A five-octave broadband LNA MMIC using bandwidth enhancement and noise reduction technique

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Abstract This letter presents the design and fabrication of a five-octave broadband low noise amplifier (LNA) using 0.1-μm GaAs pseudomorphic high-electron mobility transistor (pHEMT) technology. The multi-peaking bandwidth enhancement and noise reduction technique is proposed for a cascode topology to significantly improve the performance of the LNA. The fabricated LNA achieves a -3 dB bandwidth of 1-32 GHz with an average gain of 12.2 dB, an excellent noise figure (NF) of 1.9-2.6 dB, and an output-referred 1 dB compression point (OP1dB) of 10.2-12.7 dBm with good input/output matching over the entire bandwidth. To the best of the authors’ knowledge, these results demonstrate the lowest room-temperature NF ever reported for fully integrated MMIC amplifiers with a bandwidth of 1 to more than 30 GHz.

key words: ultra-wideband, low noise amplifier (LNA), cascode, GaAs, pseudomorphic high electron mobility transistor (pHEMT)

Classification: Integrated circuits (memory, logic, analog, RF, sensor)

1. Introduction

Advancements in wireless communication technology have prompted the demand for multi-octave broadband amplifiers for application in high data rate transmission, ultra-wideband (UWB) systems, high-resolution radars, and instrumentation where a broadband LNA is a crucial component [1-4]. For designing UWB amplifiers, Darlington configurations [5, 6, 7], feedback techniques [8-13], inductive-peaking techniques [14-17], and distributed amplifiers (DAs) [18-24] are the most popular approaches. Researchers in [5] reported broadband feedback Darlington amplifiers with bandwidth enhancement. A broadband gallium-nitride (GaN) LNA using a modified resistive-feedback topology is reported in [8]. A 0.1-20 GHz UWB LNA with the combined techniques of shunt-resistive feedback, dual inductive-peaking techniques and an improved active load is reported in [15]. The study in [18] reported a tapered, distributed LNA that can provide a lower broadband average NF compared to a uniform DA by optimal tapering of the gate and drain transmission lines and transistors. A fully integrated distributed amplifier using the GaAs HEMT–HBT cascode gain stage is explored in [19]. However, previously reported UWB amplifiers tend to have high NFs, therefore, they are not preferable in many applications as receivers. Furthermore, many reported UWB LNAs [5, 16, 17, 25] cannot realize full integration with the entire RF choke bias circuit or input/output blocking capacitors, which is inconvenient in practical applications.

In this letter, we report on a fully integrated UWB LNA with a low noise figure and flat gain over the full operation bandwidth of 1-32 GHz. We propose the multi-peaking bandwidth enhancement and noise reduction technique, which is used in input matching, inter-stage matching and the RF choke bias circuit of the LNA. The five-octave bandwidth LNA presented in this letter achieves the excellent NF, relatively high OP1dB and FOM, with comparable gain, power consumption and chip area. Meanwhile, the measured room-temperature NF is the lowest among fully integrated MMIC amplifiers ever reported with a bandwidth of 1 to more than 30 GHz.

2. Design and analysis of the UWB LNA

The LNA is implemented in the 0.1-μm AlGaAs/InGaAs pHEMT technology. The cascode topology was employed because it has wider gain bandwidth over the common-source configuration due its suppression of the Miller effect [26, 27]. Transistors M₁, M₂ have equal size of 8× 50 μm. The LNA was biased with a drain-to-source voltage (VDS) of 2 V and a gate-to-source voltage (VGS) of -0.42 V, since simulations demonstrate that the transistor exhibits the lowest minimum noise figure (NFmin) in the full operation band under this bias condition, and the NFmin is 0.7 dB at 16 GHz. The improved cascode configuration with the multi-peaking bandwidth enhancement and noise reduction technique, mainly including inductors LA, LX, LY, L₀ and L₁, is illustrated in Fig. 1. Fig. 2 shows the small-signal equivalent circuit of the proposed LNA. The inductor LA
is added in series with the total parasitic capacitance at node A, mainly including the drain-to-source parasitic capacitance of $M_1$ ($C_{gs1}$), as shown in Fig. 2. With careful selection of the inductor $L_A$, the high resonant frequency point with the capacitance at node A is introduced, thus expanding the gain bandwidth. The series inductor $L_A$ was realized using a micro-strip line with a width of 35 $\mu$m to reduce the NF because the parasitic resistance of the input matching circuit has a great influence on the NF of the total circuit. The noise introduced by $M_2$ at low frequencies of the operation band is much less. At high frequencies, the parasitic capacitance $C_X$ at node X can increase the noise considerably, where $C_X$ is the total parasitic capacitance and includes the parasitic capacitances of $M_1$ and $M_2$ at node X. Therefore, an 84 $\mu$H inductance $L_X$ is intentionally added between $M_1$ and $M_2$ to eliminate the effect of $C_X$ by resonating with it at the high operating frequency, as shown in Fig. 2. The NF of the cascode cell can be minimized accordingly [28]. Simulations show that the NF of the proposed LNA is reduced from 2.72 to 2.51 dB due to the impact of $L_X$ at 32 GHz. The effect of $L_X$ on the input is only a slight increase in the input impedance, since the inductance is small. Moreover, to meet the challenge of full integration with the broadband RF choke, the on-chip drain bias circuit ($Z_D$) including the series inductance network is employed, as shown in Fig. 1 enclosed by dash line. The large inductance $L_0$ introduces low and high resonant frequency points, while the moderate inductance $L_Y$ introduces a high resonant frequency point. The three optimized resonant frequency points help to achieve the desired RF choke performance in a wide band with the advantages of a lower NF and higher operation frequencies compared with the active load structure.

