The Design of an Ultra-Low-Power Ultra-wideband (4.5GHz-9.5GHz) Low Noise Amplifier in 0.13µm CMOS Technology

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Abstract— **An ultra-low power and ultra-wideband LNA is designed and simulated in this paper. The core purpose of the design is the minimum power consumption in 0.13 µm CMOS technology. The proposed LNA is comprised of three differently biased common-source LNAs. Plus, the new and precise formulas for input impedance, output impedance, and the gain of common-source LNA are calculated in this paper. In order to bring down the power consumption of the circuit, the forward body biasing technique is utilised. MATLAB is used to design and solve all equations proposed in this paper. Furthermore, TSMC 0.13 µm CMOS process is used in Advanced Design System (ADS) to scrutinize the LNA. The results achieved are 2.13 dB-2.32 dB, -18.7 dB, 21.94 dB, -9, and 857 µW for Noise Figure (NF), the input matching (S11), gain (S21), IIP3, and power dissipation respectively.**

Keywords: 0.13µm CMOS, Ultra-Low-Power, Ultra-wideband, Low Noise Amplifier.

I. INTRODUCTION

One of the vital components in every receiver is a Low Noise Amplifier (LNA). A system is called ultra-wideband provided that it operates from 3.1 GHz to 10.6 GHz. Criteria such as power consumption, gain, noise figure, stability, and linearity have been mentioned to evaluate the performance of an LNA. Many topologies like common-source with forward body bias, common-source with resistive feedback, and noise cancelling have been utilized to achieve the aforementioned objectives [1-11]. The minimum voltage supply used was 0.6 volts, culminating in the best power gain (S21) and the best third order interface point (IIP3) [9]. The best input impedance matching was obtained by using a common-source with resistive feedback topology [1]. The Noise cancelling technique brought about the minimum noise figure among all works [6]. The minimum power consumption, 1.68 mW, was achieved by forward body biasing technique [11]. In this paper, a three stage common-source LNA, Chebyshev filter, and body biasing technique are utilized to form an ultra-wideband, ultra-low power LNA.

II. THE PROPOSED LNA

The designed LNA is comprised of three common-source LNAs and a Chebyshev filter, demonstrated in figure 1. The equivalent circuit of the LNA is depicted in figure 2. Each stage is separated by a capacitor,Cb, so as to separate their bias. A Chebyshev filter is utilized in the input of the circuit in order to filter the signal between the desired frequencies. Each part of the LNA is designed and calculated individually with the intention of being evaluated comprehensively.

