Optimization of Current-Reused LNA with PSO Algorithm

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***Abstract*— This paper presents a tunable narrow band Low Noise Amplifier (LNA), which is optimized at the frequency of 4.4 GHz. Relating to the proposed low noise amplifier that has current-reused structure drawn from the auxiliary gate-source capacitor of the main transistor and the bypass capacitor, the performance of the LNA is tuned. The temperature and source variations can change the operational frequency and desired parameters. In this paper, the shift of the frequency is compensated using the particle swarm optimization (PSO) algorithm. The designed low noise amplifier with particle swarm optimization algorithm in the present of PVT (Process, Voltage, and Temperature) variations achieves a voltage gain of 12.52 dB, with corresponding noise figure (NF) of 1.80 dB, input return loss (S_{11}) of -37 dB, and output return loss (S_{22}) of -42 dB at the frequency of 4.4 GHz. The die area of the designed LNA is 939.5µm*746.83µm.**

***Index Terms*— Current Reused; Optimization; Low Noise Amplifier; PSO Algorithm.**

I. Introduction

The new generation of radio transceivers needs adaptive and flexible RF front ends. The text, audio, and video for multimedia applications require flexible designs that work across multiple bands and standards; thus, device related to manufacturing technology should be advanced [1]. Many transistors can be integrated on a single chip for the realization of the flexible circuits. In addition, process variation influences the circuit operation, which are working at gigahertz frequencies (GHz). The precision of the device models and process changes are usually an important cause of difference between simulation and measurement results. Furthermore, the temperature variations can also influence the operation of the RF chip in the real operating condition. Thus, self-calibration or self-tuning is needed for the contemporary RF chips [1-3].

There are several algorithms for adaptive signal processing problems, such as gradient-decent optimization [4-5], particle swarm optimization (PSO) [6-7], least mean square (LMS) [8-9], and LMS-PSO [10]. Optimization with gradient-based is used to evaluate the gradient of the error surface by following the negative direction of this estimated gradient [4-5]. The LMS algorithm is the most notable of these algorithms and is widely adopted as the dominant adaptive filtering algorithm [8-9] and its specification include the convergent local search capabilities, speed, and efficiency. However, for multimodal error surfaces, some global algorithm of search, such as PSO or genetic algorithm (GA) are needed [2]. This paper utilizes the PSO algorithm to deal with the problem of the temperature and source variations affecting the LC tanks of RF circuits. So, the performance of an LNA can be optimized to attain the desired results.

This paper is structured as follows: introduction is discussed in Section I. Section II represents the design of narrow band low noise amplifier. Section III represents the particle swarm optimization algorithm. The design of tunable LNA for 4.4 GHz by PSO algorithm is explained in Section IV. The simulation results are presented in Section V, while Section VI concludes the paper.

II. Designed Narrow Band LNA

Figure 1 illustrates the narrow band current-reused LNA [11]. The main structure of the proposed LNA is the common source to provide low noise and high gain. To attain lower power dissipation, the second stage is stacked on top of the first stage (Current-Reused technique). C_1 is a bypass capacitor. C_3 supplies signal coupling between the two stages. Spiral inductors L_{g1} and L_{s1} are used for input matching [12-13]. Furthermore, C_{ex} is the tuning capacitor placed between the gate and the source of transistor M_1 for better input matching. A parallel RLC tank is employed at the output for good output matching. The capacitor of C_1 is large enough to supply ac ideal ground in conventional narrow band designs. However, C_1 is tunable capacitor that influences the gain flatness in the desired LNA.

A. Voltage Gain

The voltage gain of the proposed low noise amplifier is presented. For simplicity, the body effect and other components are not considered in this calculation, but these formulas supply helpful insight to select the circuit elements skillfully. The small-signal model of the LNA is depicted in Figure 2. Due to the very small value of C_{in} and C_3, they are supposed to be short circuit to achieve the voltage gain.

