Genetic Algorithm Optimization of LNA for Wireless Applications in 2.4GHz Band

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ABSTRACT

The common-source low noise amplifier(LNA) with inductive degeneration using a genetic algorithm is designed and tested for a down converter in an industrial, scientific and medical (ISM) band application and a wireless broadband internet service (WiBro). The genetic algorithm optimizes the reflection coefficients to be well matched the input and output ports between multistage transistor amplifiers, and it generates low voltage standing wave ratio as well as gain flatness of the amplifier. The stability and the gain flatness of the LNA have been improved by combining the matching circuits and the series feedback microstrip lines with inductive degeneration at common-source port. In the frequency range of ISM band and WiBro application operating at 2.3GHz ~ 2.5GHz, the measured power gain and maximum voltage standing wave ratio (VSWR) of the LNA are 41 ± 0.5dB and 1.3, and the noise figure of the LNA is lower than 0.85dB. The above results are agreed well with the theoretical values of the amplifiers.

***Keywords**: Genetic Algorithm Optimization, Low Noise Amplifier, Matching Circuit, ISM, WiBro.*

1. INTRODUCTION

A low noise amplifier (LNA) requires a minimum noise level, low voltage standing wave ratio (VSWR) and maximum power gain. However, it is hard to achieve a minimum noise level, low VSWR and maximum power gain, simultaneously. The gain, VSWR and the noise level should be carefully selected from the constant circle of those in a Smith Chart [1, 2].

In, general, an LNA in a wireless communication system is an active transistor with a low noise and a high gain with low variation over the operating frequency range. The low variation of gain of an LNA over the frequency range can be achieved by a properly designed matching circuit, which is based on the characteristics of the active amplifier chip [3-6]. The stability factor of an active amplifier will be decided by the scattering coefficient and by the matching circuit of the amplifier since the scattering coefficient and the matching circuit will decide the reflection coefficients of the amplifier in the LNA circuit. The magnitude of reflection coefficients of input and output of the LNA should be smaller than 1 to have a stable amplifier over the operating frequency range.

The broadband, high gain, low VSWR and stability cannot be simultaneously achieved with a single stage amplifier design. In this paper, The LNA with three stages of amplifiers has been designed to achieve the characteristics. In order to improve the gain flatness and the stability condition of amplifier, the use of genetic algorithm and series feedback circuit with inductive degeneration at common-source port is proposed. The shape of gain flatness of the broadband LNA depends on the length of series feedback microstrip line with inductive degeneration and the reflection coefficient of each stage of the amplifier. The genetic algorithm [7-9] optimizes reflection coefficients and reduces voltage standing wave ratio (VSWR) and noise figure of the broadband LNA, and simplifies the design procedure of the 3-stage amplifiers

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2. DESIGN OF AN LNA WITH 3-STAGE AMPLIFIER

Fig. 1 shows the LNA circuit design with 3-stage amplifiers. The input and output matching circuits are used to match the LNA to the input and output ports, and the series feedback circuits using microstrip lines at common-source ports are used to make the stabilized amplifier. In addition, the inter-stage matching circuits have been used to have the flat gain over the broadband. Generally, the first consideration in the process of designing an LNA with a given specification is the selection of an appropriate transistor. The selection should be based on the requirement of characteristics in each stage, low noise figure, high power gain and stability of output power. The 1st and the 2nd stages of transistors are GaAs MESFET (EPA060B-7) which has a minimum noise figure (0.5dB) and a high gain up to 2.5GHz. It is very important to have a very low noise figure of an amplifier in the 1st stage in the multistage LNA using

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GaAs MESFET devices, since the noise figure of the 1st stage LNA plays an important role in the total noise figure of the overall amplifier. Therefore, a premium low noise transistor is used in the 1st stage and 2nd stage. In the 3rd stage, even though a transistor has a slightly higher noise figure, on-chip transistor (AH1) having a high power output in a broad frequency band is used.

