Design and Optimization of a Very Low Noise Amplifier using Particle Swarm Optimization Technique

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Abstract

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Design of a LNA is a complex process. Because it involves various parameters and needs complex trade-offs. This paper presents an optimized design of a low noise amplifier (LNA) using particle swarm optimization (PSO) technique. The proposed LNA has a cascode structure with inductive source degeneration and is implemented in TSMC 0.18 μm CMOS technology. The proposed LNA has a forward gain 26.01 dB and NF 0.32 dB at the UMTS standard frequency.

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1. Introduction

In today’s communication system low noise amplifier (LNA) function is the first level of amplification of the signal received from the antenna. The LNA function plays an incontrovertible importance part in the receiver functionality and design process. The most important function of the LNA is to amplify very low signals without adding noise. To do so, the signal to noise ratio (S/N) of the LNA should be a large number. The sensitivity of a receiver (which means the smallest possible signal that can be received by the receiver) is related to the LNA [1]. On the other hand, for larger signal levels, the received signals should be amplified without any distortion and consequently the quality of the receiver chain will be determined by the LNA functionality. In today’s communication system, LNA design has been become very acute. Because it involves simultaneous requirement such as noise figure (NF), gain, linearity, impedance matching, and power dissipation which leads to tradeoffs between the main parameters [2]. One of the most important parameters in LNA design is optimizing the NF. Manual design and optimization of analog circuits can be very time consuming
procedure. To overcome the difficulties of these procedures, automated design and optimization have been offered.

Particle Swarm Optimization (PSO) was developed by Kennedy and Eberhart in 1995 [3]. It is a stochastic optimization technique which is inspired by the behavior of bee swarms and bird flocks. It is a population based on optimization and can be applied to various optimization problems.

PSO has been used in analog circuit design and optimization, such as automatic sizing of low power analog circuits [4], [5], automatic synthesis tool of a cascade low noise amplifier (LNA) [6], microwave filter design [7], and etc. In this paper, the optimization of LNA parameters has done by using the PSO technique.

Different topologies have been offered for LNA [8, 9, 10]. The cascode structure with an inductive source degeneration has a good in-out isolation [11] and can be one of the most practical topologies. Thus in this paper automated design and optimization using PSO technique has been done on a cascode LNA with inductive source degeneration.

The main attention in this paper is put on Noise Figure (NF) and Gain tradeoffs. The noise of the receiver is related to the signal to noise ratio (SNR) of the LNA. If NF of LNA can be adjusted at low values, NF of the whole system would be a small value too. In this paper, therefore the goal is to design a LNA with a very small NF. The value of circuit components has been determined by the PSO technique. Simulation results show that the proposed LNA has a forward gain 26.01dB and NF 0.32dB. It can be considered as a good tradeoff. Because NF is a very small value against forward gain, which is a considerable value.

This paper is organized as follows. Section II describes the LNA design procedure. Section III explains the PSO algorithm and section IV presents the simulation results of the proposed LNA.

2. LNA Design:

LNA is one of the most important blocks in receiver systems. Cascode structure was first introduced in [12]. It is composed of a common source amplifier with inductive source degeneration and a common gate load. The common gate load has good wide-band characteristics [13] and common source amplifier has high gain. Hence, cascode structure with an inductive source degeneration has advantages of the both topologies. The schematic of the proposed LNA is shown in Fig.1.
LNA design includes designing: DC biasing network, stability condition, and input and output matching networks. Each section has its own role in the LNA performance.

- **DC Biasing design**
  The first step in LNA design is DC biasing network. The DC bias circuit should present stable thermal performance and also it should be cost effective with a small size. The simplest form of DC biasing network could be a single resistor. In this paper a resistor with specified value has been considered as the biasing network of the LNA as shown in Fig.1.

- **Stability design**
  The next step in LNA design, is stability analysis. The purpose of the designer is to design a circuit with unconditional stability. The stability of a circuit can be determined by using stern stability factor \( K \). Circuit is stable when \( K > 1 \) and \( \Delta < 1 \).

\[
K = \frac{1 + \Delta^2 - S_{11}^2 - S_{22}^2}{2S_{11}S_{12}} \quad (1)
\]
\[
\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (2)
\]

- **Impedance matching network design**
  The next step in LNA design is determination of the input/output impedance matching networks by using S-parameters at a specific DC-bias point. Input/output matching circuits reduce unwanted reflection of signal. In Fig. 1 input and output impedance matching networks are shown. The input network should match to the source which today LNAs are designed to have a 50Ω resistive input impedance. The input matching network also
minimizes the input return loss (S11) and reduce the NF. The output matching network determines the output return loss (S22) and should be adjusted to 50 Ω. In impedance matching networks different structures have been used [8], [14]. Each one has their own specification. To transfer the maximum power the following conditions should be satisfied.

