A broadband low noise amplifier in 70nm GaAs MHEMT process

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Abstract. In this paper, a broadband low noise amplifier (LNA) is presented with 70nm GaAs metamorphic high electron mobility transistor (MHEMT) process. The feedback and input/output impedance match techniques for broadband amplifier are presented. The stability, noise figure, gain flatness, and S-parameter performance of this LNA are analyzed and discussed. The small signal gain of the LNA is 20dB±0.2dB and noise figure of 0.86dB~1.35dB among operating from almost DC to 15GHz. This LNA exhibits reflection below -10dB, power dissipation of 70mW and chip area of 1.0mm*0.6mm. This LNA finds its application in many wideband systems.

1. Introduction

The wideband microwave LNA has been widely used in software defined radio (SDR), digital RF, ultra-wide bandwidth (UWB) transceiver, and other broadband systems [1-4]. These LNAs need low noise figure (NF), high gain, good input/output (I/O) matching, good gain flatness, unconditional stability, and acceptable linearity performance across wideband [5-8].

Several papers report the monolithic microwave integrated circuit (MMIC) LNA in different semiconductor processes, such as InP HEMT, GaAs HEMT, SiGe HBT, or GaN HEMT technology [3, 9-12]. Many papers reported feedback methods to reduce the effect of Cgs and improve wideband performance of LNA with gain compensation include: direct feedback from drain to gate with resistor, inductor and capacitor (RLC) [2-3, 5], transformer feedback [13], multi-feedback paths [4], incorporating Cgs into the match network [14] and source degeneration [1, 15]. Paper [13,16] use multi-stages to expand bandwidth and improve the gain and paper [17] presents distributed amplifiers (DA), which adopts two sets of high impedance transmission lines to connect the gates and drains of several active transistors, to get the broadband performance. However, many papers did not get the comprehensive performances of the LNA. For example, some papers have a high gain ripple [7, 16], and some I/O matching are not good enough [2, 15]. Even some LNAs have relatively high NF, large chip size or complex structure [12, 17-18]. So it is always a challenge to design a high performance broadband MMIC LNA.

We present a broadband MMIC LNA with the 70nm GaAs MHEMT process by OMMIC foundry. As shown in Figure 1, the LNA is designed with two negative feedback networks (FN) and a source self-bias network (SN) to ensure the stability and wideband I/O impedance matching. The LNA shows a NF of 0.86dB~1.35dB, a gain of 20dB and an output 1dB compression point (P1dB) of 2dBm operating from almost DC to 15GHz. The amplifier is matched at both I/O ports with S11 and S22
below -10dB. Also, the chip size is about 1.0mm*0.6mm. The overall performance of this LNA would be very good and this LNA can be applied in many broadband systems. In Section 2, the design flow and the circuit structure are described. The model and characteristic analysis of the proposed LNA is presented in Section 3. The simulation results are presented in Section 4. Finally, the Section 5 describes the conclusion.

2. Circuit design
As shown in Figure 1, this proposed wideband LNA is a two-stage cascaded configuration with two FNs and one SN. Comparing to the traditional multi-stages common source or common gate structures, this proposed LNA shows better gain flatness, broadband impedance matching, acceptable linearity and NF performances. The FN1 and FN2 consist of a resistor R and parasitical transmission line. Although these FNs contribute undesired noise to the amplifier, they play a major role in I/O matching and stability. The SN at source of M2 is made up of a resistor R4 and a capacitor C2. The SN plays an important role in gain flattening and automatic transient protection to the LNA when powered up. A series inductor L1 is added to the input stage to optimize the input reflectance and NF. Also, to achieve good output matching response, an output matching network (MN) composed of an inductor L2 and two resistors (R5, R6) is added at the output. In addition, the inter-stage MN is used to improve amplifier stability [19]. In this paper, we choose 4 fingers and 50um gate width for the M1, and 6 fingers and 40um gate width for M2.