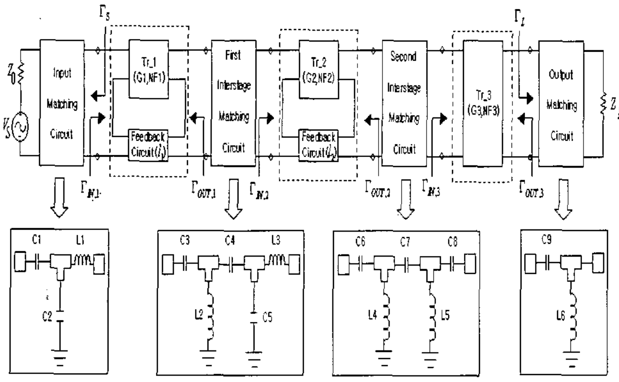

Fig. 1 Diagram of LNA composed of three-stage amplifier

The minimum noise amplifier can be obtained at the optimum reflection coefficient point of a transistor, but the input and output VSWR and the power gain are bad at the point. If only the minimum noise figure for a given device is considered, the high power gain of the multistage amplifier will not be obtained. Therefore, in the design of the 1st stage of the LNA, it is important to consider all the characteristics: noise figure, available power gain and output power level.

A transistor typically has a larger noise figure in the ultrahigh frequency band. Thus, in order to have the low noise figure and low VSWR, the important thing for an amplifier design is finding a stability condition of the transistor, and selecting the point of reflection coefficient. The common-source series feedback circuit using microstrip line with inductive degeneration is applied to select the good point of the reflection coefficient in the stability region. The optimization using genetic algorithm is required to achieve the optimum performance of the LNA since there is a trade-off among the gain, noise figure and VSWR. Therefore, a better way to design the amplifier would be to use the optimized characteristics of whole amplifier circuits instead of using the characteristic of a transistor itself.

The common-source series feedback circuits in Fig. 1 are used to improve the stability condition and the flatness of gain in the broadband. In design the common-source LNA with inductive degeneration using the series feedback microstrip line, the overall scattering parameter representation can be found by first converting the transistor's scattering parameters into impedance representation, followed by adding the impedance parameters of the series feedback microstrip line with inductive degeneration, and finally converting the result back into scattering parameters form. The overall scattering matrix of each stage of amplifier is given by Eq. (1).

$$[S_{ij}] = [z_{ij} - \delta_{ij}] \cdot [z_{ij} + \delta_{ij}]^{-1} \qquad (1)$$

Where, δ_{ij} is Kronecka-delta function, and $[z_{ij}]$ is overall impedance coefficient, normalized to a given characteristic impedance Z_0.

The $[z_{ij}]$ has a two-port network of a transistor and a two-port network of a series-feedback circuit connected to the source of the transistor.

$$[z_{ij}] = \frac{1}{\Delta}\begin{bmatrix} 1+s_{11} & s_{12} \\ s_{21} & 1+s_{22} \end{bmatrix}\begin{bmatrix} 1-s_{22} & s_{12} \\ s_{21} & 1-s_{11} \end{bmatrix} + \tanh(\gamma l) \qquad (2)$$

Where, s_{ij} is scattering coefficient of the transistor, l is length of common-source series feedback microstrip line with inductive degeneration, γ is propagation constant of microstrip line, and $\Delta = (1-s_{11})(1-s_{22}) - s_{12}s_{21}$.

3. GENETIC ALGORITHM OPTIMIZATION BY COST AND FITNESS FUNCTION

The parameters of the chromosome using genetic algorithm are source reflection coefficient Γ_S at input port, load reflection coefficient Γ_L at output port, the input reflection coefficient $\Gamma_{in,i}$ and output reflection coefficient $\Gamma_{out,i}$ of each stage of a transistor from Eq. (1). The input reflection coefficient and the output reflection coefficient of each stage of a transistor are defined by [1, 2]. And those are a function of the input and output VSWR, the total power gain G_t and the total noise figure NF_t of amplifiers. When the LNA is 3-stage transistors, the chromosome is written as: [7, 8]

$$Chromsome = [\,\Gamma_S\ \Gamma_{in,1}\ \Gamma_{out1}\ \Gamma_{in,2}\ \Gamma_{out2}\ \Gamma_{in,3}\ \Gamma_{out3}\ \Gamma_L\ \ell_1\ \ell_2\,] \quad (3)$$

The cost function evaluates to be minimized the cost value and optimized the fitness of the population. It is represented by the relation among the input and output VSWR, the total transducer gain and noise figure of the amplifier. The gain of amplifier, noise figure, input and output VSWR with fitness are found from reference [2], and the cost function on the band-limited frequency is given by

$$F(f_i) = \frac{1}{N}\sum_{i=1}^{N}\left\{\begin{matrix} K_1|G_t(f_i)-G_D|^2 + K_2|NF_t(f_i)-NF_D|^2 \\ + K_3(|VSWR_{in}(f_i)-VSWR_D|^2 + |VSWR_{out}(f_i)-VSWR_D|^2) \end{matrix}\right\} \qquad (4)$$