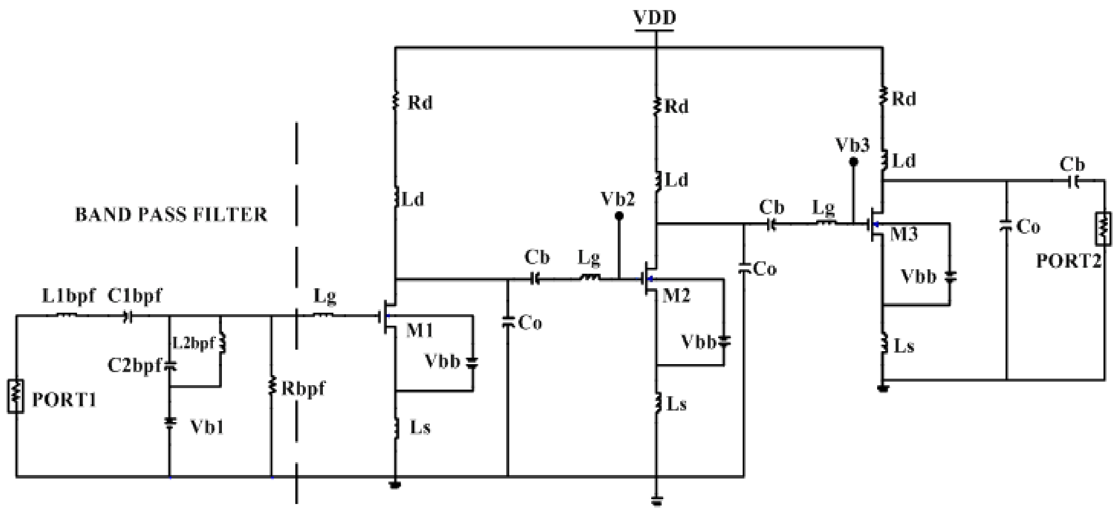

Figure 1: The proposed LNA

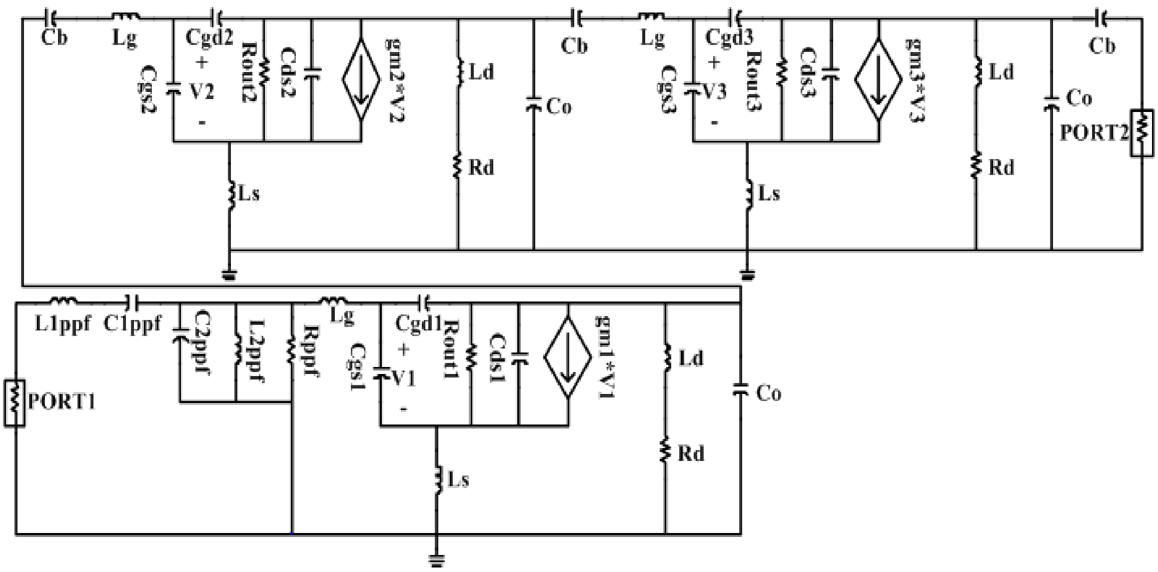

Figure 2: The equivalent circuit of the LNA

The Chebyshev filter is demonstrated in figure 3 and its components are given by:

$$L1bpf = \frac{0.5 \times Rbpf}{\pi(f2C - f1C)}$$
$$C1bpf = \frac{2(f2C - f1C)}{4 \times \pi \times Rbpf \times f2C \times f1C} \quad (1)$$
$$L2bpf = \frac{2 \times Rbpf \times (f2C - f1C)}{4 \times \pi \times (f2C \times f1C)}$$
$$C2bpf = \frac{0.5}{\pi \times Rbpf \times (f2C - f1C)}$$

In which:

f1C: lower passband frequency

f2C: higher passband frequency

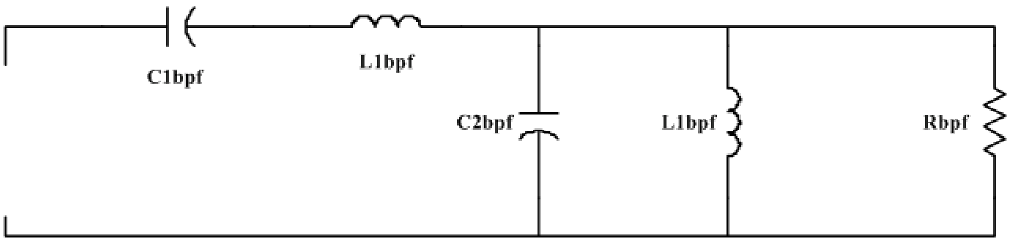

Figure 3: Chebyshev filter

Common-source (CS) LNA is an integral part of the design. Hence, input impedance, output impedance, and the gain of it are crucially significant for the sake of calculation. In many works the input impedance of a common-source is given by [12-14]:

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

Owing to the fact that the formula has an extreme error in real and imaginary parts, more precise calculations with minimum error are required to reduce the error coming from calculations [15-16]. Thus, the common-source LNA with forward body biasing technique and its equivalent circuit are shown in figure 4 and figure 5.

