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마이크로스트립 궤환 전송선을 이용한 광대역 캐스코드 전단 증폭기 해석 및 설계

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Analysis and Design of Broadband Cascode Preamplifier Using microstrip feedback line

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Abstract

A broadband, high gain and high power output low noise amplifier (LNA) is designed and fabricated for a down converter in a wireless local loop application. The LNA consists of 3 stages of amplifiers. The 1^{st} stage is designed to reduce the noise level, and the 2^{nd} stage is designed to have maximum gain. The 3^{rd} stage has characteristics of broadband and high power. The stability and the gain flatness of the LNA have been improved by using a matching circuit and a source feedback microstrip line at the first and second stages of the amplifiers. The gain of the LNA is (41 ± 0.5dB) over the broadband (2.15GHz~2.45GHz). In the operating frequency range of a wireless local loop application (2.3GHz ~ 2.33GHz), the measured power gain and VSWR of the LNA are 41.5 ± 0.05dB and 1.36, and the noise figure of the LNA is lower than 0.85dB.

Key words : Low Noise Amplifier (LNA), Down converter, Feedback & Matching Circuit

I. Introduction

A low noise amplifier (LNA) is a part of a circuit in a down converter, which converts radio frequency (RF) signals into intermediate frequency (IF) signals to extract the original signal from the modulated RF signal in a wireless application.

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The received signal at a receiver should be amplified by an LNA since the power level of the RF signal is low and mixed with noise. An LNA requires minimum noise level, low input voltage standing wave ratio (VSWR) and maximum power gain characteristics. Since it is hard to achieve a minimum noise level, low VSWR and maximum power gain, simultaneously, the gain and the noise level should be carefully selected from the constant circle of those in a Smith Chart. In addition, a broadband LNA design can be achieved by using a combination of the following methods: matching network, balanced amplifiers and feedback circuits [1-5].

An LNA in a wireless communication system consists of a low noise amplifier and its bias circuit. The low noise amplifier is an active transistor with a low noise characteristic 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. The references [2, 3] show the requirements of having an unconditionally stable amplifier over the operating frequency range.

The stability factor of an active amplifier in the LNA 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.

LNA characteristics, broadband, high gain, low VSWR and stable characteristic over the operating frequency range cannot be achieved with a single stage amplifier design. In this paper, an LNA with three stages of amplifiers has been designed to achieve the characteristics. The 1^{st} and the 2^{nd} stage amplifiers are composed of low noise MESFETs. The 3^{rd} stage amplifier is an MMIC transistor having high power output over the operating frequency range. Even though the MMIC transistorin the 3^{rd} stage has a slightly higher noise figure, it is used in the 3^{rd} stage since the total noise figure of the LNA is basically determined by the noise figure of the 1^{st} stage and the 2^{nd} stage amplifiers. In addition, the characteristics of the input and output matching circuit should be placed in a stable region todesign an amplifier with a low noise level over the operational frequency band. The points of reflection coefficient should be carefully selected to improve the VSWR and the power gain of the amplifier simultaneously. This paper also proposes the use of source series feedback circuits with the loseless micro-strip lines at the 1^{st} and the 2^{nd} stages of amplifiers to improve the gain flatness and the stability condition in the wide frequency range. The wide frequency range includes the frequency range of a down converter in a wireless local loop (WLL) application.

II. Design of an LNA with 3-stage amplifiers

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 $1^{st}$and the 2^{nd} stages of transistors are GaAs MESFET (EPA060B-7) which have a low noise figure(0.5dB) and a high gain up to 2GHz. It is very important to have a very low noise figure of an amplifier in the 1^{st} stage in a multistage LNA using GaAs MESFET devices, since the noise figure of the 1^{st} 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 1^{st} stage. In the 3^{rd} stage, even though the MMIC transistor has a slightly higher noise figure, the MMIC (AH1), having a high power output in a wide frequency band, is used.

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 ofthe multistage amplifier will not be obtained. Therefore, in the design of the 1st stage of the amplifier, it is important to consider all the characteristics: noise figure, available gain and output power.

