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Research Article

The Design of an Ultralow-Power Ultra-wideband (5 GHz–10 GHz) Low Noise Amplifier in 0.13 μm CMOS Technology

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The calculation and design of an ultralow-power Low Noise Amplifier (LNA) are proposed in this paper. The LNA operates from 5 GHz to 10 GHz, and forward body biasing technique is used to bring down power consumption of the circuit. The design revolves around precise calculations related to input impedance, output impedance, and the gain of the circuit. MATLAB and Advanced Design System (ADS) are utilized to design and simulate the LNA. In addition, TSMC 0.13 μm CMOS process is used in ADS. The LNA is biased with two different voltage supplies in order to reduce power consumption. Noise Figure (NF), input matching (S11), gain (S21), IIP3, and power dissipation are 1.46 dB–2.27 dB, −11.25 dB, 13.82 dB, −8.5, and 963 μW, respectively.

1. Introduction

Low Noise Amplifiers (LNAs) are integral parts of every receiver. They can be categorized into two divergent classes according to the frequency at which they operate. In fact, the LNA is called ultra-wideband (UWB) provided that it works over a series of frequencies. The system working from 3.1 GHz to 10.6 GHz has been considered as an ultra-wideband system. The main architecture of both UWB receiver and transmitter is demonstrated in Figure 1. The circuit is comprised of RF band pass filter (RF BPF), Low Noise Amplifier (LNA), Variable Gain Amplifier (VGA), and mixer. The BPF selects the signal between two desired frequencies. Because of the BPF loss and the high noise figure of the mixer, the LNA should decrease noise figure appreciably. Besides, it should amplify the signal properly during the desired frequencies. In addition, VGA is supposed to control its own gain appropriately so as to create a proper signal level for analog-to-digital converter (ADC).

Many works have been proposed to achieve appropriate objectives required in the system. In other words, criteria such as lower power consumption, flat gain, noise figure during the bandwidth, stability, and linearity have been widely scrutinized. Different techniques consisting of Chebyshev filter amplifiers, feedback amplifiers, and distributed amplifiers have been used [1–10]. Indeed, the minimum power consumption was obtained by utilizing Chebyshev filter [7]. The best power gain, however, was obtained by feedback amplifiers [8]. In addition, distributed amplifiers had the best input impedance matching among all works [8]. Ultimately, feedback amplifiers had the best noise figure [10]. Owing to the fact that the life expectancy of an LNA is predicated upon its power consumption, the power consumption should be considerably minimized. Successful approaches such as current-reuse topology and forward body bias technique are utilized to bring down the power consumption [11–15]. In this paper, Chebyshev filter, forward body bias technique, cascode LNA, and common-source LNA are used to form the proposed LNA in 0.13 μm CMOS technology.

2. The Proposed LNA

The proposed LNA is comprised of three main parts, namely, a band pass filter, a common-source LNA, and a cascode LNA, demonstrated in Figure 2. Besides, the equivalent circuit of the cascode LNA is depicted in Figure 3. Each part is analyzed separately so as to be scrutinized more precisely.

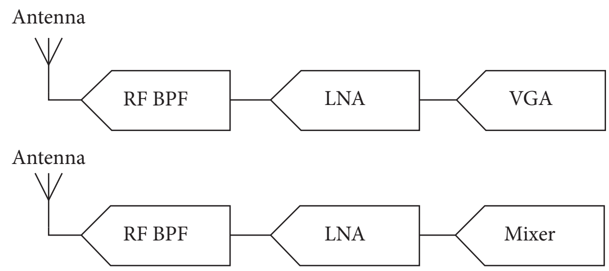

Figure 1: The main blocks in receiver and transmitter architecture.

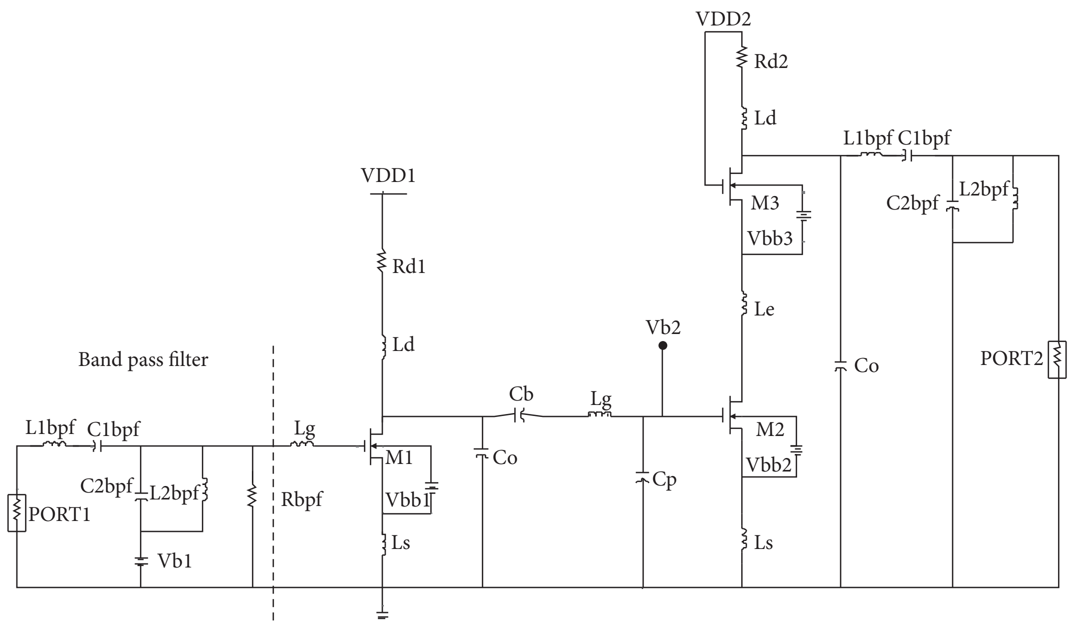

Figure 2: The proposed LNA.

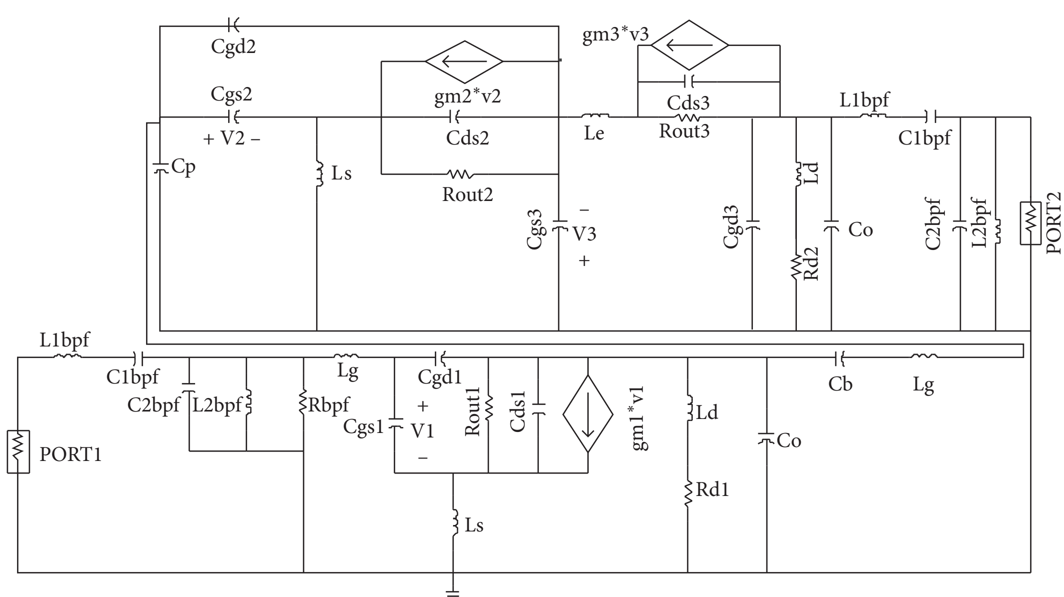

Figure 3: The equivalent circuit of Figure 1.