Where, $G_t(f_i)$ is total gain of the amplifier ($G_1G_2G_3$), $VSWR_{in,\,out}(f_i)$ is total input or output voltage standing wave ratio, and $NF_t(f_i)$ is total noise figure of the amplifier $\{NF_1 + (NF_2-1)/G_1 + (NF_3-1)/G_1G_2\}$. Also, G_D, $VSWR_D$ and NF_D are the goal of gain, VSWR and noise figure on the band-limited frequency ($f_L \le f_i \le f_U$), respectively. The constants K_1, K_2 and K_3 are the weighting values and determined through the convergence rate. In general, The K_1, K_2 and K_3 are chosen in the interval of $0 < K_i \le 1$ in order to minimize the VSWR, noise figure and maximize the gain of the amplifier. Therefore, the GA minimizes the cost values of an amplifier in the range of operating frequency. The genes are encoded with 8-bits. The genetic parameters had 196 members in the initial population, 0.5 discard rate, and 5% mutation rate. The GA procedure to optimize the LNA is as follow.

Step 1. Create the initial population, evaluate costs and sort
  Chromosomes=random(population_size, 8_bits);
  Cost=cost_function(Chromosomes);
Step 2. Evaluate cost statistics
  Mincost=minimum(Cost);
  Stdcost=standard_deviation(Cost);
Step 3. Chromosomes are paired and offspring (50% discard rate) are reproduced
  [Mom Dad]=pair(Chromosomes, Cost);
  Chromosomes=offspring(Mom, Dad, Chromosomes);
Step 4. Mutate the population with mutation rate(5%)
  Chromosomes=mutate(Chromosomes, mutate_rate);
Step 5. Check for convergence
  IF(Mincost <goal_Mincost & Stdcost <goal_std) break;
  else step2
  end

4. NUMERICAL AND EXPERIMENTAL RESULTS

In GA procedure, the LNA is composed of GaAs MESFET (EPA060B-70) and MMIC (AH1) devices used in this paper. In order to improve stability condition and get flat gain of a transistor, the common-source series feedback microstrip line circuit is connected between the source port of transistor (EPA060B-70) and the conducting ground. In addition, to reduce the noise level of the 1st and the 2nd stage amplifier, reflection coefficients are optimized as $\Gamma_S = 0.16\angle 61.5$, $\Gamma_{in,1} = 0.38\angle -54.9$, $\Gamma_{out,1} = 0.57\angle -23.9$, $\Gamma_{in,2} = 0.37\angle -62.2$ and $\Gamma_{out,2} = 0.57\angle -17.9$. The power gain indicates the gain as 16.5dB, while the noise figure indicates the low noise figure as 0.5dB. At the 3rd stage amplifier, reflection coefficients are optimized as $\Gamma_{in,3} = 0.52\angle -175.7$, $\Gamma_{out,3} = 0.245\angle -156$ and $\Gamma_L = 0.05\angle -94$ using GA. It shows that the characteristic of the 3rd stage on-chip amplifier (AH1) is 12.5dB power gain and 2.2dB noise figure. Also, the optimized lengths of the common-source series feedback microstrip lines with unconditionally stable condition are obtained by 0.0125λ at the design frequency of 2.315GHz.

The broadband amplifier design should contain the matching circuit to achieve a constant gain over the operating frequency range of the amplifier. In this paper, there are double T-type matching circuits in the inter-stage matching between the 1st and the 2nd stages and between the 2nd and the 3rd stages the amplifiers. To have a low input VSWR, the input matching circuit matches the source impedance to Γ_S. The input port of the first part of the inter-stage matching circuit is to be the conjugate of the output port reflection coefficient $\Gamma_{out,1}$ of the 1st stage of the amplifier and matched to 50 ohm of the input port of the second part of the inter-stage matching circuit. The output port of the second part of the inter-stage matching is to be the conjugate of the input port reflection coefficient $\Gamma_{out,2}$ of the 2nd stage the amplifier and matched to 50 ohm of the output port of the 1st part of the inter-stage matching circuit. Two matching circuits between the amplifiers using two-stage matching method provide the flat gain and low VSWR over the wide frequency range. According to the relationship of the load reflection coefficient, $\Gamma_L = \Gamma^*_{out,3}$, the load conjugate matching circuit of the 3rd stage is designed to have the maximum transducer power gain. The parameters of the LNA circuit in Fig. 1 are shown in Table 1.