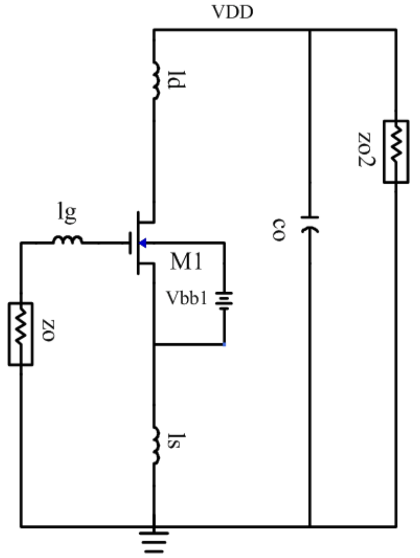

Figure 4: Common-Source LNA

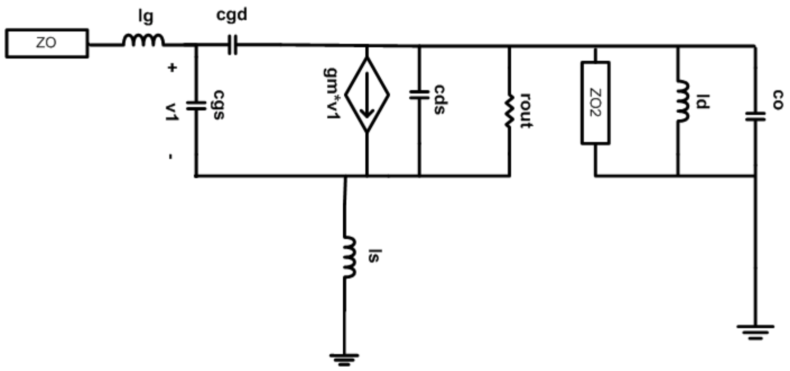

Figure 5: the equivalent circuit of common-source LNA

The existing circuit in figure 5 is solved and gain of the circuit (GAIN), output impedance (ZOUT), and input impedance (ZIN) are achieved and demonstrated from equation (3) to equation (5).

$$GAIN_{common-source} = \frac{numgain}{dengain} \quad (3)$$

numgain=ld×zo2×(cgs×cgd×ls×rout+cgs×cds×ls×rout+cgd×cds×ls×rout)×s^4+ld×zo2×(cgs×ls+cgd×ls+cgd×gm×ls×rout)×s^3 +cgd×ld×rout×zo2×s^2 -gm×ld×rout×zo2×s

dengain=(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+cgs×cgd×co×ld×ls×rout×zo×zo2+cgs×cds×co×ld×ls×rout×zo×zo2+cgd×cds×co×ld×ls×rout×zo×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×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)×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

$$ZOUT_{common-source} = \frac{numzout}{denzout} \quad (4)$$

numzout=(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=(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

$$ZIN_{common-source} = \frac{numzin}{denzin} \quad (5)$$

numzin=(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=(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

In which:

rout: the output resistor of M1

zo2= the impedance of output port

cgd: the capacitor seen through gate-to-drain of M1

cds: the capacitor seen through drain-to-source of M1

cgs: the capacitor seen through gate-to-source of M1

gm: transconductance of M1

f: frequency

Although the formulas might be conceptualized as complicated, all formulas are solved by MATLAB easily. Plus, unlike other formulas in other works, the formulas have not any approximation, resulting in minimizing the error in calculations.

III. RESULTS AND DISCUSSION

The LNA is composed of three common-source LNAs working in different regions. M1 and M3 are biased to work in strong inversion and M2 is biased to operate in moderate inversion. In addition, VDD is 0.2 volts for the purpose of reducing the power consumption of the circuit. The simulated results are depicted from figure 6 to figure 11.