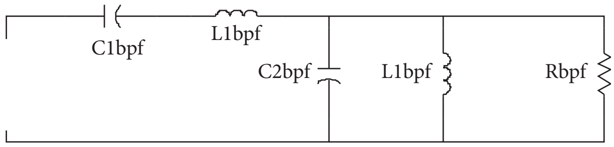

Figure 4: Chebyshev filter.

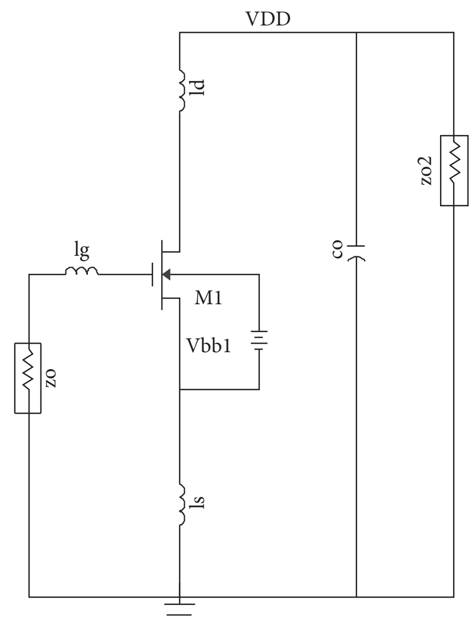

Figure 5: Common-source LNA.

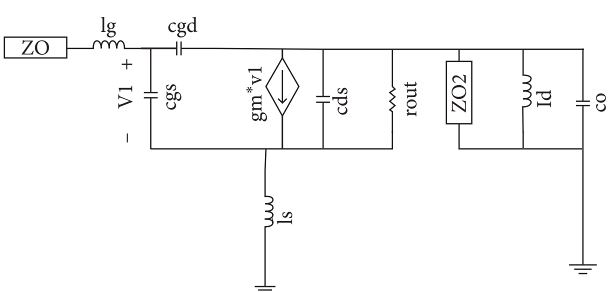

Figure 6: The equivalent circuit of common-source LNA.

A band pass filter or Chebyshev filter is utilized to assist the LNA to amplify the signal across the desired frequency, demonstrated in Figure 4.

The inductors and capacitors in the filter are calculated by

$$\begin{aligned} \text{L1bpf} &= \frac{0.5 \times \text{Rbpf}}{\pi\,(\text{f2C} - \text{f1C})}, \\ \text{C1bpf} &= \frac{2\,(\text{f2C} - \text{f1C})}{4 \times \pi \times \text{Rbpf} \times \text{f2C} \times \text{f1C}}, \\ \text{L2bpf} &= \frac{2 \times \text{Rbpf} \times (\text{f2C} - \text{f1C})}{4 \times \pi \times (\text{f2C} \times \text{f1C})}, \\ \text{C2bpf} &= \frac{0.5}{\pi \times \text{Rbpf} \times (\text{f2C} - \text{f1C})}. \end{aligned} \tag{1}$$

Here, f1C is lower passband frequency and f2C is higher passband frequency.

The second part, in addition, is a common-source (CS) LNA. The most famous formula used to calculate the input impedance of the circuit is given by [16–18]

$$z_{\text{in}} \approx s \times (\text{lg} + \text{ls}) + \frac{1}{s \times \text{cgs}} + \frac{\text{gm} \times \text{ls}}{\text{cgs}}. \tag{2}$$

It is proved that the formula has a drastic error in both imaginary and real parts [19, 20]. Owing to the fact that Lg, Ls, and Ld are designed by the formulas of Zin, Zout, and gain, the error stemming from the formulas brings about an extreme error in calculating the aforementioned elements. Hence, new and precise calculation is required to bring down the error stemming from equation (2). The common-source LNA and its equivalent circuit are demonstrated in Figures 5 and 6. The calculated values for Chebyshev filter is used in both input and output of the circuit. In other words, the filter designed for the input of the circuit is the same as the filter used in the output of the circuit.

After solving the circuit shown in Figure 6, the gain, the input impedance, and the output impedance of the common-source LNA are given by equations (3)–(5).

$$\text{gain}_{\text{common-source}} = \frac{\text{numgain}\,(\text{cs})}{\text{dengain}\,(\text{cs})}. \tag{3}$$

numgain(cs) = ld × zo2 × (cgs × cgd × ls × rout × cgs × cds × ls × rout × cgd × cds × ls × rout) × $\hat{s}4$ × ld × zo2 × (cgs × ls × cgd × ls × cgd × gm × ls × rout) × $\hat{s}3$ × cgd × ld × rout × zo2 × $\hat{s}2$-gm × ld × rout × zo2 × s.

dengain(cs) = (cgs × cgd × co × ld × lg × ls × rout × zo2 × cgs × cds × co × ld × lg × ls × rout × zo2 × cgd × cds × co × ld × lg × ls × rout × zo2) × $\hat{s}6$ × (cgs × cgd × ld × lg × ls × rout × cgs × cds × ld × lg × ls × rout × cgd × cds × ld × lg × ls × rout × cgs × co × ld × lg × ls × zo2 × cgd × co × ld × lg × ls × zo2 × cgd × co × gm × ld × lg × ls × rout × zo2 × cgs × cgd × co × ld × ls × rout × zo × zo2 × cgs × cds × co × ld × ls × rout × zo × zo2 × cgd × cds × co × ld × ls × rout × zo × zo2) × $\hat{s}5$ × (cgs × ld × lg × ls × cgd × ld × lg × ls × cgd × gm × ld × lg × ls × rout × cgs × cgd × ld × lg × rout × zo2 × cgs × cds × ld × lg × rout × zo2 × cgd × cds × ld × lg × rout × zo2 × cgs × cgd × ld × ls × rout × zo × cgs × cds × ld × ls × rout × zo × cgs × cgd × ld × ls × rout × zo2 × cgd × cds × ld × ls × rout × zo × cgs × cds × ld × ls × rout × zo2 × cgd × cds × ld × ls × rout × zo2 × cgs × cgd × lg × ls × rout × zo2 × cgs × cds × lg × ls × rout × zo2 × cgd × cds × lg × ls × rout × zo2 × cgs × co × ld × lg × rout × zo2 × cgd × co × ld × lg × rout × zo2 × cgs × co × ld × ls × rout × zo2 × cds × co × ld × ls × rout × zo2 × cgs × co × ld × ls × zo × zo2 × cgd × co × ld × ls × zo × zo2 × cgd × co × gm × ld × ls × rout × zo × zo2) × $\hat{s}4$ × (cgs × ld × lg × rout × cgd × ld × lg × rout × cgs × ld × ls × rout × cds × ld × ls × rout × cgs × ld × lg × zo2 × cgd × ld × lg × zo2 × cgs × ld × ls × zo × cgd × ld × ls × zo × cgs × ld × ls × zo2 × cgd × ld × ls × zo2 × cgs × lg × ls × zo2 × cgd × lg × ls × zo2 × co × ld × ls × zo2 × cgd × gm × ld × lg × rout × zo2 × cgd × gm × ld × ls × rout × zo × cgd × gm × ld × ls × rout × zo2 × cgd × gm × lg × ls × rout × zo2 × co × gm × ld × ls × rout × zo2 × cgs × cgd × ld × rout × zo × zo2 × cgs × cds × ld × rout × zo × zo2 × cgd × cds × ld × rout × zo ×

zo2 × cgs × cgd × ls × rout × zo × zo2 × cgs × cds × ls × rout × zo × zo2 × cgd × cds × ls × rout × zo × zo2 × cgs × co × ld × rout × zo × zo2 × cgd × co × ld × rout × zo × zo2) × s^3 × (ld × ls × gm × ld × ls × rout × cgs × ld × rout × zo × cgd × ld × rout × zo × cgd × ld × rout × zo2 × cds × ld × rout × zo2 × cgs × lg × rout × zo2 × cgd × lg × rout × zo2 × cgs × ls × rout × zo2 × cds × ls × rout × zo2 × co × ld × rout × zo2 × cgs × ld × zo × zo2 × cgd × ld × zo × zo2 × cgs × ls × zo × zo2 × cgd × ls × zo × zo2 × cgd × gm × ld × rout × zo × zo2 × cgd × gm × ls × rout × zo × zo2) × s^2 × (ld × rout × ld × zo2 × ls × zo2 × gm × ls × rout × zo2 × cgs × rout × zo × zo2 × cgd × rout × zo × zo2) × s × rout × zo2