A transistor typically has a larger noise figure in the high frequency band. Thus, in order to have the low noise figure and low VSWR, the important thing for an amplifier design is drawinga stability circle of the transistor, and selecting the point of reflection coefficient. The source series feedback circuit using a lossless micro-strip lineis applied to select the good point of the reflection coefficient in the stability circle. Therefore, a better way to design the amplifier would be to use the constant noise circles of whole circuits instead of using the constant noise circles of a transistor itself. Some modifications are required to achieve the optimum performance of the system since there is a trade-off among the gain, noise figure and VSWR [2, 3].

The source series feedback circuits are used to improve the flatness of gain and the stability condition in the broadband. To design a source series feedback circuit with a transistor connected to the two ports network, the scattering matrix is required. The scattering matrix of a two ports matrix is given by (1).

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

where,

δ_{ij} = Kronecka-delta function,

z_{ij} = overall impedance coefficient, normalized to a given characteristic impedance Z_0.

The overall impedance matrix $[z_{ij}]$ has a two-port network of a transistor and a two-port network of a source series-feedback microstrip line connected to the source of the transistor in the equation (2).

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

where, s_{ij} = scattering coefficient of the transistor,

$\Delta = (1-s_{11})(1-s_{22}) - s_{12}s_{21}$,

$\gamma = \alpha + j\beta$,

$$\alpha = \frac{\omega\sqrt{\mu_0\varepsilon_0}\,\varepsilon_r(\varepsilon_{ref}-1)\tan\delta}{2\sqrt{\varepsilon_{ref}}(\varepsilon_r-1)} + \frac{1}{Z_0 W}\sqrt{\frac{\omega\mu_0}{2\sigma}}$$

$\beta = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_{ref}}$,

$$\varepsilon_{ref} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12h/W}}$$

l = length of the microstrip line,

$\tan\delta$ = loss tangent of the dielectric of microstrip line,

W = conductor width of microstrip line,

σ = conductivity of microstrip line,

h = thickness of the dielectric slab,

μ_0 = permeability of the free space,

ε_0 = permittivity of free space.

ε_r = relative permittivity.

Fig. 1 shows the LNA circuit design with 3-stage amplifiers. It consists of input and output matching circuits, the 1st, 2nd and 3rd stage transistors, two source series feedback circuits and two inter-stage matching circuits between the transistors. The input/output matching circuits are used to match the LNA to the input and output ports, and the source series feed back circuits are used to make the transistor stable. In addition, the inter-stage matching circuits have been used to have the flat gain over the broad frequency band.

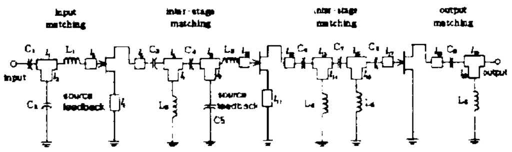

Fig. 1. Circuit layout of LNA with three-stage amplifiers.

Since the stability circles are potentially unstable before the source feedback, it was hard to decide the design point among the power gain circle, the noise figure circle and the operating power gain circle. After the feedback, the centers of the noise figure circles and power gain circles are concentrated in the specific area and located in the unconditionally stable region. Therefore, it allowed us to locate the amplifier design point at the concentrated area of the circles, and to find the reflection coefficient of the transistor to be matched to that of the input and output ports using the matching circuit. The source series feedback circuit is constructed between the source port of transistor (EPA060B-70) and the conducting ground. The optimum length of the source series feedback of the micro-strip line is 0.0125λ at the center frequency of 2.315GHz.

The design specification of power and noise figure of the EPA060B-70 with the source series feedback are the 16.5dB available power gain circle and 0.5dB noise figure circle, respectively. The available power gain and the operating power gain of a transistor are defined and their relationships among these parameters are explained [6, 7]. The available power gain is a function of the source reflection coefficient at the input port (Γ_S) and of the scattering parameters of a transistor. And the operating power gain is a function of the load reflection coefficient at the output port (Γ_L) and of the scattering parameters of a transistor. The input reflection coefficient (Γ_{IN}) and the output reflection coefficient (Γ_{OUT}) of a transistor are shown by (3) and (4). The S parameters are calculated with the equation (1).

