

1–30 GHz ultra-wideband low noise amplifier with on-chip temperature-compensation circuit

Lin Yang¹, Lin-An Yang^{1a)}, Taotao Rong¹, Zhi Jin², and Yue Hao¹

¹ State Key Discipline Laboratory of Wide Band Gap Semiconductor Technology, School of Microelectronics, Xidian University, Xi'an, 710071, China

² Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China
a) layang@xidian.edu.cn

Abstract: A 1–30 GHz ultra-wideband low noise amplifier (LNA) MMIC with a simplified on-chip temperature-compensation circuit is presented in this paper. The temperature-compensation circuit composed of two GaAs mesa resistors and two Nickel Chromium (Ni/Cr) thin-film resistors is able to compensate the variation of temperature accurately over a wide operating frequency range. The fabricated LNA has demonstrated the improvement of gain variation from 3.4 to 0.8 dB (0.4 dB/Stage) in the temperature range from -55°C to $+125^{\circ}\text{C}$. It exhibits the lowest the gain variation (0.0022 dB/ $^{\circ}\text{C}$ /Stage) with temperature ever reported for the ultra-wideband LNA. By contrasting the LNA with and without the temperature-compensation circuit, it is also found that the use of the temperature-compensation circuit neither degrades other aspects of the circuit performance nor increases the area of the original amplifier chip.

Keywords: LNA, temperature compensation, ultra-wideband, pHEMT

Classification: Integrated circuits

References

- [1] G. Nikandish, *et al.*: “A broadband multistage LNA with bandwidth and linearity enhancement,” *IEEE Microw. Wireless Compon. Lett.* **26** (2016) 834 (DOI: 10.1109/LMWC.2016.2605446).
- [2] W. Chen, *et al.*: “4–20 GHz low noise amplifier MMIC with on-chip switchable gate biasing circuit,” *IEICE Electron. Express* **14** (2017) 20170711 (DOI: 10.1587/elex.14.20170711).
- [3] X. Ding and L. Zhang: “A high-efficiency GaAs MMIC power amplifier for multi-standard system,” *IEEE Microw. Wireless Compon. Lett.* **26** (2016) 55 (DOI: 10.1109/LMWC.2015.2505615).
- [4] M. A. Alim and A. A. Rezazadeh: “Temperature-dependent DC and small-signal analysis of AlGaAs/InGaAs pHEMT for high-frequency applications,” *IEEE Trans. Electron Devices* **63** (2016) 1005 (DOI: 10.1109/TED.2016.2517934).
- [5] C. W. Huang, *et al.*: “A Ku-band four-stage temperature compensated PHEMT MMIC power amplifier,” *Microw. Opt. Technol. Lett.* **44** (2005) 480 (DOI: 10.1002/mop.20673).

- [6] B.-J. Huang, *et al.*: “Millimeter-wave low power and miniature CMOS multicascade low-noise amplifiers with noise reduction topology,” *IEEE Trans. Microw. Theory Techn.* **57** (2009) 3049 (DOI: 10.1109/TMTT.2009.2033238).
- [7] S. M. Sze: *Physics of Semiconductor Devices* (Wiley, New York, 1981) 2nd ed. 55.
- [8] Analog Device, Inc.: HMC903 datasheet (2017) <http://www.analog.com>.
- [9] MACOM: MAAL-011130 datasheet (2017) <https://www.macom.com/>.
- [10] K. Yamanaka, *et al.*: “Ku-band low noise MMIC amplifier with bias circuit for compensation of temperature dependence and process variation,” *IEEE MTT-S Int. Microw. Symp. Dig.* **3** (2002) 1427 (DOI: 10.1109/MWSYM.2002.1012123).