$$\text{zout}_{\text{common-source}} = \frac{\text{numzout}(\text{cs})}{\text{denzout}(\text{cs})}. \quad (4)$$

numzout(cs) = (cgs × cgd × ld × lg × ls× rout + cgs × cds × ld × lg × ls × rout + cgd × cds × ld × lg × ls × rout) × s^5 + (cgs × ld × lg × ls + cgd × ld × lg × ls + cgd × gm × ld × lg × ls × rout + cgs × cgd × ld × ls × rout × zo + cgs × cds × ld × ls ×rout × zo + cgd × cds × ld × ls × rout × zo) × s^4 + (cgs × ld × lg× rout + cgd × ld × lg × rout + cgs × ld × ls × rout + cds × ld ×ls × rout + cgs × ld × ls × zo + cgd × ld × ls × zo + cgd × gm ×ld × ls × rout × zo) × s^3 + (ld × ls + gm × ld × ls× rout + cgs × ld × rout × zo + cgd × ld × rout × zo) × s^2 + ld × rout × s.

denzout(cs) = (cgs × cgd × co × ld × lg × ls × rout + cgs × cds × co × ld × lg × ls × rout + cgd × cds × co × ld × lg × ls × rout) × s^6 + (cgs × co × ld × lg × ls + cgd × co × ld × lg × ls + cgd × co × gm × ld × lg × ls × rout + cgs × cgd × co × ld × ls × rout × zo + cgs × cds × co × ld × ls × rout × zo + cgd × cds × co × ld × ls × rout × zo) × s^5 + (cgs × cgd × ld × lg × rout + cgs × cds × ld × lg × rout + cgd × cds × ld × lg × rout + cgs × cgd × ld × ls × rout + cgs × cds × ld × ls × rout + cgd × cds × ld × ls × rout + cgs × cgd × lg × ls × rout + cgs × cds × lg × ls × rout + cgd × cds × lg × ls × rout + cgs × co × ld × lg × rout + cgd × co × ld × lg × rout + cgs × co × ld × ls × rout + cds × co × ld × ls × rout + cgs × co × ld × ls × zo + cgd × co × ld × ls × zo + cgd × co × gm × ld × ls × rout × zo) × s^4 + (cgs × ld × lg + cgd × ld × lg + cgs × ld × ls + cgd × ld × ls + cgs × lg × ls + cgd × lg × ls + co × ld × ls + cgd × gm × ld × lg × rout + cgd × gm × ld × ls × rout + cgd × gm × lg × ls × rout + co × gm × ld × ls × rout + cgs × cgd × ld × rout × zo + cgs × cds × ld × rout × zo + cgd × cds × ld × rout × zo + cgs × cgd × ls × rout × zo + cgs × cds × ls × rout × zo + cgd × cds × ls × rout × zo + cgs × co × ld × rout × zo + cgd × co × ld × rout × zo) × s^3 + (cgd × ld × rout + cds × ld × rout + cgs × lg × rout + cgd × lg × rout + cgs × ls × rout + cds × ls × rout + co × ld × rout + cgs × ld × zo + cgd × ld × zo + cgs × ls × zo + cgd × ls × zo + cgd × gm × ld × rout × zo + cgd × gm × ls × rout × zo) × s^2 + (ld + ls + gm × ls × rout + cgs × rout × zo + cgd × rout × zo) × s + rout

$$\text{zin}_{\text{common-source}} = \frac{\text{numzin}(\text{cs})}{\text{denzin}(\text{cs})}. \quad (5)$$

numzin(cs) = (cgs × cgd × co × ld × lg × ls × rout × zo2 + cgs × cds × co × ld × lg × ls × rout × zo2 + cgd × cds × co × ld × lg × ls × rout × zo2) × s^6 + (cgs × cgd × ld × lg × ls × rout + cgs × cds × ld × lg × ls × rout + cgd × cds × ld × lg × ls × rout + cgs × co × ld × lg × ls × zo2 + cgd × co × ld × lg × ls × zo2 + cgd × co × gm × ld × lg × ls × rout × zo2) × s^5 + (cgs × ld × lg × ls + cgd × ld × lg × ls + cgd × gm × ld × lg × ls × rout + cgs × cgd × ld × lg × rout × zo2 + cgs × cds × ld × lg × rout × zo2 + cgd × cds × ld × lg × rout × zo2 + cgs × cgd × ld × ls × rout × zo2 + cgs × cds × ld × ls × rout × zo2 + cgd × cds × ld × ls × rout × zo2 + cgs × cgd × lg × ls × rout × zo2 + cgs × cds × lg × ls × rout × zo2 + cgd × cds × lg × ls × rout × zo2 + cgs × co × ld × lg × rout × zo2 + cgd × co × ld × lg × rout × zo2 + cgs × co × ld × ls × rout × zo2 + cds × co × ld × ls × rout × zo2) × s^4 + (cgs × ld × lg × rout + cgd × ld × lg × rout + cgs × ld × ls × rout + cds × ld × ls × rout + cgs × ld × lg × zo2 + cgd × ld × lg × zo2 + cgs × ld × ls × zo2 + cgd × ld × ls × zo2 + cgs × lg × ls × zo2 + cgd × lg × ls × zo2 + co × ld × ls × zo2 + cgd × gm × ld × lg × rout × zo2 + cgd × gm × ld × ls × rout × zo2 + cgd × gm × lg × ls × rout × zo2 + co × gm × ld × ls × rout × zo2) × s^3 + (ld × ls + gm × ld × ls × rout + cgd × ld × rout × zo2 + cds × ld × rout × zo2 + cgs × lg × rout × zo2 + cgd × lg × rout × zo2 + cgs × ls × rout × zo2 + cds × ls × rout × zo2 + co × ld × rout × zo2) × s^2 + (ld × rout + ld × zo2 + ls × zo2 + gm × ls × rout × zo2) × s + rout × zo2.

denzin(cs) = (cgs × cgd × co × ld × ls × rout × zo2 + cgs × cds × co × ld × ls × rout × zo2 + cgd × cds × co × ld × ls × rout × zo2) × s^5 + (cgs × cgd × ld × ls × rout + cgs × cds × ld × ls × rout + cgd × cds × ld × ls × rout + cgs × co × ld × ls × zo2 + cgd × co × ld × ls × zo2 + cgd × co × gm × ld × ls × rout × zo2) × s^4 + (cgs × ld × ls + cgd × ld × ls + cgd × gm × ld × ls × rout + cgs × cgd × ld × rout × zo2 + cgs × cds × ld × rout × zo2 + cgd × cds × ld × rout × zo2 + cgs × cgd × ls × rout × zo2 + cgs × cds × ls × rout × zo2 + cgd × cds × ls × rout × zo2 + cgs × co × ld × rout × zo2 + cgd × co × ld × rout × zo2) × s^3 + (cgs × ld × rout + cgd × ld × rout + cgs × ld × zo2 + cgd × ld × zo2 + cgs × ls × zo2 + cgd × ls × zo2 + cgd × gm × ld × rout × zo2 + cgd × gm × ls × rout × zo2) × s^2 + (cgs × rout × zo2 + cgd × rout × zo2) × s.

Here,

rout is the output resistor of M1,

zo2 is the impedance of output port,

cgd is the capacitor seen through gate-to-drain of M1,

cds is the capacitor seen through drain-to-source of M1,

cgs is the capacitor seen through gate-to-source of M1,

gm is transconductance of M1,

s: $2 \times \pi \times f \times \sqrt{-1}$,

f is the frequency.

In order to demonstrate the considerable error coming from miscalculation of input impedance, output impedance, or gain, the input impedance is simulated by HSPICE and compared to the formula which has been utilized to calculate Lg, Ls, and Ld, depicted in Figure 7.