\[ \Gamma_{IN} = \Gamma_{S}^* = S_{11} + \frac{S_{12}S_{21}\Gamma_{L}}{1 - S_{22}\Gamma_{L}} \]  

\[ \Gamma_{OUT} = \Gamma_{L}^* = S_{22} + \frac{S_{12}S_{21}\Gamma_{S}}{1 - S_{11}\Gamma_{S}} \]  

Where, \( \Gamma_{S} \) is the input power reflection coefficient and \( \Gamma_{L} \) is load reflection coefficient. S11, S12, S21 and S22 are scattering parameters.

2. Particle Swarm Optimization

In general, an optimization problem can be defined as:

Minimize \( f(\vec{x}) \); \( f(\vec{x}) \in R^{k} \) 

Such that:

\[ \vec{g}(\vec{x}) \leq 0; \quad \vec{g}(\vec{x}) \in R^{m} \]

\[ \vec{h}(\vec{x}) = 0; \quad \vec{h}(\vec{x}) \in R^{n} \]

where \( x_{Li} \leq x_{i} \leq x_{Ui}, \quad i \in [1, p] \).

Where \( f(x) \) shows the \( k \) objective functions, \( g(x) \) represents the \( m \) inequality constraint functions, \( h(x) \) represents \( n \) equality constraint functions, \( p \) shows the parameters to manage, and \( x_{L} \) and \( x_{U} \) are vectors determine the lower and upper boundaries of the parameters.

The PSO algorithm is a population based stochastic optimization technique. In PSO algorithm multiple candidate solutions will be considered and each one is called a particle with randomized velocity. For each problem a specific multidimensional search space is considered. Particles fly through the search space and looks for the optimal position [16]. Each particle remembers its best position (p_{best}) in the problem search space. g_{best} is the global best position found by all particles.

Assuming an n-dimensional search space and the ith particle as \( X_{i} = (x_{i,1}, x_{i,2}, ..., x_{i,n}) \), and its velocity as \( V_{i} = (v_{i,1}, v_{i,2}, ..., v_{i,n}) \), and also the best position of that particle (p_{best})\( P_{i} = (p_{i,1}, p_{i,2}, ..., p_{i,n}) \) and the best position found by the entire swarm (g_{best}) as \( g = (g_{1}, g_{2}, ..., g_{n}) \). Over the course of search process, at the end of each iteration, each particle moves in the search space and updates its position and velocity [3]. The following equations are employed to update the values of velocity and position of the ith particle.
Where $w$ is the inertial weight, $c_1$ and $c_2$ are scaling factors and $r_1$ and $r_2$ are two uniformly distributed random variables. PSO algorithm first determines the random initial values of particles. Each particle has its own position and velocity in the search space. In each of iterations, all particles update their positions and velocities. This is done according to their $p_{best}$ and the $g_{best}$. Fig. 2 presents the flow chart.

\begin{equation}
V_{i}^{t+1} = wV_{i}^{t} + c_1 r_1(p_{i}^{t} - X_{i}^{t}) + c_2 r_2(p_{g}^{t} - X_{i}^{t})
\end{equation}
\begin{equation}
X_{i}^{t+1} = X_{i}^{t} + V_{i}^{t+1}
\end{equation}

The main constraints for the LNA design are as follow.

- Impedance matching
- Stability
- LNA Gain
- Small circuit sizing
In this paper the LNA noise figure has been considered as the objective function. It should attain its minimum value at the UMTS standard frequency. The noise figure of this LNA is given as [15]:

\[
F = 1 + \frac{\beta \left( Q^2 + \frac{1}{4}\right) \left( Q \cdot \frac{4}{3} \omega_0 R_S C\alpha W L \right)^2 + \frac{\beta}{4}}{R_S Q^2 \sqrt{2\mu_{eff} C\alpha W L_{ds} / L}}
\] (8)

Where:

\[
Q = \frac{1}{2 R_S \omega_0 C_{gs}}
\] (9)

3. Simulation Results

The designed LNA has a very simple biasing network and is implemented in TSMC 0.18 μm CMOS technology at the UMTS standard frequency (2.14 GHz). The optimum values of circuit components have been calculated by using PSO algorithm. The value of parameters of PSO algorithm and circuit components are presented in table 1 and table 2.