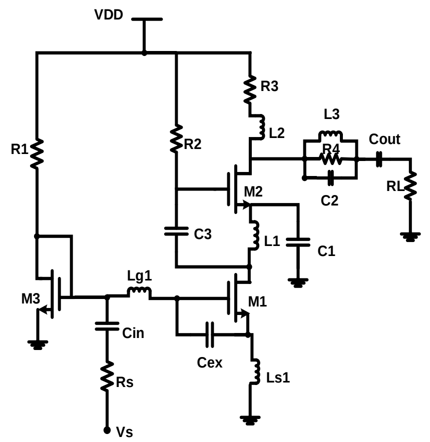

Figure 1: Narrow band low noise amplifier

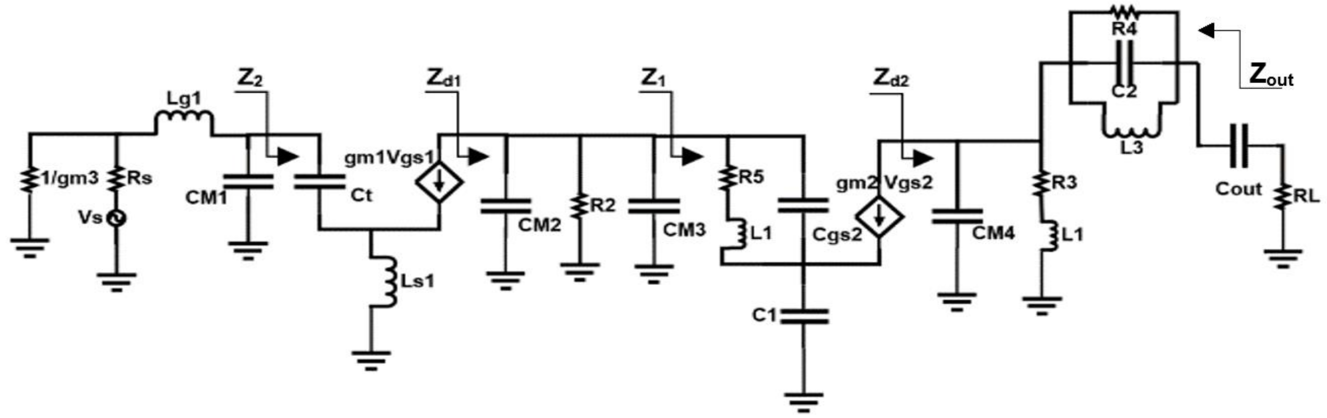

Figure 2 Small signal model of the proposed LNA.

The Series resistance of inductors are very small; so, it is not considered in this analysis. The transistor M_3 is defined by the resistance $1/g_{m3}$. The Miller gate-drain capacitance of M_1 ($C_{gd,M1}$) is separated into C_{M1} and C_{M2}. Also, the Miller gate-drain capacitance of M_2 ($C_{gd,M2}$) is broken up into C_{M3} and C_{M4}, where Z, Z_{d1}, C_t, Z_{d2}, Z_1, and Z_2 are calculated as (2), (3), (4), (5), (6), and (7), respectively.

Z is expressed as:

$$A_V=\left(\frac{R_L}{R_L+Z}\times g_{m2}\cdot\frac{sC_1}{sC_{gs2}+g_{m2}+sC_1+\frac{1}{R_5+sL_1}}\cdot Z_{d2}\right)$$
$$\times\left(g_{m1}\cdot\frac{\frac{1}{sC_t}}{sL_{s1}+\frac{1}{sC_t}+\frac{g_{m1}L_{S1}}{C_t}}\cdot Z_{d1}\times\frac{(Z_{CM1}\|Z_2)}{sL_{g1}+(Z_{CM1}\|Z_2)}\right)$$
$$\times\left(\frac{\frac{1}{g_{m3}}\|\left[sL_{g1}+(Z_{CM1}\|Z_2)\right]}{\left[\frac{1}{g_{m3}}\|\left[sL_{g1}+(Z_{CM1}\|Z_2)\right]\right]+R_S}\right) \quad (1)$$

$$Z=\left[(R_4\|sL_3)\|\frac{1}{sC_2}\right]+\frac{1}{sC_{out}} \quad (2)$$

Z_{d1} is calculated as:

$$Z_{d1}=Z_{CM2}\|Z_{CM3}\|R_2\|Z_1 \quad (3)$$

C_t is defined as:

$$C_t=C_{ex}+C_{gs1} \quad (4)$$

Z_{d2} is expressed as:

$$Z_{d2}=(R_3+sL_2)\|Z_{CM4}\|(R_L+Z) \quad (5)$$

Z_1 is derived as:

$$Z_1=\left(\begin{array}{l}(C_{gs2}L_1+C_1L_1)S^2+(C_{gs2}R_1+C_1R_5+g_{m2}L_1)S\\+(1+g_{m2}R_5)\end{array}\right)\times\frac{1}{S^3C_{gs2}C_1L_1+S^2C_{gs2}C_1R_5+S\,C_1} \quad (6)$$

Z_2 is defined as:

$$Z_2=\frac{1}{sC_t}+sL_{s1}+\frac{g_{m1}L_{s1}}{C_t} \quad (7)$$

B. Input and Output Impedance Matching

To attain output and input impedances, the output resistance of transistors M_1, M_2, and M_3 are considered as r_{o1}, r_{o2}, and r_{o3}, respectively. The input impedance, Z_{in}, is equal to:

$$Z_{in}=\left[sL_{g1}+\frac{1}{sC_t}+sL_{S1}+\frac{g_{m1}L_{S1}}{C_t}\cdot\left(\frac{r_{o1}}{r_{o1}+sL_{S1}+Z_{d1}}\right)\right]\|\frac{1}{g_{m3}} \quad (8)$$

where Z_{d1} is defined as (3).

The input return loss is expressed as:

$$S_{11}=\left(\frac{Z_{in}-R_S}{Z_{in}+R_S}\right) \quad (9)$$

Following the derivation of Z_{out}, the output return loss is gained as below.

$$S_{22}=\left(\frac{Z_{out}-R_L}{Z_{out}+R_L}\right) \quad (10)$$

Z_{out} can be derived from Figure2. So, the output impedance is

$$Z_{out}=\frac{V_X}{i_X}=Z+Z' \quad (11)$$

where Z and Z' are achieved from (2) and (12), respectively.

$$Z'=S\left(C_{gs2}+C_{gd1}\right)+\frac{1}{R_5+sL_1}+\frac{1}{R_2}+sC_{gd2}+A\times$$
$$\left(g_{m1}\cdot\frac{\frac{1}{sC_t}}{sL_{s1}+\frac{1}{sC_t}+\frac{g_{m1}L_{S1}}{C_t}}\cdot Z_{d1}\times\frac{(Z_{CM1}\|Z_2)}{sL_{g1}+(Z_{CM1}\|Z_2)}\right) \quad (12)$$

$$A=\frac{sg_{m1}}{sC_{gd1}+sC_t+\frac{1}{Z_{eq}}}\cdot\left(C_{gd2}+\frac{C_t\cdot\left(\frac{sL_{S1}}{r_{o1}}\right)}{\frac{1}{R_3+sL_2}+sC_{gd2}}\right)$$

C. Noise Performance

In the cascaded stages, the former stages are important in noise performance. The main noise contribution in the input stage of the desired LNA are the resistor thermal noise and the channel thermal noise of the transistors, which could be represented as [14]:

$$\overline{V^2_{n,Ri}} = 4KTR_i$$
$$\overline{V^2_{n,Mi}} = 4KT\frac{\gamma}{\alpha}\frac{1}{g_{mi}} \quad (13)$$

where K, T, and γ are Boltzmann constant, absolute temperature in Kelvin and noise parameter in MOS transistors, respectively. Here, γ is in the range of 2/3–2 for short channel devices. Moreover, $\alpha = g_{mi}/g_{d0}$, where g_{d0} is the channel conductance for V_{DS}=0V and α is often less than unity.