As can be observed in Figure 7, both imaginary and real parts of the Zin are demonstrated. The circuit, in Figure 5, is designed at 7 GHz for the best S11. Hence, the real part of Zin should be 50 and the imaginary part should be 0. The elements are designed by the precise formulas and the

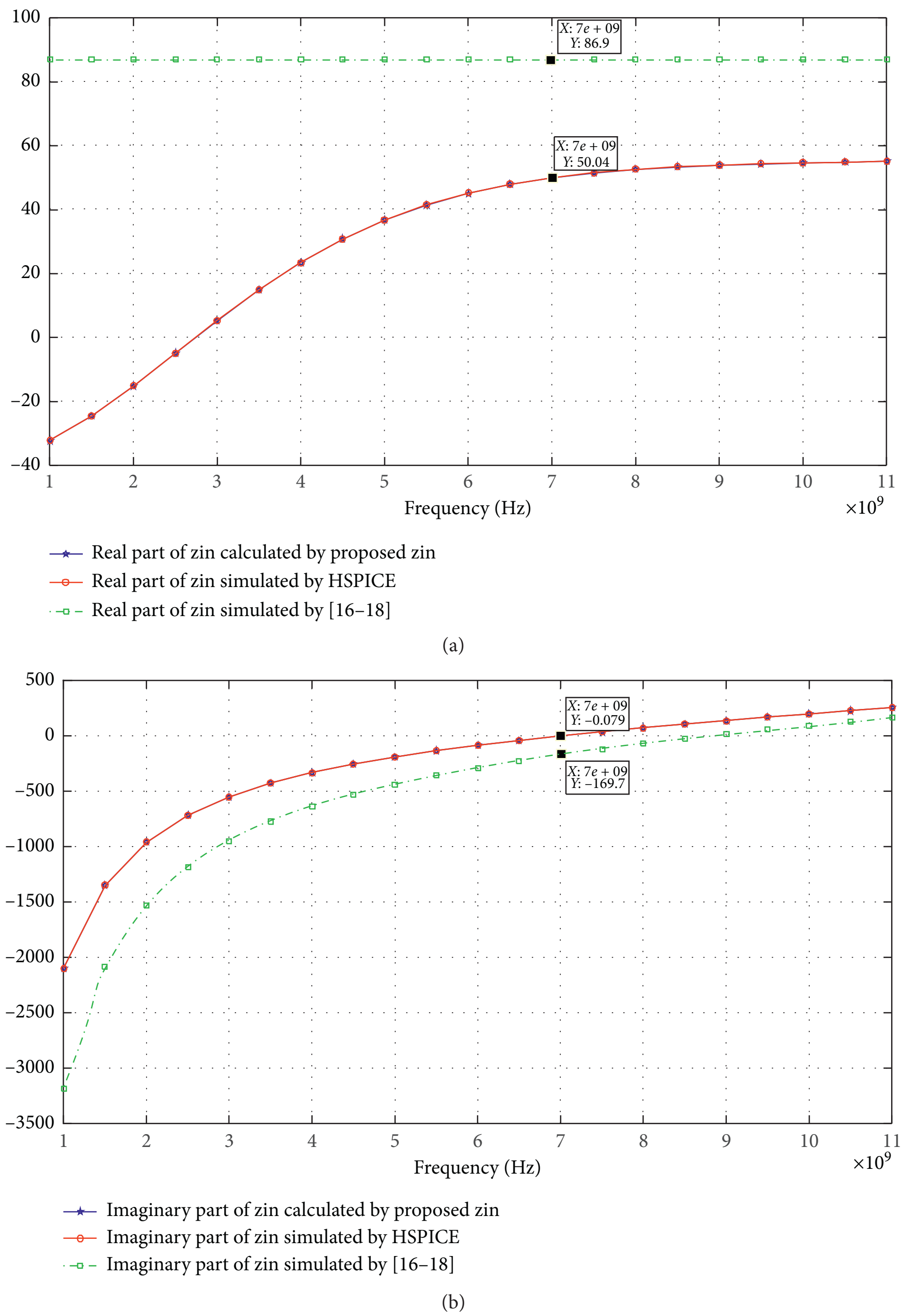

Figure 7: Comparison of the real part and imaginary part of input impedance.

output is demonstrated in Figure 7. The imaginary part, at 7 GHz, is −169.7, coming from previous formulas, versus −0.079, coming from the precise equation (5) proposed in this paper and HSPICE simulation. In addition, the real part, at 7 GHz, is 86.9 calculated by previous formula versus 50.04 calculated with both proposed formula and HSPICE simulation. It can be obviously observed that the error between imaginary parts and real parts of the precise formulas, calculated in this paper, and HSPICE simulation is zero. The previous formula, on the other hand, has more than 100% error in calculation. The aforementioned comments are applicable to both gain and output impedance. Hence, barely can elements be accurately designed by the formulas which have been proposed so far. Indeed, the more precise the formulas are, the more accurate the design will be.

The output of the proposed LNA is a cascode LNA. The LNA and its equivalent circuit are depicted in Figures 8 and 9.

The cascode LNA is used to bring down S12 considerably, thereby making the LNA more stable. Furthermore, it is utilized to enhance s21 too. Consequently, the main

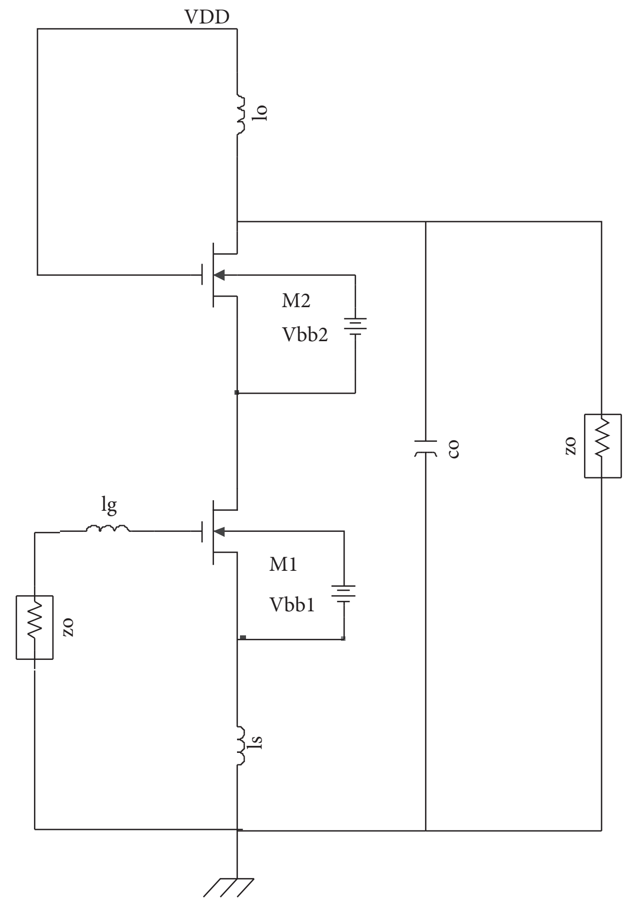

Figure 8: Cascode LNA.