Table1. Design parameters of the three stages LNA.

Elements	Designed values	Elements	Designed values
C_1, C_3, C_4, C_6, C_7	39 pF	L_1, L_3, L_6	3.3 nH
C_2, C_5	0.5 pF	L_2, L_4	3.9 nH
C_8	1.5 pF	L_5	2.2 nH
C_9	2.5 pF	l_1, l_2	2.0mm

Fig. 2 shows the cost values and standard deviation of cost calculated with Eq. (3) and Eq. (4). The cost value and the standard deviation of the cost at the design frequency (2.315GHz) converge to almost zero after fifteen iterations. Also, Fig. 3 shows the flatness of the total transducer gain, noise figure and VSWR, and those converge well to the goals of the amplifier (G_D=41dB, $VSWR_D$=1.2, NF_D=0.5dB).

An LNA with three-stage amplifiers is simulated and fabricated based on the design specification. The characteristics of Teflon substrate are tangent loss=0.0024, thickness=31mil and the relative dielectric constant = 2.3. A vector network analyzer and a spectrum analyzer are used for testing the LNA.

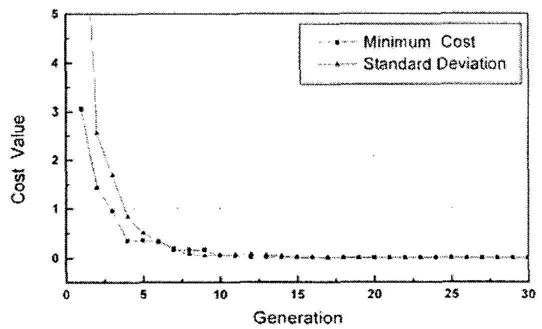

Fig. 2. Cost values and standard deviations vs. generations (K1=K2=K3=1, G_D=41dB, $VSWR_D$=1.2, NF_D=0.5dB).

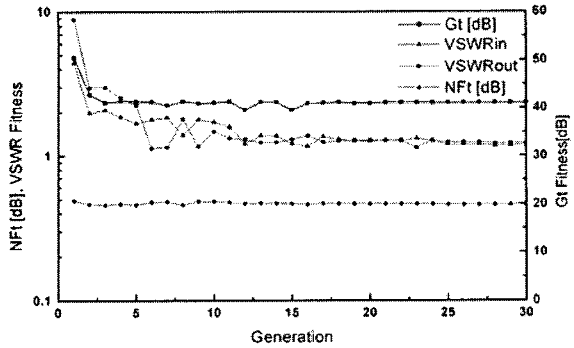

Fig. 3. Fitness values vs. generations for the transducer gain, noise figure and VSWR ($K1=K2=K3=1$, G_D=41dB, $VSWR_D$=1.2, NF_D=0.5dB)

Fig. 4 shows the measured and the simulated scattering parameters of the LNA. From the measured result, the LNA has the gain (41 ± 0.5dB) over the broadband of between 2.2GHz and 2.6GHz. It is more than 3dB higher than the gain of other LNAs with three-stage amplifiers, and good enough for the desired bandwidth from 2.2GHz to 2.6GHz including an ISM band and WiBro application. The measured and the simulated gains are well-agreed. The S_{11} parameters of the LNA should be lower than −14dB to achieve the lower than 1.5 VSWR.

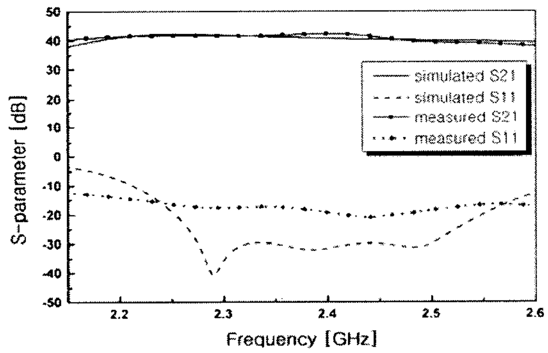

Fig. 4. Simulated and measured scattering parameters of the LNA

Fig. 5 shows the simulated and the measured input and the output VSWR of the LNA. The input VSWR is 1.3 and the output VSWR is 1.2 on the operating frequency range of the LNA in an ISM band (2.4GHz ~ 2.5GHz) and WiBro application (2.3GHz ~ 2.4GHz), while the input and output VSWR are lower than 2 in the frequency band from 2.2GHz to 2.6GHz. Therefore, the designed LNA has the low VSWR and the high gain with very low variation in a wide frequency range.