The noise spectral density due to the source resistances (R_s) and M_3 are expressed as:

$$\overline{I^2_{n,out,Rs,M3}} = \frac{g^2_{m1}\left(\overline{V^2_{n,Rs}} + g^2_{m3}R^2_S\overline{V^2_{n,M3}}\right)}{\left[\left(L_{g1}+L_{S1}\right)S^2 + S\left(L_{S1}g_{m1}+R_SC_t\right)+1\right]^2} \quad (14)$$

The noise spectral density due to the channel thermal noise of the transistor M_1 is given by:

$$\overline{I^2_{n,out,M1}} = \frac{\left(C_tR_S\right)^2\overline{i^2_{n,M1}}}{\left[C_tR_S+1+SL_{S1}C_t+g_{m1}L_{S1}\right]^2} \quad (15)$$

Then, the total output noise of the former stage is equal to:

$$\overline{I^2_{n,out,Rs,M1,M3}} = \overline{I^2_{n,out,Rs,M3}} + \overline{I^2_{n,out,M1}} \quad (16)$$

And finally, th enoise factor is obtained as the following:

$$F = \frac{\overline{I^2_{n,out,Rs,M1,M3}}}{\overline{I^2_{n,out,Rs}}} \quad (17)$$

III. Particle Swarm Optimization Algorithm

The standard particle swarm optimization (PSO) algorithm starts by initializing the N particles in random swarm, each having H parameters which is unknown to be optimized. To simplify a global search, the initial particles are typically distributed uniformly about the assumed parameter space, while there is prior knowledge about the parameter space. At each iteration, according to the chosen fitness function, fitness of each particle is estimated. The algorithm saves and progressively changes the most fit parameters of each particle ($pbest_i$, i=1, 2,…, M) as well as a single most fit particle (*gbest*) as better fit parameters are considered. At each iteration (n), the parameters of each particle (p_i) in the swarm are updated according to the following equations:

$$\overline{vel_i}(n) = W * \overline{vel_i}(n-1)$$
$$+ acc_1 * diag\left[e_1, e_2, \ldots, e_R\right]_1 * \left(gbest - p_i(n-1)\right) \quad (18)$$
$$+ acc_2 * diag\left[e_1, e_2, \ldots, e_R\right]_2 * \left(gbest - p_i(n-1)\right)$$
$$p_i(n) = p_i(n-1) + \overline{vel_i}(n) \quad (19)$$

where $\overline{vel_i}(n)$ is the velocity vector of particle i, e_r is a vector of random values, $\{e_r \in (0,1)\}$, acc_1, and acc_2 are the acceleration coefficients toward *gbest*, and $pbest_i$, respectively. Also, W is the inertia weight.

It can be collected from the update equations that the path of each particle is affected in a direction that is specified by the prior velocity and the position of gbest, and $pbest_i$.

The inertia weight adjusts the effect of the previous velocity. Inertia weight linearly decreases, as below:

$$W\_PSO = Wmax - (Wmax - Wmin) / max - iter \quad (20)$$

where max-iter shows the maximum number of iterations. So, W declines linearly from W_{max} to W_{min}.

The cost function of designing optimized LNA is as follows:

$$Out.Total = W\_S_{11} * S_{11} + W\_A_V * A_V + W\_F_{tot} * F_{tot} + W\_S_{22} * S_{22} \quad (21)$$

where, the values of S_{11}<-20 dB, A_v>12, 1.5<F_{tot}<3 dB, and S_{22}<-30 dB are considered.

IV. Design Of Tunable LNA For 4.4 GHz By PSO Algorithm

In order to find the optimum LNA parameters for 4.4 GHz, the PSO algorithm is applied. The proposed PSO method is explained as the following:

Step1. Randomly the speeds and the positions of particles are initialized by uniform probability distribution.

Step2. For each primitive individual population, the values of the S_{11}<-20 dB, A_v>12, 1.5<F_{tot}<3 dB, and S_{22}<-30 dB are considered.

Step3. Considering fitness of particles with its *pbest*. The current value is set as the new *pbest* if it is better.

Step4. All particles evaluate the best position with *gbest*. If the running value is better, put the current best value as *gbest*.

Step5. Improve the velocity of particles according to (18).