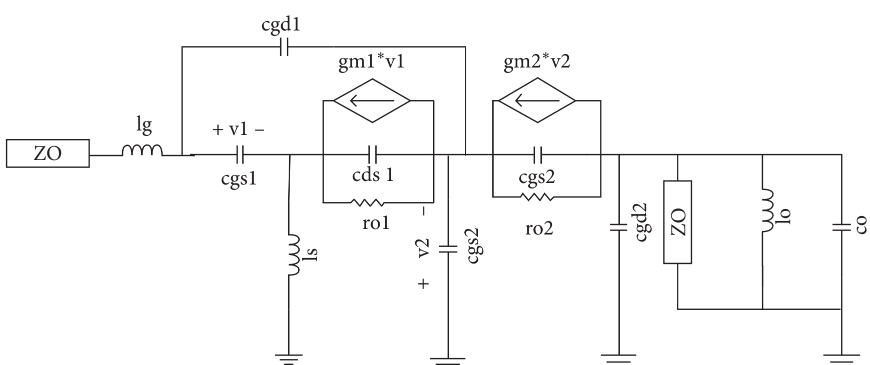

Figure 9: The equivalent circuit of the cascode LNA.

purpose of the cascode LNA is to amplify the signal appropriately. Hence, the calculation of the gain is calculated by solving the circuit existing in Figure 9. The gain of the cascode LNA is given by

$$\text{gaincas} = \frac{\text{numcas}}{\text{dencas}}. \tag{6}$$

$\text{numcas} = ((\text{cgs1} \times \text{cgd1} \times \text{cds2} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo} + \text{cgs1} \times \text{cds1} \times \text{cds2} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo} + \text{cgd1} \times \text{cds1} \times \text{cds2} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo}) \times s^5 + (\text{cgs1} \times \text{cgd1} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{zo} + \text{cgs1} \times \text{cds1} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{zo} + \text{cgs1} \times \text{cds2} \times \text{ls} \times \text{lo} \times \text{ro2} \times \text{zo} + \text{cgd1} \times \text{cds1} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{zo} + \text{cgd1} \times \text{cds2} \times \text{ls} \times \text{lo} \times \text{ro2} \times \text{zo} + \text{cgs1} \times \text{cgd1} \times \text{gm2} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo} + \text{cgs1} \times \text{cds1} \times \text{gm2} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo} + \text{cgd1} \times \text{cds1} \times \text{gm2} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo} + \text{cgd1} \times \text{cds2} \times \text{gm1} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo}) \times s^4 + (\text{cgs1} \times \text{ls} \times \text{lo} \times \text{zo} + \text{cgd1} \times \text{ls} \times \text{lo} \times \text{zo} + \text{cgs1} \times \text{gm2} \times \text{ls} \times \text{lo} \times \text{ro2} \times \text{zo} + \text{cgd1} \times \text{gm1} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{zo} + \text{cgd1} \times \text{gm2} \times \text{ls} \times \text{lo} \times \text{ro2} \times \text{zo} + \text{cgd1} \times \text{cds2} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo} + \text{cgd1} \times \text{gm1} \times \text{gm2} \times \text{ls} \times \text{lo} \times \text{ro1} \times \text{ro2} \times \text{zo}) \times s^3 + (\text{cgd1} \times \text{lo} \times \text{ro1} \times \text{zo} + \text{cgd1} \times \text{gm2} \times \text{lo} \times$

ro1 × ro2 × zo-cds2 × gm1 × lo × ro1 × ro2 × zo) × s^2-(gm1 × lo × ro1 × zo-gm1 × gm2 × lo × ro1 × ro2 × zo) × s).

dencas = ((cgs1 × cgs2 × cgd1 × cgd2 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cgd1 × cds2 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cgd2 × cds1 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cds1 × cds2 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgd1 × cgd2 × cds2 × ls × lg × lo × ro1 × ro2 × zo × cgs2 × cgd1 × cgd2 × cds1 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgd2 × cds1 × cds2 × ls × lg × lo × ro1 × ro2 × zo × cgs2 × cgd1 × cds1 × cds2 × ls × lg × lo × ro1 × ro2 × zo × cgd1 × cgd2 × cds1 × cds2 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cgd1 × co × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cds1 × co × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgd1 × cds2 × co × ls × lg × lo × ro1 × ro2 × zo × cgs2 × cgd1 × cds1 × co × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cds1 × cds2 × co × ls × lg × lo × ro1 × ro2 × zo × cgd1 × cds1 × cds2 × co × ls × lg × lo × ro1 × ro2 × zo) × s^7 × (cgs1 × cgs2 × cgd1 × ls × lg × lo × ro1 × ro2 × cgs1 × cgs2 × cds1 × ls × lg × lo × ro1 × ro2 × cgs1 × cgd1 × cds2 × ls × lg × lo × ro1 × ro2 × cgs2 × cgd1 × cds1 × ls × lg × lo × ro1 × ro2 × cgs1 × cds1 × cds2 × ls × lg × lo × ro1 × ro2 × cgd1 × cds1 × cds2 × ls × lg × lo × ro1 × ro2 × cgs1 × cgs2 × cgd1 × ls × lg × lo × ro1 × zo × cgs1 × cgs2 × cgd2 × ls × lg × lo × ro2 × zo × cgs1 × cgs2 × cds1 × ls × lg × lo × ro1 × zo × cgs1 × cgd1 × cgd2 × ls × lg × lo × ro1 × zo × cgs1 × cgs2 × cds2 × ls × lg × lo × ro2 × zo × cgs2 × cgd1 × cgd2 × ls × lg × lo × ro2 × zo × cgs1 × cgd2 × cds1 × ls × lg × lo × ro1 × zo × cgs2 × cgd1 × cds1 × ls × lg × lo × ro1 × zo × cgs1 × cgd2 × cds2 × ls × lg × lo × ro2 × zo × cgs2 × cgd1 × cds2 × ls × lg × lo × ro2 × zo × cgd1 × cgd2 × cds1 × ls × lg × lo × ro1 × zo × cgd1 × cgd2 × cds2 × ls × lg × lo × ro2 × zo × cgs1 × cgs2 × co × ls × lg × lo × ro2 × zo × cgs1 × cgd1 × co × ls × lg × lo × ro1 × zo × cgs2 × cgd1 × co × ls × lg × lo × ro2 × zo × cgs1 × cds1 × co × ls × lg × lo × ro1 × zo × cgs1 × cds2 × co × ls × lg × lo × ro2 × zo × cgd1 × cds1 × co × ls × lg × lo × ro1 × zo × cgd1 × cds2 × co × ls × lg × lo × ro2 × zo × cgs1 × cgs2 × cgd1 × cgd2 × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgs2 × cgd1 × cds2 × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgs2 × cgd2 × cds1 × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgs2 × cds1 × cds2 × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgd1 × cgd2 × cds2 × ls × lo × ro1 × ro2 × zo^2 × cgs2 × cgd1 × cgd2 × cds1 × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgd2 × cds1 × cds2 × ls × lo × ro1 × ro2 × zo^2 × cgs2 × cgd1 × cds1 × cds2 × ls × lo × ro1 × ro2 × zo^2 × cgd1 × cgd2 × cds1 × cds2 × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgs2 × cgd1 × co × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgs2 × cds1 × co × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgd1 × cds2 × co × ls × lo × ro1 × ro2 × zo^2 × cgs2 × cgd1 × cds1 × co × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cds1 × cds2 × co × ls × lo × ro1 × ro2 × zo^2 × cgd1 × cds1 × cds2 × co × ls × lo × ro1 × ro2 × zo^2 × cgs1 × cgd1 × cgd2 × gm2 × ls × lg × lo × ro1 × ro2 × zo × cgs2 × cgd1 × cgd2 × gm1 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgd2 × cds1 × gm2 × ls × lg × lo × ro1 × ro2 × zo × cgs2 × cgd1 × cds2 × gm1 × ls × lg × lo × ro1 × ro2 × zo × cgd1 × cgd2 × cds1 × gm2 × ls × lg × lo × ro1 × ro2 × zo × cgd1 × cgd2 × cds2 × gm1 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cgd1 × co × gm2 × ls × lg × lo × ro1 × ro2 × zo × cgs2 × cgd1 × co × gm1 × ls × lg × lo × ro1 × ro2 × zo × cgs1 × cds1 × co × gm2 × ls × lg × lo × ro1 × ro2 × zo × cgd1 × cds1 × co × gm2 × ls × lg × lo × ro1 × ro2 × zo × cgd1 × cds2 × co × gm1 × ls × lg × lo × ro1 × ro2 × zo) × s^6 × (cgs1 × cgs2 × ls × lg × lo × ro2 × cgs1 × cgd1 × ls × lg × lo × ro1 × cgs2 × cgd1 × ls × lg × lo × ro2 × cgs1 × cds1 × ls × lg × lo × ro1 × cgs1 × cds2 × ls × lg × lo × ro2 × cgd1 × cds1 × ls × lg × lo × ro1 × cgd1 × cds2 × ls × lg × lo × ro2 × cgs1 × cgs2 × ls × lg × lo × zo × cgs1 × cgd2 × ls × lg × lo × zo × cgs2 × cgd1 × ls × lg × lo × zo × cgd1 × cgd2 × ls × lg × lo × zo × cgs1 × co × ls × lg × lo × zo × cgd1 × co × ls × lg × lo × zo × cgs1 × cgs2 × cgd1 × ls × lo × ro1 × zo^2 × cgs1 × cgs2 × cgd2 × ls × lo × ro2 × zo^2 × cgs1 × cgs2 × cds1 × ls × lo × ro1 × zo^2 × cgs1 × cgd1 × cgd2 × ls × lo × ro1 × zo^2 × cgs1 × cgs2 × cds2 × ls × lo × ro2 × zo^2 × cgs2 × cgd1 × cgd2 × ls × lo × ro2 × zo^2 × cgs1 × cgd2 × cds1 × ls × lo × ro1 × zo^2 × cgs2 × cgd1 × cds1 × ls × lo × ro1 × zo^2 × cgs1 × cgd2 × cds2 × ls × lo × ro2 × zo^2 × cgs2 × cgd1 × cds2 × ls × lo × ro2 × zo^2 × cgd1 × cgd2 × cds1 × ls × lo × ro1 × zo^2 × cgd1 × cgd2 × cds2 × ls × lo × ro2 × zo^2 × cgs1 × cgs2 × co × ls × lo × ro2 × zo^2 × cgs1 × cgd1 × co × ls × lo × ro1 × zo^2 × cgs2 × cgd1 × co × ls × lo × ro2 × zo^2 × cgs1 × cds1 × co × ls × lo × ro1 × zo^2 × cgs1 × cds2 × co × ls × lo × ro2 × zo^2 × cgd1 × cds1 × co × ls × lo × ro1 × zo^2 × cgd1 × cds2 × co × ls × lo × ro2 × zo^2 × cgs1 × cgd1 × gm2 × ls × lg × lo × ro1 × ro2 × cgs2 × cgd1 × gm1 × ls × lg × lo × ro1 × ro2 × cgs1 × cds1 × gm2 × ls × lg × lo × ro1 × ro2 × cgd1 × cds1 × gm2 × ls × lg × lo × ro1 × ro2 × cgd1 × cds2 × gm1 × ls × lg × lo × ro1 × ro2 × cgs2 × cgd1 × gm1 × ls × lg × lo × ro1 × zo × cgs1 × cgd2 × gm2 × ls × lg × lo × ro2 × zo × cgd1 × cgd2 × gm1 × ls × lg × lo × ro1 × zo × cgd1 × cgd2 × gm2 × ls × lg × lo × ro2 × zo × cgs1 × co × gm2 × ls × lg × lo × ro2 × zo × cgd1 × co × gm1 × ls × lg × lo × ro1 × zo × cgd1 × co × gm2 × ls × lg × lo × ro2 × zo × cgs1 × cgs2 × cgd1 × ls × lg × ro1 × ro2 × zo × cgs1 × cgs2 × cds1 × ls × lg × ro1 × ro2 × zo × cgs1 × cgd1 × cds2 × ls × lg × ro1 × ro2 × zo × cgs2 × cgd1 × cds1 × ls × lg × ro1 × ro2 × zo × cgs1 × cds1 × cds2 × ls × lg × ro1 × ro2 × zo × cgd1 × cds1 × cds2 × ls × lg × ro1 × ro2 × zo × cgs1 × cgs2 × cgd1 × ls × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cgd2 × ls × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cds1 × ls × lo × ro1 × ro2 × zo × cgs1 × cgd1 × cgd2 × ls × lo × ro1 × ro2 × zo × cgs1 × cgs2 × cds2 × ls × lo × ro1 × ro2 × zo+2.0 × cgs1 × cgd1 × cds2 × ls × lo × ro1 × ro2 × zo × cgs1 × cgd2 × cds1 × ls × lo × ro1 × ro2 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lo × ro1 × ro2 × zo × cgs1 × cgd1 × co × ls × lo × ro1 × ro2 × zo × cgs1 × cds1 × co × ls × lo × ro1 × ro2 × zo × cgs1 × cds2 × co × ls × lo × ro1 × ro2 × zo × cgs2 × cds1 × co × ls × lo × ro1 × ro2 × zo × cgd1 × cds1 × co × ls × lo × ro1 × ro2 × zo × cds1 × cds2 × co × ls × lo × ro1 × ro2 ×