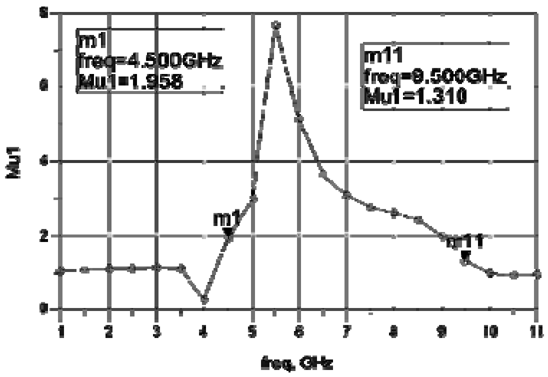

Figure 6: μ test for stability

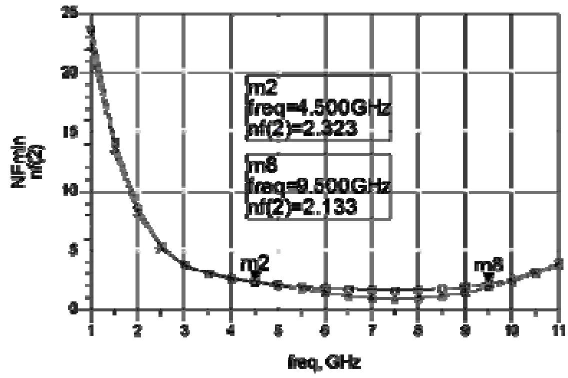

Figure 7: Noise Figure and Noise Figure minimum

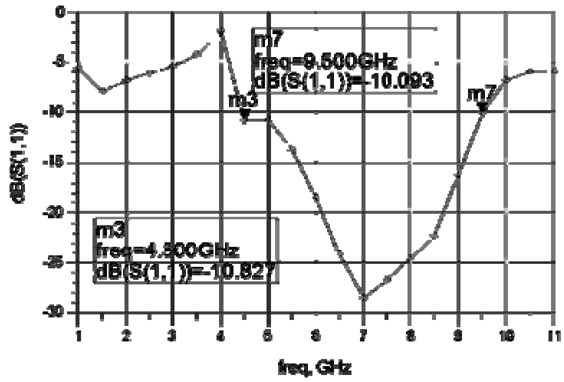

Figure 8: S11

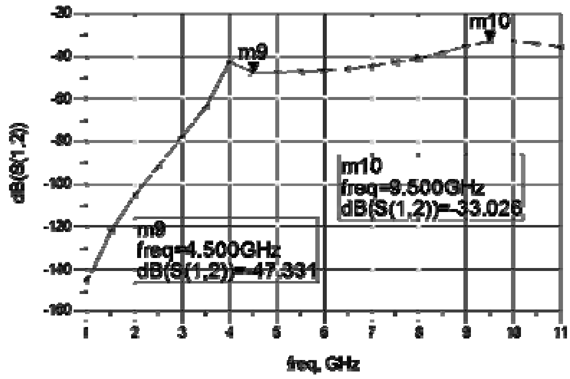

Figure 9: S12

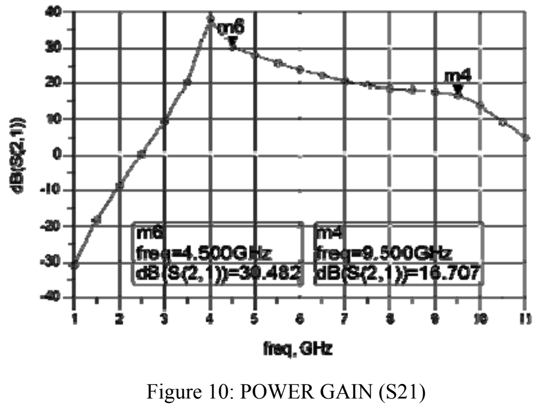

Figure 10: POWER GAIN (S21)