$$\Gamma_{IN} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \tag{3}$$

$$\Gamma_{OUT} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} \tag{4}$$

The input reflection coefficient, Γ_{IN}, will be decided by Γ_L, and the output reflection coefficient, Γ_{OUT}, will be decided by Γ_S. The value of Γ_S and Γ_L should not be too close in their respective stability circles, because oscillation might occur due to component variation.Since the value of the Γ_S affects the output power and voltage standing wave ratio (VSWR), the Γ_S value should be selected close to the center of the Smith Chart to have a small input VSWR. In addition, to reduce the noise level of the 1st stage amplifier, reflection coefficients are selected from the 0.5dB noise circle as $\Gamma_S = 0.16\angle 61.51$ and $\Gamma_{OUT1} = 0.57\angle -23.89$ ($\Gamma_{OUT} = \Gamma_{OUT1}$), where the given optimum reflection coefficient of the transistor is $\Gamma_{OPT} = 0.38\angle 54.94$.

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 (Γ_{OUT1}) of the 1ststage 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 theconjugate of the input port reflection coefficient (Γ_{IN2}) 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. At the 2nd stage amplifier, $\Gamma_{IN2} = 0.37\angle -62.16$ and $\Gamma_{OUT2} = 0.57\angle -17.91$ are used.

The characteristic circles of the 3rd stage amplifier MMIC (AH1) are in the stable region. It shows 13dB power gain of circle, and 2.5dB noise figure circle. To have a high gain, the input and output reflection coefficients are selected on the high power gain circles. This is done even though the noise figure is high because the noise figure of the LNA is mainly decided by the noise figures of the 1st and the 2nd stage of the amplifiers. Therefore, the input and output reflection coefficients of the output stage (3rd stage) are selected as $\Gamma_{IN3} = 0.52\angle -175.68$ and $\Gamma_{OUT3} = 0.05\angle -94.02$, respectively. According to the relationship of the load reflection coefficient, $\Gamma_L = \Gamma^*_{OUT3}$, the load 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.

Table 1. Design parameters of the LNA with three -stage amplifier.

Elements	Designed values	Elements	Desinged values
C1	39 pF	l4	2 mm
C2	0.5 pF	l5	2.43 mm
C3	39 pF	l6	4.25 mm
C4	39 pF	l7	1.74 mm
C5	0.5 pF	l8	2 mm
C6	39 pF	l9	3.4 mm
C7	39 pF	l10	2.32 mm
C8	1.5 pF	l11	2 mm
C9	2.5 pF	l12	2.43 mm
L1	3.3 nH	l13	4.25 mm
L2	3.9 nH	l14	1.74 mm
L3	3.3 nH	l15	3.92 mm
L4	3.9 nH	l16	0.79 mm
L5	2.2 nH	l17	3.4 mm
L6	3.3nH	l18	2.62 mm
l1	2 mm	l19	1.99 mm

One of the most important considerations in a bias circuit design is the voltage and current stability at the bias point of a transistor. A good dc bias circuit functions to maintain the bias voltage and current as a constant at the operating point of a transistor even though the transistor parameters are varied by wide temperature variation. A pnp BJT for an active dc biasing circuit is used to stabilize the operating point of the microwave transistor.

III. Experimental results

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.

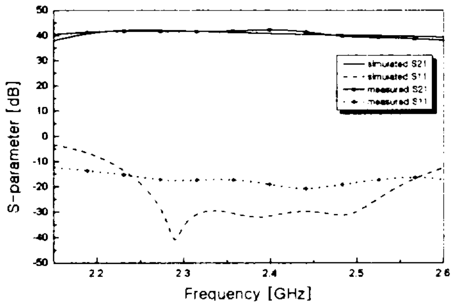

Fig. 2. Simulated and measured scattering parameters of the LNA.

Fig. 2 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 2.15GHz and 2.45GHz. In addition, the fabricated amplifier has obtained the gain with very low variation (41.6±0.05dB) over the operating frequency range from 2.3GHz to 2.33GHz. It is more than 3dB higher than the gain of other LNAs with three-stage amplifiers, and good enough for the desired bandwidth from 2.3GHz to 2.33GHz of the wireless local loop applications. 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. In Fig. 2, the frequency band having lower than 14dB of S_{11} is from 2.2GHz to 2.6GHz, which is wider than the specification.