1 Introduction

The advancement in wireless communication technology has urged the demand of multi-octave broadband amplifiers for application in high-speed transceivers, ultra-wideband (UWB) systems, high-resolution radars, and instrumentations, where the broadband LNA is an essential component in the receiver systems [1]. GaAs pHEMT has been found wide applications in most commercial microwave/millimeter-wave transceiver systems, due to both low noise figure and high gain performance [2, 3]. However, there exists a temperature dependence of the gain resulting from variations in field-effect-transistor (FET) parameters such as the transconductance [4], which leads to a severe limit for application of FET-based circuits. Therefore, it is of great significance to reduce the temperature sensitivity of UWB LNAs based on FETs. In order to compensate the gain of the amplifier with temperature, some design methods have been reported to control the gate voltage of the FET, including the series or the feedback resistors or FETs to make up temperature-compensation circuits [2, 5]. However, the lack of accurate calculation in these methods cannot achieve optimal gain compensation with temperature, and the temperature-compensation circuits usually occupy a large area of the chip. To circumvent these problems, in this letter, we present a simplified on-chip temperature-compensation circuit, which consists of only two GaAs mesa resistors and two Ni/Cr thin-film resistors. It aims to control the gate voltage in order to keep the gain constant with temperature. The gain of the amplifier is accurately compensated at three temperature points -55°C , 25°C , and 125°C by precisely calculating the resistivity of resistors. The fabricated UWB LNAs demonstrate that the gain variation has a great improvement from 3.4 dB to 0.8 dB in the temperature range from -55°C to 125°C . To the best of our knowledge, it is the lowest the gain variation (0.0022 dB/ $^{\circ}\text{C}/\text{Stage}$) for UWB LNAs with temperature ever reported. Moreover, the present temperature-compensation circuit neither degrades other aspects of the circuit performance nor increases the area of the original amplifier chip comparing with UWB LNAs without the temperature-compensation circuit.

2 The UWB LNA design and temperature characteristics

Most of DC and small signal parameters show a negative trend with temperature, such as drain–source output current I_{ds} , extrinsic transconductance g_{m} , effective

electron velocity v_{eff} , threshold voltage V_T [4], resulting in a negative temperature-dependence of the gain of amplifier. A 1–30 GHz ultra-wideband LNA using 0.1- μm GaAs pHEMT technology was firstly designed and fabricated, where it required for the MMIC LNA to achieve high gain and low noise figure in broadband simultaneously. To provide flat high gain in a broad frequency band, we designed a cascode configuration with reasonable matching circuit to improve the bandwidth of LNA, in particular, an inductor was designed between the common-gate and the common-source transistors to minimize the noise figure of the cascode cell [6]. The gate width of the transistor was chosen to achieve low noise performance. Under the bias of $V_{\text{DS}} = 4\text{ V}$ and $V_{\text{GS}} = -0.27\text{ V}$, the circuit provides a nominal gain of 13.2 dB while the NF is 1.9–3.1 dB, the output-referred 1 dB compression point (Output P1dB) is 14 dBm across the frequency range 1–30 GHz. Fig. 1 shows measurements of the gain as a function of the gate voltage at the three temperature points $-55\text{ }^\circ\text{C}$, $25\text{ }^\circ\text{C}$, and $125\text{ }^\circ\text{C}$, respectively, and the LNA operates at 25 GHz.

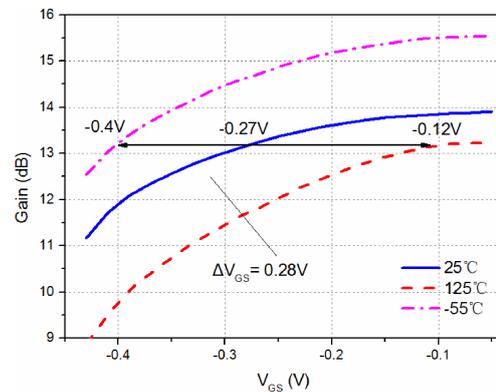


Fig. 1. Measured gain characteristics of the UWB LNA at 25 GHz ($V_{\text{DS}} = 4\text{ V}$).

It can be seen that the gain can be kept constant in the wide range of temperature by adjusting the gate voltage of each transistor of the amplifier. In our circuit, the constant gain of 13.2 dB can be achieved in the temperature range between $-55\text{ }^\circ\text{C}$ and $125\text{ }^\circ\text{C}$ by adjusting the gate voltage from -0.40 V to -0.12 V , as shown in Fig. 1.

3 Temperature-compensation circuit

Aforementioned analysis shows that the gain variation against temperature of the amplifier can be compensated by increasing the gate voltage of each stage with an increase of temperature. It is known that the resistivity of a GaAs mesa resistors increases monotonously with the increasing temperature from $-55\text{ }^\circ\text{C}$ to $125\text{ }^\circ\text{C}$ [7], because of the negatively temperature-dependent mobility which is related to the lattice scattering. Table I shows the temperature dependence of the GaAs mesa resistor. In contrast, the resistivity of Ni/Cr thin-film resistors is almost independent of temperature. Therefore, GaAs mesa resistors can be used together with Ni/Cr resistors in the gate bias circuit to keep the gain constant with temperature.