Step6. The particle's position is updated by (19), the Inertia weight (W) is set by (20).

Step7. Return to the step (2**)** until the maximum iteration and the best result according to (2) can be attained. C_{ex} and C_1 are tunable capacitors. Input return loss (S_{11}) is optimized by C_{ex}; and power gain, noise figure, and output return loss are optimized by C_1 [18]. Device parameters of tunable LNA is listed in Table 1.

Table 1
Device Parameters of Tunable LNA

Parameters	Sizes	Parameters	(W/L)
L_{g1}	1.93nH	W_1	160µm
L_s	0.964nH	W_2	112 µm
L_1	3.2nH	W_3	5 µm
L_2	2.5nH	C_{ex}	21fF
L_3	0.23nH	C_1	1.1pF
R_3	18ohm	C_3	82fF
R_1	2Kohm	C_2	0.9pF
R_4	88ohm		
R_2	1.7Kohm		

V. Simulation Results

The proposed narrow band low noise amplifier is optimized for 4.4 GHz by the PSO algorithm. The process, voltage, and temperature (PVT) variations shift the operating frequency. For tuning and calibration of the proposed low noise amplifier, the particle swarm optimization (PSO) algorithm is applied. A shift in operating frequency is compensated with this algorithm. Figure 3(a) depicts the input return loss (S_{11}) with PVT variations, which is not optimum at the desired frequency of 4.4 GHz, but by PSO algorithm, as illustrated in Figure 3(b), minimum S_{11} of -37dB at the interested frequency can be attained.

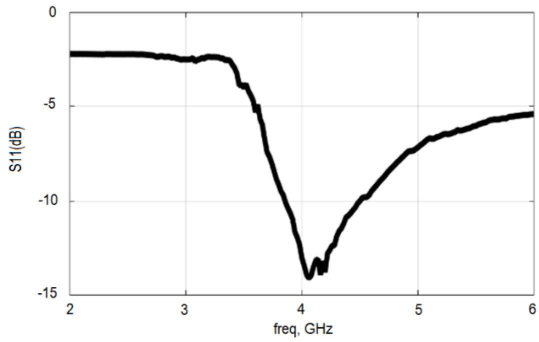

Figure 3(a). S_{11}(dB) in the present of PVT variations without applying PSO algorithm.

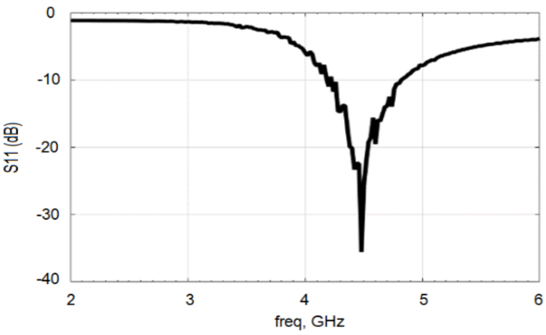

Figure 3(b). S_{11}(dB) in the present of PVT variations with applying PSO algorithm.

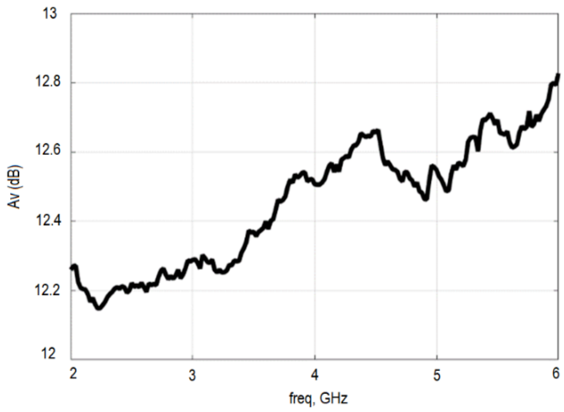

Figure 4(a). Av(dB) in the present of PVT variations without applying PSO algorithm.