### Table 1: Parameters of PSO algorithm

<table>
<thead>
<tr>
<th>Size of the Swarm</th>
<th>Number of iteration</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( \omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1000</td>
<td>0.5+log(2)</td>
<td>0.5 + log(2)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Table 2: Optimized value of circuit components

<table>
<thead>
<tr>
<th>( W_1 / L_1 )</th>
<th>( W_2 / L_2 )</th>
<th>( L_g )</th>
<th>( L_s )</th>
<th>( L_a )</th>
<th>( L_1 )</th>
<th>( L_2 )</th>
<th>( R )</th>
<th>( C_d )</th>
<th>( C_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(µm)</td>
<td>(µm)</td>
<td>(nH)</td>
<td>(pH)</td>
<td>(pH)</td>
<td>(nH)</td>
<td>(nH)</td>
<td>(Ω)</td>
<td>(pF)</td>
<td>(fF)</td>
</tr>
<tr>
<td>250/0.18</td>
<td>250/0.18</td>
<td>1</td>
<td>320</td>
<td>550</td>
<td>2</td>
<td>6.7</td>
<td>800</td>
<td>10</td>
<td>90</td>
</tr>
</tbody>
</table>

Simulation results of NF and NFmin are shown in Fig. 3. The NF of the presented LNA is 0.325 dB at the UMTS standard frequency (2.14 GHz) which is a very low value and can be considered as a good advantage for the proposed LNA.
The forward power gain (S21) of the presented LNA is shown in Fig. 4. The value of S21 of the presented LNA is 26.01 dB at the UMTS frequency which can be considered as a very high gain for the proposed LNA.

Fig. 3: Simulated noise figure at the UMTS standard frequency

Fig. 4: Simulated S21 (forward power gain) at the UMTS standard frequency

Fig. 5 shows the input return loss (S11) and output return loss (S22) of the LNA. At UMTS frequency the value of S11 and S22 is -11.07 and -7.37 respectively.

Fig. 5: Simulated input and output return losses
LNA stability can be determined by using stern stability factor. LNA is stable when $K>1$ and $\Delta<1$. As it is shown in Fig.6 $k=1.016$ and $\Delta = 0.62$. According to stern stability criteria the LNA is stable.

![Stability factor vs. frequency](image)

**Fig. 6: Stability factor vs. frequency**

The performance of the proposed LNA is compared with other circuits and the results are summarized in Table 3.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Freq. (GHz)</th>
<th>NF (dB)</th>
<th>S21 (dB)</th>
<th>S11 (dB)</th>
<th>Tech (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[5]</td>
<td>2.14</td>
<td>0.91</td>
<td>13.35</td>
<td>-</td>
<td>0.35</td>
</tr>
<tr>
<td>[9]</td>
<td>2.4</td>
<td>2.16</td>
<td>21.4</td>
<td>-15.5</td>
<td>0.18</td>
</tr>
<tr>
<td>[17]</td>
<td>2.4</td>
<td>0.47</td>
<td>17.33</td>
<td>-10.07</td>
<td>-</td>
</tr>
<tr>
<td>[18]</td>
<td>2.4</td>
<td>3.9</td>
<td>20</td>
<td>-</td>
<td>0.12</td>
</tr>
<tr>
<td>[19]</td>
<td>2.0</td>
<td>1.6</td>
<td>18</td>
<td>-19.7</td>
<td>0.13</td>
</tr>
<tr>
<td>[20]</td>
<td>0.9</td>
<td>2.95</td>
<td>11</td>
<td>-11.5</td>
<td>0.35</td>
</tr>
<tr>
<td>[21]</td>
<td>2.0</td>
<td>2.6</td>
<td>14.5</td>
<td>-8</td>
<td>0.13</td>
</tr>
<tr>
<td>[22]</td>
<td>2.0</td>
<td>4</td>
<td>25.67</td>
<td>-14.6</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>This Work</strong></td>
<td><strong>2.14</strong></td>
<td><strong>0.32</strong></td>
<td><strong>26.01</strong></td>
<td><strong>-11.07</strong></td>
<td><strong>0.18</strong></td>
</tr>
</tbody>
</table>
4. Conclusions

A cascode LNA with inductive source degeneration was presented. PSO technique has been used to optimize the LNA parameters. The LNA simulate in TSMC 0.18 μm CMOS technology. The designed LNA has high gain (26 dB) and very low noise figure (0.325). The input insertion loss S11 is -11.07 dB and the output insertion loss S22 is -7.37 dB at the UMTS standard frequency.

References