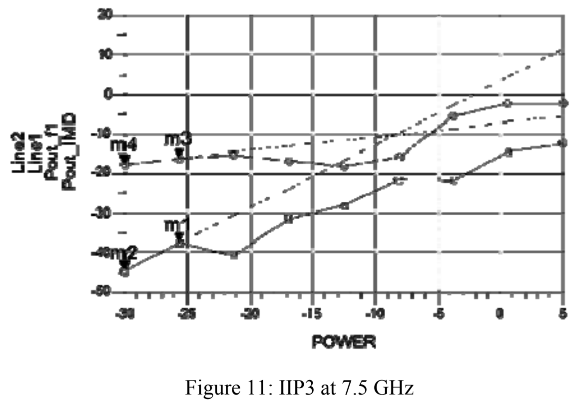

Figure 11: IIP3 at 7.5 GHz

The test by which the stability of the LNA can be guaranteed is μ test, given by:

$$\mu = \frac{1 - |S11|^2 - |S22|^2 + |\Delta|^2}{2 \times |S12|^2 \times |S21|^2} \quad (6)$$

$$\Delta = S11 \times S22 - S12 \times S21$$

In fact, an LNA is unconditionally stable provided that μ is larger than one, demonstrated in figure 6. The noise figure is between 2.32 dB and 2.13 dB and on average it is 1.84 dB, shown in figure 7. The input impedance matching, S11, is less than -10 dB during the frequencies and on average it is -18.7 dB, depicted in figure 8. Furthermore, the power gain of the LNA, S21, is between 30.48 dB and 16.7 dB and on average it is 21.94dB, illustrated in figure 10. S12, in addition, is less than -33 dB, making the LNA more stable. The linearity of the circuit, IIP3=-9 dBm, is measured at 7.5 GHz and demonstrated in figure 11.

The performance of an LNA can be evaluated more scrupulously provided that the four parameters including S21, bandwidth (BW), power consumption (Pdc), and Noise Figure create a figure of merit (FOM) [17]:

$$FOM = \frac{|S21| \times BW\,(GHz)}{|NF - 1| \times P_{dc}\,(mW)} \tag{7}$$

The results and the FOM are compared in table 1. The FOM is enhanced considerably because of the appropriate power consumption and noise figure. In fact, the power consumption is the minimum among all works.

Table 1: Performance Summary and Comparison with Other State-of-the-Art

	TECH	BW	VDD	Power	S21	NF	S11	IIP3	**FOM**
unit	µm	GHz	V	mW	dB	dB	dB	dBm	
This work	0.13	4.5-9.5	0.2	0.857	21.94	2.13-2.32	<-10	-9 (7.5GHz)	**128**
[1]	0.9	3.1–10.6	1.2	21.6	10.6	3.075	<-14.1	4	**3.68**
[8]	0.9	2.6–10.2	1.2	7.2	12.5	3-7	<-9	-	**2.2**
[2]	0.9	0.2–9	1.2	20	10	4.2	<-10	-8	**1.375**
[9]	0.13	3.1–10.6	0.6	4.1	21	1-3.9	<-5	4.56 (6GHz)	**13.25**
[10]	0.13	3.0–10.0	1	13.0	12.1	3.04–3.48	<-11.4	-6.6 (6GHz)	**2.63**
[3]	0.13	2.3–9.37	1.3	9.97	10.3	3.68–9.2	<-8	-4 (4.5GHz)	**8.9**
[7]	0.18	3–5.6	1	9	9	4.6–5.3	<-9	2 (5.3GHz)	**0.61**
[4]	0.18	3.1–10.6	1.5	9	15.8	2.2–3.2	<-10.6	-6	**6**
[5]	0.18	3.1–10.6	1.2	12.14	13.5	2.5–3.7	<-5.5	-8.2 (5GHz)	**3.1**
[6]	0.18	3–12	1.8	23.23	20.24	1.72–1.99	<-10	-	**7.92**
[11]	0.18	5	0.6	1.68	14.1	3.65	<-8	-17.1	**15.83**

IV. Conclusion

The design proposed in this paper revolves around precise calculations and minimizing power consumption of the LNA. Three common-source LNAs biased differently are utilized and the voltage supply decreased to 0.2 volts. The implementation of the circuit can be considered as interesting task. Notwithstanding, it is validated by other works that the results measured in implementation are close to the results coming from simulation. Therefore, it can be deduced that should the LNA be implemented, the results might be close enough to the simulated results. Plus, the technology utilized in this paper is 0.13µm and the size of transistors has been scaled down to nanometer. Nevertheless, the calculations are applicable to all CMOS transistors in any sizes because they are predicated upon the model of CMOS transistors which are irrelevant to the size of transistors.

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