![Figure 1. The schematic diagram of the proposed LNA.](image)

The DC biasing network (BN) act an important role in protecting the RF signal from the circuit’s DC supplied [19]. However, the BN on chip will make larger chip area. In this paper, the transistors gates and drains are biased by off-chip high performance inductors to save chip size. In addition, some off-chip bypass capacitors are used to filter the dithering noise coming from the DC supply. In this proposed LNA, we choose Vg1, Vd1 of the M1 as 0V and 1V. As the R4 is located at the source of the M2, the Vd2 is increased to 1.2V to making the Vds2 as about 1V. Setting the Vg2 as 0V, the Vgs2 of M2 will be biased at about -0.2V. All these networks and bias condition will determine the stability, I/O impedance, NF and S-parameter performances of the LNA.

3. Performances analysis
The stability, noise and S-parameters performances are the main aspects in the LNA design [19]. Since the MHEMT’s $f_t$ (Characteristic frequency) in this technology is very high, the stability analysis is simulated up to 100GHz [20]. For improving stability, we do not use the source degeneration inductors, which are widely used in LNA design, because of the requirement of bigger
chip size with little performance improvement at low frequency. In the proposed LNA, there are multi-feedback paths with resistors, which will make the LNA more stable. Additional small resistors were added at the inter stage and output respectively to ensure unconditional stability without increasing much noise.

In this proposed LNA, the FN1 not only feeds the signal back to the input and adds noise, but also optimizes the input impedance of the LNA [2, 4]. The PRC noise model of the LNA can be established by simplifying the circuit model with neglecting the sub-circuits, and detailed analysis can be found in Reference [4, 19]. The simplified small signal PRC model of this LNA for noise evaluation includes three major noise current sources (a gate one at the M1 input, a drain one at the M1 output and a R1 equivalent source between gate and drain of M1) [4,19]. Although the R1 optimizes the input matching bandwidth and stability, the gain and NF will be degraded seriously if the R1 is too small. However, at high frequency, long resistor in the layout behaves as transmission line, and these distributed effects have influence to the resistance.

As we know, the transistor gain rolls off with frequency. In this circuit, the FNs and SN are designed to get a wideband gain flatten with guaranteeing stability and I/O matching within the frequency band. At low frequency, the SN of M2 is equivalent to a small resistor which deteriorates the gain inevitably, while the FN is equivalent to a resistor which deteriorates the gain too. However, at the high frequency (such as above 10GHz), the SN is shorted by the capacitance, which would not obviously decrease the gain of the LNA. Also, the FN is equivalent to a resistor with a small parasitic on-chip transmission line inductance which decreases gain more slightly than at low frequency.

In order to design the LNA working in broadband with smaller chip size, we adopted small lumped elements rather than distributed elements for impedance matching. The feedback topologies in this paper, which make the Γopt closer to the Γs in the Smith Chart, are a good trade-off for noise and broad input matching. The input of LNA is designed for minimum NF with one series inductor L1. The output is designed for maximum wideband matching with two resistances R5, R6 (which will reduce the gain), and a series L2 [21]. The FNs and SN reduce gain at low frequency, and the overall gain slope could become positive with the small on-chip I/O MNs.

Generally, a larger transistor with higher Vds will provide good linearity performance. However, in this LNA, we add resistances at output, which sacrifice the P1dB to optimize broadband output matching and get good overall performance.

4. Simulation results
In this design, we choose the D007IH MHEMT process, which is built on GaAs substrate with 100um thickness, from OMMIC foundry. The LNA circuit is designed by Advanced Design System (ADS) software including schematic and layout EM simulation to optimize the performance. Gates and drains of transistors are biased through off-chip inductance BN and the bond wires and on-chip pads are also taken into account in the EM simulation. Figure 2 shows the 3D circuit layout of the MMIC with an area of 1.0mm*0.6mm.

![Figure 2. 3D layout of the proposed LNA.](image-url)
From the simulation results of Figure 3(a), we can see that the LNA is unconditionally stable up to 100GHz. And Figure 3(b) shows I/O return loss is better than -10dB from almost DC to 15GHz. In Figure 3(b) and Figure 3(c) the simulated LNA presents a gain about 20dB±0.2dB and NF of 0.86dB~1.35dB in the band of interest. Figure 3(d) demonstrates the simulated output P1dB>2dBm at different frequencies. Also, we should note that the simulation results in Figure 3(d) are based on large signal model, and the S-parameters simulation results in Figure 3(b) are based on small signal model. These different models which provided by OMMIC foundry make the simulation results of gain a little difference [20]. We suspect that the different models are extracted by different methods, which make the simulation results of gain a little difference. As it is a LNA, we take the gain of the amplifier in the Figure 3(b) as the standard.