Figure 4(a) shows the voltage gain (A_v) of the proposed LNA with PVT variations. A_V without applying the PSO algorithm is 12.45 with variation of ± 0.4 dB. Figure 4(b) illustrates the voltage gain by using the PSO algorithm: Using this method, the flat voltage gain with flatness of 12.5± 0.02 dB can be attained. Its maximum voltage gain is 12.52 dB at the frequency of 4.4 GHz. The noise figure of the proposed LNA with exposing in PVT variations is depicted in Figure 5(a). The noise figure variations is between 3 and 7.7 dB at the frequency range of 4 to 6 GHz. By applying the PSO algorithm, minimum noise figure of 1.8 dB with low changes can be attained, as represented in Figure 5(b).

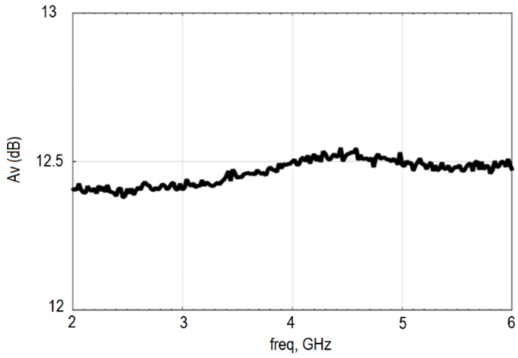

Figure 4(b). Av(dB) in the present of PVT variations with applying PSO algorithm.

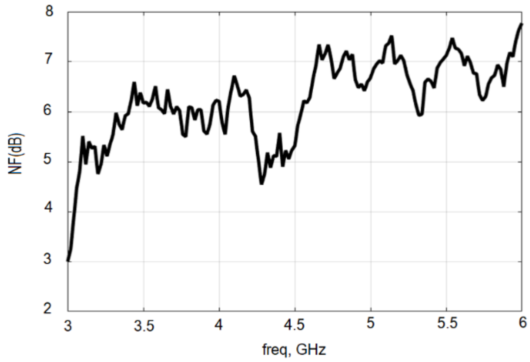

Figure 5(a) NF(dB) in the present of PVT variations without applying PSO algorithm.

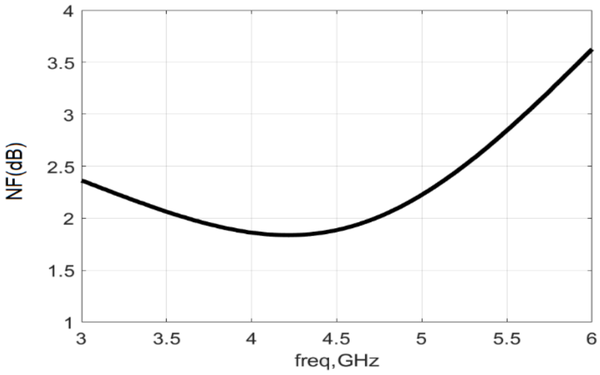

Figure 5(b). NF (dB) in the present of PVT variations with applying PSO algorithm.

Figure 6 illustrates the output return loss (S_{22}) of the proposed narrow band LNA. In Figure 6(a), S_{22} is -35dB at the frequency of 4.4 GHz. Around 7 dB optimization can be attained by using the PSO algorithm and it is shown in Figure 6(b). The Smith chart of S_{11} is depicted in Figure7, the input impedance is around 50Ω. The layout of the designed low noise amplifier is shown in Figure 8. Table 2 determines the performance summary and optimization of the other works and this work. LNAs in [15-16] are optimized digitally, while [17-19] and this work optimized the proposed LNA by the PSO algorithm.

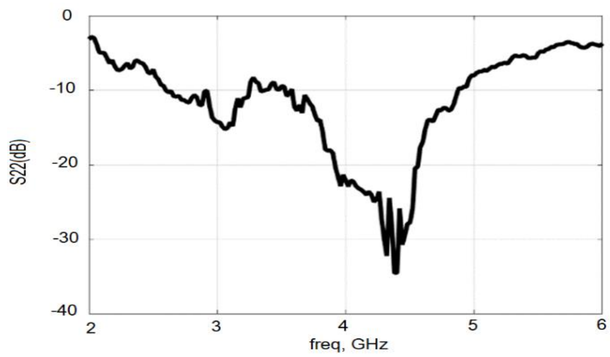

Figure 6(a). S_{22}(dB) in the present of PVT variations without PSO algorithm.