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× gm1 × gm2 × ls × lg × lo × ro1 × ro2 × zo) × s^5 × (cgs1 × ls × lg × lo × cgd1 × ls × lg × lo × cgs1 × cgs2 × ls × lo × zo^2 × cgs1 × cgd2 × ls × lo × zo^2 × cgs2 × cgd1 × ls × lo × zo^2 × cgd1 × cgd2 × ls × lo × zo^2 × cgs1 × co × ls × lo × zo^2 × cgd1 × co × ls × lo × zo^2 × cgs1 × gm2 × ls × lg × lo × ro2 × cgd1 × gm1 × ls × lg × lo × ro1 × cgd1 × gm2 × ls × lg × lo × ro2 × cgs1 × cgs2 × ls × lo × ro1 × ro2 × cgs1 × cgd1 × ls × lo × ro1 × ro2 × cgs1 × cds1 × ls × lo × ro1 × ro2 × cgs1 × cds2 × ls × lo × ro1 × ro2 × cgs2 × cds1 × ls × lo × ro1 × ro2 × cgd1 × cds1 × ls × lo × ro1 × ro2 × cds1 × cds2 × ls × lo × ro1 × ro2 × cgs1 × cgs2 × lg × lo × ro1 × ro2 × cgs1 × cgd1 × lg × lo × ro1 × ro2 × cgs2 × cgd1 × lg × lo × ro1 × ro2 × cgs1 × cds1 × lg × lo × ro1 × ro2 × cgs1 × cds2 × lg × lo × ro1 × ro2 × cgd1 × cds1 × lg × lo × ro1 × ro2 × cgd1 × cds2 × lg × lo × ro1 × ro2 × cgs1 × cgs2 × ls × lg × ro2 × zo × cgs1 × cgd1 × ls × lg × ro1 × zo × cgs2 × cgd1 × ls × lg × ro2 × zo × cgs1 × cds1 × ls × lg × ro1 × zo × cgs1 × cds2 × ls × lg × ro2 × zo × cgd1 × cds1 × ls × lg × ro1 × zo × cgd1 × cds2 × ls × lg × ro2 × zo × cgs1 × cgs2 × ls × lo × ro1 × zo × cgs1 × cgs2 × ls × lo × ro2 × zo+2.0 × cgs1 × cgd1 × ls × lo × ro1 × zo × cgs1 × cgd2 × ls × lo × ro1 × zo × cgs1 × cgd2 × ls × lo × ro2 × zo × cgs2 × cgd1 × ls × lo × ro2 × zo × cgs2 × cgd2 × ls × lo × ro2 × zo+2.0 × cgs1 × cds1 × ls × lo × ro1 × zo × cgs2 × cds1 × ls × lo × ro1 × zo+2.0 × cgs1 × cds2 × ls × lo × ro2 × zo × cgd1 × cgd2 × ls × lo × ro2 × zo × cgs2 × cds2 × ls × lo × ro2 × zo+2.0 × cgd1 × cds1 × ls × lo × ro1 × zo × cgd2 × cds1 × ls × lo × ro1 × zo+2.0 × cgd1 × cds2 × ls × lo × ro2 × zo × cgd2 × cds2 × ls × lo × ro2 × zo × cgs1 × cgs2 × lg × lo × ro1 × zo × cgs1 × cgd1 × lg × lo × ro1 × zo × cgs1 × cgd2 × lg × lo × ro1 × zo × cgs2 × cgd1 × lg × lo × ro1 × zo × cgs1 × cgd2 × lg × lo × ro2 × zo × cgs1 × cds1 × lg × lo × ro1 × zo × cgd1 × cgd2 × lg × lo × ro1 × zo × cgs1 × cds2 × lg × lo × ro2 × zo × cgd1 × cgd2 × lg × lo × ro2 × zo × cgd1 × cds1 × lg × lo × ro1 × zo × cgd1 × cds2 × lg × lo × ro2 × zo × cgs1 × co × ls × lo × ro1 × zo × cgs1 × co × ls × lo × ro2 × zo × cgs2 × co × ls × lo × ro2 × zo × cgd1 × co × ls × lo × ro2 × zo × cds1 × co × ls × lo × ro1 × zo × cds2 × co × ls × lo × ro2 × zo × cgs1 × co × lg × lo × ro1 × zo × cgs1 × co × lg × lo × ro2 × zo × cgd1 × co × lg × lo × ro1 × zo × cgd1 × co × lg × lo × ro2 × zo × cgs2 × cgd1 × gm1 × ls × lo × ro1 × zo^2 × cgs1 × cgd2 × gm2 × ls × lo × ro2 × zo^2 × cgd1 × cgd2 × gm1 × ls × lo × ro1 × zo^2 × cgd1 × cgd2 × gm2 × ls × lo × ro2 × zo^2 × cgs1 × co × gm2 × ls × lo × ro2 × zo^2 × cgd1 × co × gm1 × ls × lo × ro1 × zo^2 × cgd1 × co × gm2 × ls × lo × ro2 × zo^2 × cgs1 × cgs2 × cgd1 × ls × ro1 × ro2 × zo^2 × cgs1 × cgs2 × cds1 × ls × ro1 × ro2 × zo^2 × cgs1 × cgd1 × cds2 × ls × ro1 × ro2 × zo^2 × cgs2 × cgd1 × cds1 × ls × ro1 × ro2 × zo^2 × cgs1 × cds1 × cds2 × ls × ro1 × ro2 × zo^2 × cgd1 × cds1 × cds2 × ls × ro1 × ro2 × zo^2 × cgs1 × 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zo × cds2 × co × gm1 × ls × lo × ro1 × ro2 × zo × cgs1 × co × gm2 × lg × lo × ro1 × ro2 × zo × cgd1 × co × gm1 × lg × lo × ro1 × ro2 × zo × cgd1 × co × gm2 × lg × lo × ro1 × ro2 × zo × cgd1 × cgd2 × gm1 × gm2 × ls × lo × ro1 × ro2 × zo^2 × cgd1 × co × gm1 × gm2 × ls × lo × ro1 × ro2 × zo^2) × s^4 × (cgs1 × ls × lo × ro1 × cgs1 × ls × lo × ro2 × cgs2 × ls × lo × ro2 × cgd1 × ls × lo × ro2 × cds1 × ls × lo × ro1 × cds2 × ls × lo × ro2 × cgs1 × lg × lo × ro1 × cgs1 × lg × lo × ro2 × cgd1 × lg × lo × ro1 × cgd1 × lg × lo × ro2 × cgs1 × ls × lg × zo × cgd1 × ls × lg × zo+2.0 × cgs1 × ls × lo × zo × cgs2 × ls × lo × zo+2.0 × cgd1 × ls × lo × zo × cgd2 × ls × lo × zo × cgs1 × lg × lo × zo × cgd1 × lg × lo × zo × co × ls × lo × zo × cgs1 × cgs2 × ls × ro2 × zo^2 × cgs1 × cgd1 × ls × ro1 × zo^2 × cgs2 × cgd1 × ls × ro2 × zo^2 × cgs1 × cds1 × ls × ro1 × zo^2 × cgs1 × cds2 × ls × ro2 × zo^2 × cgd1 × cds1 × ls × ro1 × zo^2 × cgd1 × cds2 × ls × ro2 × zo^2 × cgs1 × cgs2 × lo × ro1 × zo^2 × cgs1 × 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Here,