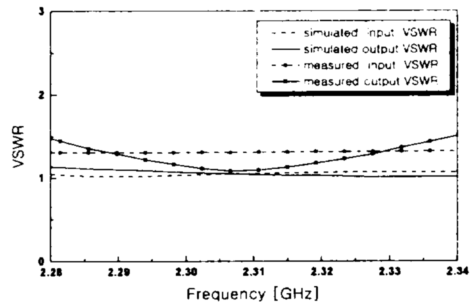

Fig. 3. Simulated and measured VSWR of the LNA with three-stage amplifiers.

Fig. 3 shows the simulated and the measured input and the output VSWR of the LNA. The input VSWR is 1.32 and the output VSWR is 1.36 on the operating frequency range (2.3GHz ~ 2.33GHz) of the LNA in a WLL application, while the input and output VSWR are lower than 1.5 in the frequency band from 2.28GHz to 2.34GHz. These are lower than the design specification of VSWR=1.5 for a WLL application. Therefore, the designed LNA has the low VSWR and the high gain with very low variation in a wide frequency range.

Fig. 4 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 center frequency (2.315GHz) by spectrum analyzer. The noise figure of a system is given by the following equation.

$$NF = P_{RF} - P_n - 10\ Log_{10}(RB/Hz) + C/N \quad [dB]$$

Where P_{RF} is the input power of the signal at the center frequency, and P_n is a noise power per 1Hz at the normal temperature (T=290K). 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 is 0.73dB at the center frequency, and 0.85dB in the WLL bandwidth (2.3~2.33GHz). The noise figure of the fabricated LNA is less than that of the design specification (1.2dB) for a WLL.

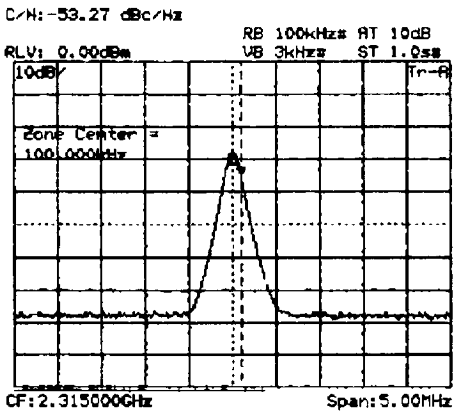

Fig. 4. Measured C/N ratio of the LNA with three-stage amplifiers.

IV. Conclusion

A low noise amplifier (LNA)broadband, high gain and high power outputusing the three-stage amplifiers with a source series feedback has been designed and tested for a down converter in a WLL application. Stability and variation of gain for the LNA have been improved by using a source feedback circuit. Especially, a low noise figure and a low VSWR are obtained in the operating bandwidth in a WLL. The transducer power gain of the fabricated LNA is (41±0.5dB) over the broadband (2.15GHz ~ 2.45GHz). In addition, in the operating frequency range of WLL (2.3GHz ~ 2.33GHz), the gain is 41.6±0.05dB, and the input and output VSWR are 1.36. 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 a WLL, and it outperforms a general LNA in a WLL application.

요 약

무선가입자망(WLL) 응용시스템의 다운 컨버터에 사용되는 광대역, 고이득, 고출력 저잡음 증폭기(LNA)를 설계하고 제작하였다. LNA는 3단 증폭기로 구성되었으며, 첫단은 잡음 레벨을 감소시키도록 설계하였고 둘째단은 최대 이득을 얻도록 그리고 셋째단은 광대역 특성과 고출력 특성을 갖도록 설계하였다. 정합회로와 증폭기의 첫단과 둘째단에 소스궤환 마이크로스트립라인을 사용하여 LNA의 안정도와 이득평탄도를 개선시켰다. LNA의 이득은 2.15GHz 2.45GHz의 광대역에서 41±0.5dB로 측정되었으며, 측정된 전력이득과 VSWR은 무선가입자망 주파수대역 (2.3GHz2.33GHz) 범위에서 41.5±0.05dB와 1.36 그리고 저잡음 특성은 0.85dB보다 낮게 나타났다.

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