Furthermore, the inductor $L_4$ is used to compensate for the roll-off of the output impedance of the cascode topology, thus enhancing the gain in high operation frequency bands [15]. The resistors $R_d$ and $R$ are employed to decrease the quality factor of the bias circuit and enhance the circuit stability, as shown in Fig. 1. The design employs an R-L-C feedback loop to achieve a flat gain response in a wide band and improve the stability of the LNA, as shown in Fig. 2.

### 3. Measurement and discussions

The die photograph of the LNA is shown in Fig. 3. The chip area is 1.3 mm$\times$1.4 mm including pads. The LNA RF performance was measured with a KEYSIGHT
N5245A PNA-X at room temperature. The on-wafer measurement results are shown in Figs. 4–5. Fig. 4 shows the measured and simulated S-parameters including $S_{21}$, $S_{11}$, and $S_{22}$. The measured $S_{21}$ reaches a peak value of 13.1 dB at 16 GHz and an average value of 12.2 dB over the 1 to 32 GHz band (3 dB bandwidth). The measured $|S_{11}|$ is better than -8 dB between 1.5 and 32 GHz, and $|S_{22}|$ is better than -8 dB between 2 and 32 GHz. Fig. 5 shows the measured and simulated NF and $OP_{1dB}$. The measured NF is 1.9-2.6 dB throughout the band, and the average NF is 2.1 dB. The measured $OP_{1dB}$ is from 10.2-12.7 dBm over the entire bandwidth, as shown in Fig. 5. The LNA is unconditionally stable for all frequencies ($K > 1$). The above measurement results are obtained with a $V_{GS}$ of -0.42 V and a total drain voltage ($V_{DD}$) of 4.0 V. The whole chip draws 44 mA from the power supply, resulting in a power consumption of 176 mW. A comparison between this work and the previously reported III–V compound-based broadband amplifiers with various technologies is summarized in Table I. The five-octave bandwidth LNA presented in this letter exhibits the lowest room-temperature NF ever reported for fully integrated MMIC amplifiers over the 1-32 GHz band. Meanwhile, it achieves higher $OP_{1dB}$ and FOM with comparable small signal gain among the listed amplifiers in Table I.

Table I. Performance comparison.

| Ref | Bandwidth (GHz) | Gain (dB) | NF (dB) | $OP_{1dB}$ (dBm) | FOM |
|-----|-----------------|-----------|---------|-----------------|-----|
| [6] | dc-25.3 | 13.2 | 7.8 | -0.7 | - |
|     | 1.8-26 | 11 | 8.6 | -0.75 | - |
|     | dc-29.8 | 10 | 10.2 | 1.46 | - |
| [8] | 1-25 | 13 | 3.3-4.6 | 17.5 | 0.1 |
| [15] | 0.1-20 | 28.6 | 3.1-5.8 | 7.8-12.7 | 1.0 |
| [19] | dc-40.4 | 8.2 | 4.2-16.5* | 7 | 0.49 |
|     | dc-43.5 | 8.5 | 4.2-18.5* | 8 | 0.32 |
| [29] | 1-13 | 13.1-18.2 | >5.28 | -15* | 2.7 |
| [30] | 0.5-30 | 10.5 | 7.5* | >5 | 0.53 |
| This work | 1-32 | 12.2 | 1.9-2.6 | 10.2-12.7 | 1.3 |

*estimate value from figure; # average NF from 1 to 30 GHz; the figure-of-merit (FOM) is defined in [31].

6. Conclusion

A fully integrated LNA MMIC using a 0.1-μm GaAs pHEMT process has been successfully presented in this letter. The multi-peaking bandwidth enhancement and noise reduction technique is proposed and successfully used in a feedback cascode topology. The bandwidth and noise performance of the LNA are strongly improved. The 1–32 GHz LNA obtains a relatively flat gain of 12.2 dB, a noise figure of 1.9-2.6 dB, and a maximum $OP_{1dB}$ of 12.7 dBm with good input/output matching. The proposed UWB LNA can be further applied to modern high-speed data communications due to its superior performance.

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