ro1 is the output resistor of M1,

ro2 is the output resistor of M2,

zo is the impedance of input or output port,

cgd1 is the capacitor seen through gate-to-drain of M1,

cds1 is the capacitor seen through drain-to-source of M1,

cgs1 is the capacitor seen through gate-to-source of M1,

cgd2 is the capacitor seen through gate-to-drain of M2,

cds2 is the capacitor seen through drain-to-source of M2,

cgs2 is the capacitor seen through gate-to-source of M2,

gm1 is transconductance of M1,

gm2 is transconductance of M2,

s: $2 \times \pi \times f \times \sqrt{-1}$,

f is the frequency.

The calculated formulas might be considered long and complicated. Nevertheless, owing to the fact that all formulas are solved by MATLAB, they have been solved easily.

3. Results and Discussion

One of the main objectives of the proposed LNA is having the minimum power consumption. Therefore, biasing technique and voltage supply are crucially significant. As can be observed in Figure 1, the LNA has two different voltage supplies: the first VDD1 = 0.3 volts; the second VDD2 = 0.6 volts. This technique reduces power consumption in the common-source LNA, thus decreasing the power consumption in the whole circuit. Besides, each of the transistors is biased in different regions. By allocating Vbb1 = 0.3 volts, M1 operates in weak inversion. The power consumption in the first stage, as a result, is 325 μW. M2 is designed to work in moderate inversion by Vbb2 = 0.5 volts. Moreover, M3 is put in strong inversion by Vbb3 = 0.3 volts. The power consumption in the second stage of the LNA is 638 μW. Therefore, the power consumption of the proposed LNA is 963 μW. The proposed LNA is designed to operate from 5 GHz to 10 GHz. The simulated results are depicted in Figures 10–15.

The stability of the circuit has been evaluated by

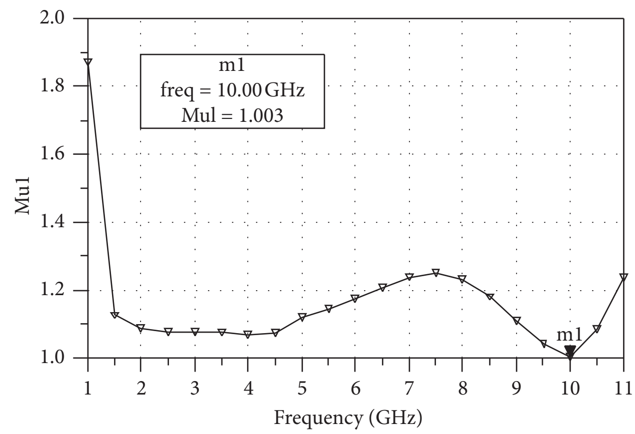

Figure 10: μ test.

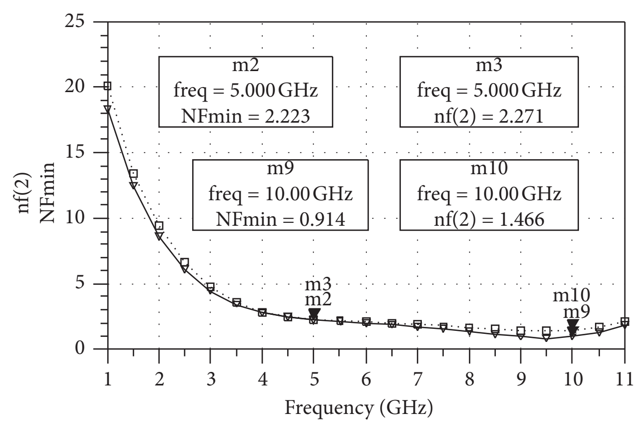

Figure 11: Noise figure and noise figure minimum.