Figure 3. The EM simulation results of the proposed LNA: (a)Stability; (b)S-parameters (c)Noise; (d)P1dB.

The FOM can be used to evaluate the performance of an LNA. The FOM relates to the gain-bandwidth product (GBP), NF and DC power consumption. The S21, mag is the magnitude of the small signal gain, NFmag is the magnitude of the noise figure, and Pdc is the dc power consumption in milli-watt [4].

\[
FOM = \frac{S21_{mag} \times Bandwidth}{(NFmag^{-1}) \times P_{dc}} \left[ \frac{GHz}{mW} \right]
\]  

(1)

The Table 1 summarizes the performance of this proposed LNA and recent published similar wideband LNA MMICs. Reference [2] and Reference [5] present PHEMT based LNA which shows good FOM performance but with bad S11 and large chip size. The multi-stage feedback LNAs in Reference [4] and Reference [17] have high NF and low gain. In the Reference [6], a distributed wideband LNA is designed and implemented in a 0.1um GaAs pHEMT process with big chip size and
high dc power. The LNA in Reference [12] and Reference [16] are based on GaAs 0.1um PHEMT, and they show poor gain flatness compared with this work.

In this paper, the high gain, low NF, small chip size performances with an FOM of 70.7GHz/mW make this proposed broadband LNA competitive. And the performance of the positive increase gain with the frequency in-band is valuable for engineering practice. Given the authors’ experience, it must be noted that when the design is fabricated, the results are expected to be similar to the ones obtained in the EM simulation.

Table 1. The FOM of the recent published LNA MMICs.

| Ref | Technology | Frequency (GHz) | Gain** (dB) | NF** (dB) | S11 in band (dB) | Gain variation (dB) | Chip Area (mm2) | Pdc (mW) | FOM (GHz/mW) |
|-----|------------|----------------|-------------|-----------|-----------------|---------------------|-----------------|----------|--------------|
| [2] | 0.15-μm pHEMT | 3.2-14.7 | 34 | 1.3 | <.5* | 0.8 | 2.5x1.5 | 45 | 1839 |
| [4] # | 0.5-μm pHEMT | 0-6 | 16 | 1.5-2.2 | <10 | 0.4 | 20 | 42.5 | 10.9* |
| [5] | 0.10-μm pHEMT | 3.8-19.8 | 20 | 2 | <.5* | 3 | 1.5x1.0 | 40 | 68.4* |
| [6] | 0.15-μm pHEMT | 0.1-20 | 28.6 | 3.1-5.8 | <10 | 5* | 1.53 | 505 | 15.7* |
| [12] | 0.07-μm pHEMT | 5-15 | 33* | 1.4* | <.9* | 4* | *** | 220 | 238* |
| [16] | 0.15-μm pHEMT | 3-15 | 28 | 2* | <.7* | 7* | 2*1 | 200 | 64.7* |
| [17] | 0.1-μm pHEMT | 2-40 | 15.2 | 2.3 | <.5 | 4* | 1.88 | 110 | 16.4* |
| This work | 0.07-μm pHEMT | 0-15 | 20 | 0.86-1.3 | <10 | 0.4 | 1.0x0.6 | 70 | 70.7 |

PS: *estimated from the data shown in the paper; ** average in band; *** not described in the paper; #simulation results

5. Conclusions

A broadband MMIC LNA based on a commercial 70nm GaAs MHEMT process has been designed and simulated. This proposed LNA with multi-feedback networks operating from almost DC to 15GHz for broadband applications. This LNA is unconditionally stable, and it has a gain of 20±0.2 dB, a NF less than 1.35dB up to 15GHz. Also the return loss is better than -10dB at both I/O ports, and the output P1dB is better than 2dBm. The results suggest that the proposed LNA, whose chip size is less than 1.0mm*0.6mm, is suited for many wideband systems.

