.3/−27.9/−26.5 дБ на частоте 2,45 ГГц при максимальном усилении. Спроектированное решение обеспечивает высокий коэффициент усиления, низкий уровень шума, высокую линейность и диапазон регулировки усиления 9,5 дБ.

Ключевые слова: малошумящий усилитель (МШУ); цифровая регулировка усиления; КМОП; КнИ; ISM; WLAN.