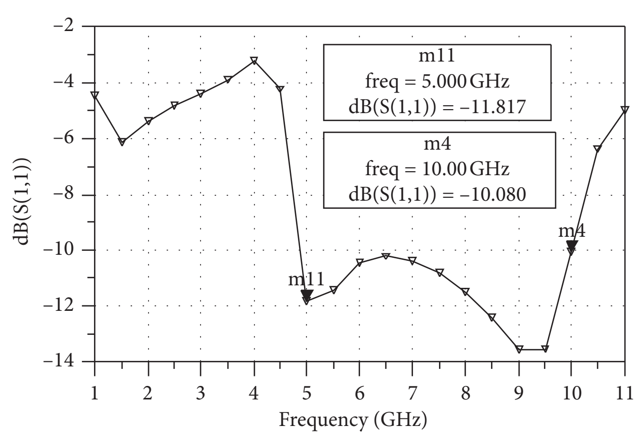

Figure 12: S11.

$$\mu = \frac{1 - |S11|^2 - |S22|^2 + |\Delta|^2}{2 \times |S12|^2 \times |S21|^2},$$
$$\Delta = S11 \times S22 - S12 \times S21. \quad (7)$$

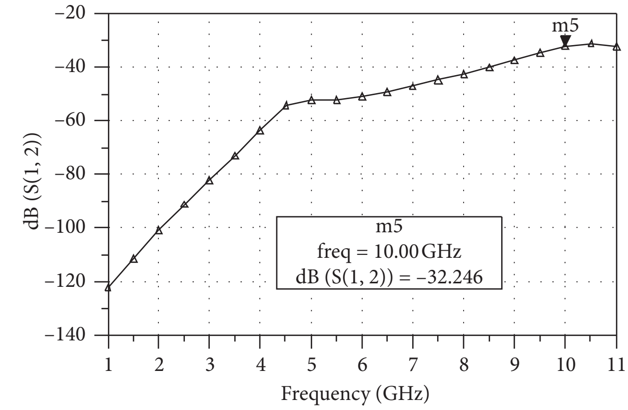

Figure 13: S12.

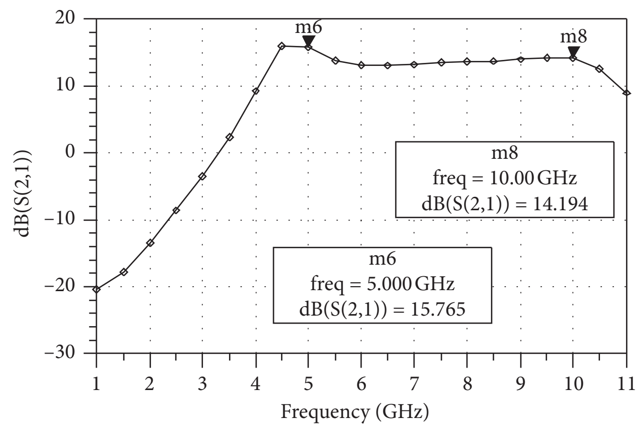

Figure 14: S21.

The stability of the LNA is guaranteed provided that μ is larger than one, demonstrated in Figure 10. The noise figure is shown in Figure 11 and it varies from 2.27 dB to 1.466 dB. The noise performance of the LNA is better at higher frequencies. The input impedance matching, S11, is less than −10 dB. On average, on the other hand, S11 is −11.52 dB. The power gain of the circuit, S21, is more than 13 dB and in average is 13.82 dB. The cascode LNA makes S12 less than −32 dB, making the LNA more stable.

The linearity of the LNA is simulated at 7.5 GHz and demonstrated in Figure 15. To evaluate the LNA with considering more results together, a figure of merit (FOM) is proposed [21].

$$\text{FOM} = \frac{|S21| \times \text{BW}\,(\text{GHz})}{|\text{NF} - 1| \times P_{\text{dc}}\,(\text{mW})}. \quad (8)$$

All results and the FOM are compared to other works in Table 1. The FOM is enhanced appreciably because of the power consumption and appropriate noise figure. Furthermore, the maximum rate of noise figure is used to calculate the FOM. As always, trade-offs can be mentioned in all parameters. For instance, if VDD1 is increased to 0.6 volts, noise figure is between 1.42 dB and 2 dB. Besides, power gain increases to more than 14 dB. In fact, the trade-off is between power consumption and power gain and noise figure. Indeed, by increasing VDD1 to 0.6 volts the power consumption has

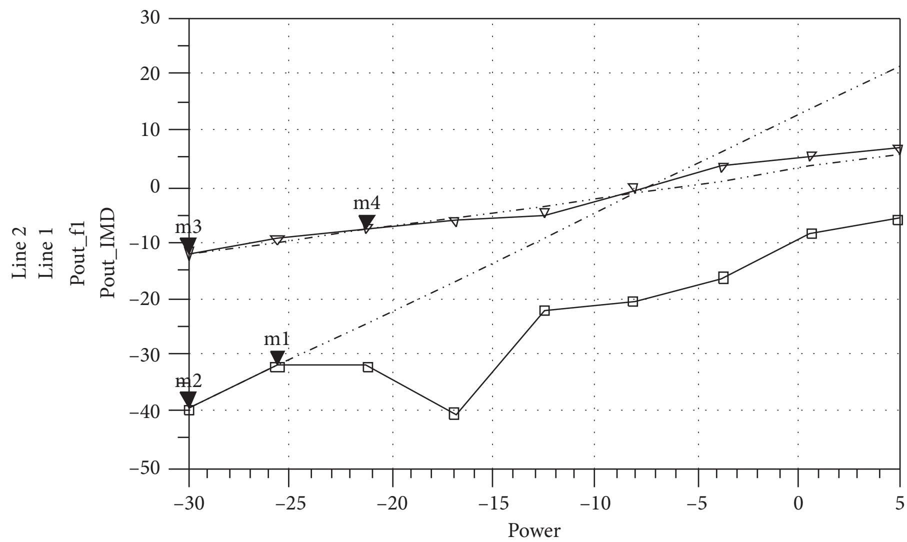

Figure 15: IIP3 at 7.5 GHz.

Table 1: Performance summary and comparison with other state-of-the-art works.

unit	Tech μm	BW GHz	Power mW	S21 dB	NF dB	S11 dB	IIP3 dBm	FOM
This work	0.13	5–10	0.963	13.82	1.46–2.27	<−11	−8	**56**
[22]	0.13	3.1–10.6	9	16.5	2–2.8	<−9.9	−5.1	13.75
[23]	0.13	1–10.6	26	16	2.3–4.5	<−12	2	4.55
[24]	0.13	2–9.6	19	11	3.6–4.8	<−8.3	−7.2	1.69
[25]	0.13	3–11	2.4	10	2.9–3.6	<−7.5	9.5	17.54
[26]	0.13	3.1–10.6	14.4	12.4	2.7–3.7	<−7.3	−3.8	3.8
[27]	0.09	0.02–2.3	18	21	1.4	<−10	−1.5	6.65
[28]	0.13	0.8–2	17.4	14.5	2.6	<−8.5	16	0.625
[29]	0.13	0.2–3.8	5.7	19	2.8–3.4	<−9	−4.2	6.67
[30]	0.065	0.2–5.2	21	13–15.6	<3.5	<−10	>0	1.24
[31]	0.13	0.1–2.1	3.11	19.2	2.4	–	9.6	35.1
[32]	0.13	3–12	8.5	13.5	4.3	<−11	−7	3.41
[33]	0.13	0.1–2.2	0.4	12.3	4.9	<−9	−10	17.9
[34]	0.09	0.1–7	0.75	12.6	5.5	–	−9	20.89
[35]	0.09	7.6	11.8	12.52	3–7	−9	−12	–

increased to 1.4 mW. In addition, even in comparison to other works, the power consumption is acceptable.

4. Conclusions

An ultra-wideband ultralow power LNA is proposed in this paper. The calculation and power consumption are the principal objectives of this paper. The sizes of transistors have been scaled down to nanometre, and the calculations proposed in this paper are applicable to all sizes of CMOS transistors. Since the purpose is the calculation and design, the implementation is not carried out. Nevertheless, many works have proved that the simulation results and the measured results are practically close to each other.

Data Availability

The data used to support the findings of this study are available from the author Hemad Heidari Jobaneh upon request via his e-mail: emehhj@gmail.com.

Conflicts of Interest

The author declares no conflicts of interest.

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