References

[1] Banerjee P and Majumder A 2015 Computer-aided-design of an 18–40 GHz MMIC low noise amplifier using RLC and series inductive feedback 2015 IEEE MTT-S International Microwave and RF Conference (IMaRC) IEEE

[2] Wang Y, Chiong C C, Nai J K and Wang H 2015 A high gain broadband LNA in GaAs 0.15-μm pHEMT process using inductive feedback gain compensation for radio astronomy applications IEEE International Symposium on Radio-frequency Integration Technology IEEE

[3] Nguyen D P, Pham B L, Pham T and Pham A V 2017 A 14–31 GHz 1.25 dB NF enhancement mode GaAs pHEMT low noise amplifier IEEE MTT-S International Microwave Symposium

[4] Sun Zhengyu, Yang Hongwen and Zhang Lijun 2013 A technique for bandwidth extension and noise optimization of wideband; low-noise amplifier with dual feedback loops Analog Integrated Circuits & Signal Processing

[5] Chen YenChih, Wang Yunshan, Chiong ChauChing and Wang Huei 2017 An ultra-broadband low noise amplifier in GaAs 0.1-μm pHEMT process for radio astronomy application IEEE International Symposium on Radio-Frequency Integration Technology IEEE
[6] Hu J, Ma K, Mou S and Meng F 2018 A Seven-Octave Broadband LNA MMIC Using Bandwidth Extension Techniques and Improved Active Load IEEE Transactions on Circuits and Systems 3150-3161
[7] Kumar C and Wekhande R 2014 A prospective design methodology of MMIC 2–6 GHz low noise amplifier 2014 International Conference on Power Automation and Communication (INPAC) IEEE
[8] Li Ruwei, MA K, Mou Shouxian and Meng Fanyi 2017 A 0.1–6 GHz digital controlled variable gain low noise MMIC amplifier 477-481 10.1109/PIERS-FALL.2017.8293186
[9] Viaud J P, Serru V and Bois J R 2014 GaAs and GaN RF chipset solutions for AESA Radar International Radar Conference IEEE
[10] Alam M S, Mukerjee A and Schroter M 2015 Performance investigation of dual band millimetre wave SiGe low noise amplifier (LNA) 2015 IEEE MTT-S International Microwave and RF Conference (IMaRC) IEEE
[11] Rudolph M, Andrei C, Doerner R, Chevtchenko S A and Heinrich W 2017 Noise in GaN HEMTs and circuits International Conference on Noise & Fluctuations
[12] Chen Ying, Wu KunLong, Huang ChingYing and Chang CheKun 2017 OMMIC 70nm-mHEMT LNA design 2017 IEEE Asia Pacific Microwave Conference (APMC) Kuala Lumpur pp 1192-1195
[13] Nikandish G, Yousefi A and Kalantari M 2016 A Broadband Multistage LNA With Bandwidth and Linearity Enhancement IEEE Microwave and Wireless Components Letters 26(10) 834-836
[14] Chou C F, Chang Y C, Wang H and Chiong C C 2015 High gain fully on-chip LNAs with wideband input matching in 0.15-μm GaAs pHEMT for radio astronomical telescope European Microwave Conference IEEE
[15] Chen B Y, Chiong C C and Wang H 2014 A high gain K-band LNA in GaAs 0.1-μm pHEMT for radio astronomy application Asia-Pacific Microwave Conference IEEE
[16] Hui Z, Qian G, Zhong W and Cong L 2017 A 3–15 GHz ultra-wideband 0.15-μm pHEMT low noise amplifier design IEEE International Conference on Communication Systems
[17] Nikandish G and Medi A 2018 A 40-ghz bandwidth tapered distributed lna IEEE Transactions on Circuits and Systems II: Express Briefs 65(11) 1614-1618
[18] Khan M, Khan U, Peng Z, Buzdar A R, Buzdar A, Li L, et al. 2016 Ka-band GaAs MMIC LNA using a 0.15um metamorphic InGaAs MTT-S International Wireless Symposium IEEE
[19] Bahl I. J 2009 Fundamentals of RF and Microwave Transistor Amplifiers Wiley-Interscience
[20] D007IH process OMMIC http://www.ommic.com/
[21] Colangeli S, Cicognani W, Salvucci A and Limiti E 2017 Deterministic design of simultaneously matched two-stage low-noise amplifiers IEEE Asia Pacific Microwave Conference IEEE