Figure 6(b). S_{22}(dB) in the present of PVT variations with applying PSO algorithm.

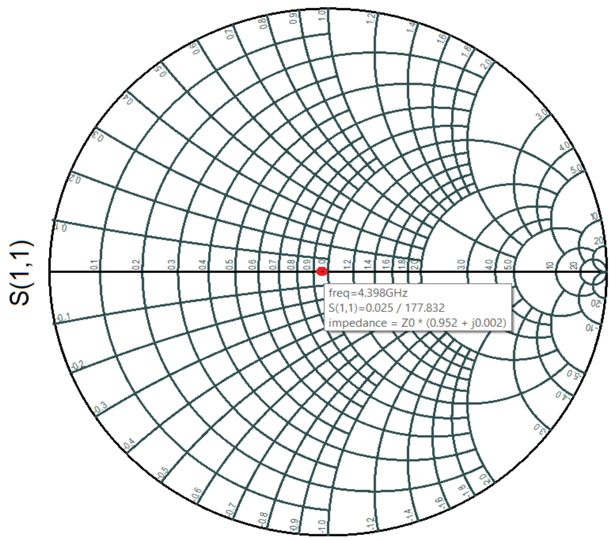

Figure 7 Smith chart of proposed LNA for S_{11}(dB).

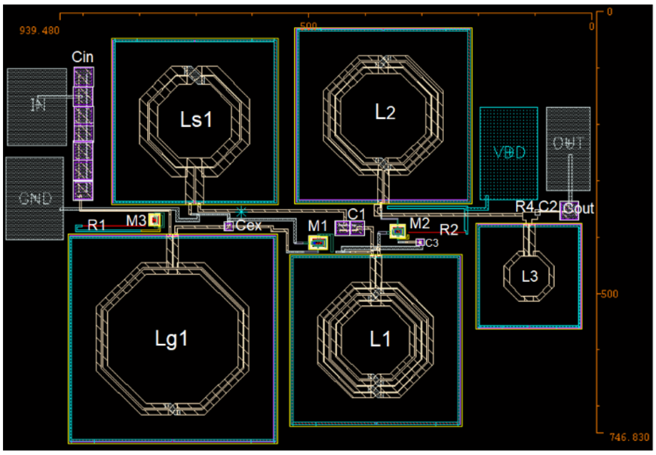

Figure 8 The layout of the designed low noise amplifier.

Table 2
Performance Comparison with Existing Tunable LNA

	Frequency	S_{11}	Av	NF	S_{22}
[15]					
Reference LNA(dB)	2.45GHz	-25.47	21.43	1.34	-
Tunable LNA(dB)		-30.24	20.92	1.51	-
[16]					
Reference LNA(dB)	2.4GHz	-7	10	2.92	-
Tunable LNA(dB)		-12	13	2.62	-
[17]					
Reference LNA(dB)	2GHz	-	10.7	3.27	-
Tunable LNA(dB)		-	12.6	3.2	-
[18]	5.5GHz	-19.06	22.3	1.44	-17.68
[19]	2.4GHz	-14.08	8.6	1.78	-7.8
This work					
Reference LNA(dB)	4.4GHz	-10	£12.45±0.4	£ 3-7.7	-35
Tunable LNA(dB)		-37	£12. 5±0.1	£1.8-3.6	-42

£: 2-6 GHz

VI. CONCLUSIONS

An optimized low noise amplifier is designed for 4.4 GHz frequency. Process, voltage, and temperature variations can shift the operating frequency. With the PSO (Particle Swarm Optimization) algorithm, this variation can be compensated and optimized at the frequency of 4.4 GHz. The input and output return loss (S_{11} and S_{22}) improvement are around -17 dB and -7 dB, respectively. Also, NF improvement is about 3.5 dB at the interested frequency. By the PSO algorithm, high gain is achieved.

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