Fig. 6 shows the measured result of the carrier-to-noise ratio (C/N) of the fabricated LNA. The carrier to noise ratio at the output port of the LNA is measured when the applied RF input power is −70dBm. C/N is measured as -53.27dBm at the offset frequency of 100KHz away from the design frequency (2.315GHz) by spectrum analyzer.

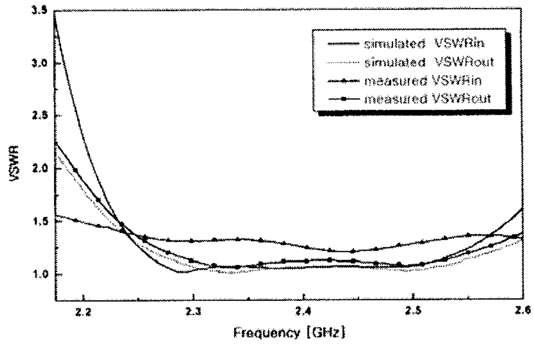

Fig. 5. Simulated and measured VSWR of the LNA with three-stage amplifiers

The noise figure of a system is given by the following equation.

$$NF = P_{RF} - P_n - 10\log_{10}(RB/Hz) + C/N \quad (5)$$

where, P_{RF} is the input power of the signal at the design frequency, and P_n is a noise power per 1Hz at the normal temperature (T=290°K). The value of the P_n is 174dBm/Hz generally. RB is the resolution bandwidth (100KHz), which is the same as the offset frequency in the measurement. Thus, the noise figure of the fabricated LNA is 0.73dB at the design frequency, and 0.85dB in the bandwidth (2.3~2.5Hz).

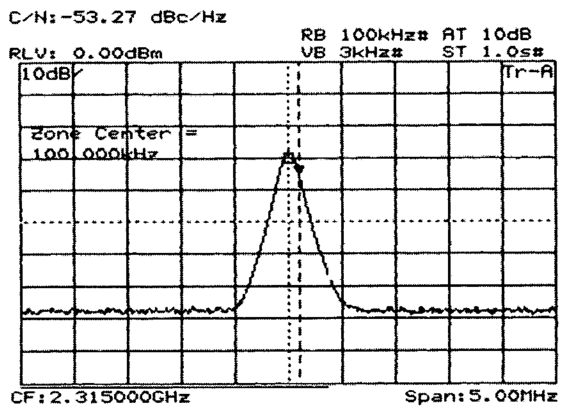

Fig. 6. Measured C/N ratio of the LNA with three-stage amplifiers

5. CONCLUSION

The common-source low noise amplifier (LNA) with inductive degeneration based on a genetic algorithm has been designed and tested for a down converter in an ISM and WiBro application. The genetic algorithm optimized source reflection coefficient, load reflection coefficient, input and output reflection coefficients, lengths of common-source series feedback microstrip lines for the design of three-stage amplifiers. The optimized LNA has low voltage standing wave ratio, noise figure and broadband high gain flatness of the amplifier. Stability and variation of gain for the LNA have been improved by using the optimized parameters by a GA. Especially, a low noise figure and a low VSWR are obtained in the operating bandwidth in an ISM and WiBro application. The transducer power gain of the fabricated LNA is (41 ± 0.5dB) over the broadband (2.2GHz ~ 2.6GHz). In addition, in the operating frequency range of the bandwidth (2.3GHz ~ 2.5GHz), the input and output VSWR are below 1.3, and the noise figure of the LNA is also achieved lower than 0.85dB. Therefore, the performance of LNA in this paper has been satisfied with the specifications of an ISM band and WiBro application.

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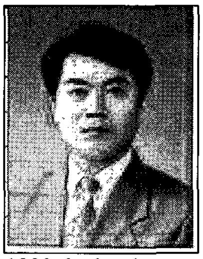

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