The fabrication procedure of Ni/Cr resistors involves Ni/Cr film deposition on silicon nitride (SiN_x) coated GaAs wafers. The resistors are defined by photolithography and selective etching. The proposed temperature-compensation configuration is shown in Fig. 2.

Table I. The resistivity of GaAs mesa resistors at different temperature

Temperature (°C)	-55	-25	0	25	50	75	100	125
Resistivity (Ω)	79	85	92	100	119	126	133	143

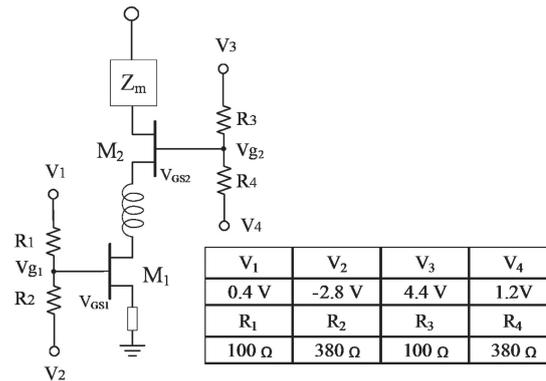


Fig. 2. The topology of proposed temperature-compensation circuit.

The required variation of gate voltage ΔV_{GS} is 0.28 V ($V_{DS} = 4$ V) in the temperature range between -55 °C and 125 °C, as shown in Fig. 1. The resistors R_1 and R_3 are Ni/Cr resistors, R_2 and R_4 are GaAs mesa resistors. The values of voltage and resistors are given in the inset of Fig. 2. According to the principle of resistive divider, $V_{g1} = -0.27$ V and $V_{g2} = 3.73$ V at 25 °C, so both V_{GS1} and V_{GS2} are set to be -0.27 V. When the temperature decreases to -55 °C, V_{g1} and V_{g2} decrease to about -0.4 V and 3.6 V, respectively, because R_2 and R_4 decrease to 289 Ω, thus, V_{GS1} and V_{GS2} decrease to about -0.4 V. At the high temperature of 125 °C, V_{g1} and V_{g2} increase to -0.12 V and 3.88 V, respectively, because R_2 and R_4 increases to 521 Ω, as a result, V_{GS1} and V_{GS2} increase to -0.12 V. Thus, the gain variation of the amplifier can be minimized when V_{GS} is set along the contour line of equal gain with temperature. Due to the large resistor between the temperature-compensation network and the gate of each transistor, the temperature-compensation network will not degrade other aspects of the amplifier performance, such as the S-parameter, the noise figure, etc.

4 Fabrication and experimental results

The LNA is implemented in the 0.1 - μ m AlGaAs/InGaAs pHEMT technology with the substrate thickness of 70 μ m. Fig. 3 shows the die photograph with a chip area of 1.6 mm \times 1.6 mm including pads. The temperature-compensation circuit is integrated on the GaAs chip of the amplifier. The chip is biased with $V_{DS} = 4$ V and the total drain current is $I_{ds} = 80$ mA at 25 °C. Fig. 4 shows the measured small signal gains of the UWB-LNAs with and without the on-chip temperature-compensation circuit with temperature varies from -55 °C to 125 °C.

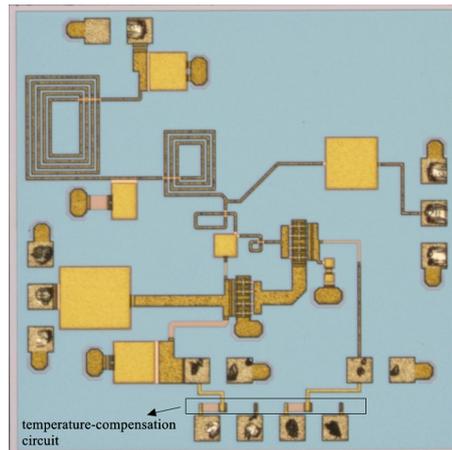


Fig. 3. Die photograph of the UWB LNA with the temperature-compensation circuit.

For the UWB LNA without the temperature-compensation circuit, the gain variation increases with the operating frequency, as shown in Fig. 4(a). It is significantly improved by using the on-chip temperature-compensation circuit, as shown in Fig. 4(b). Estimation gives that the gain variation is improved from 3.4 dB to 0.8 dB in the temperature range from -55°C to 125°C by using the on-chip temperature-compensation circuit for the MMIC amplifier. However, the average small-signal gain of 13.2 dB and 13.4 dB, respectively, can be still achieved (25°C) for the amplifier with and without the on-chip temperature-compensation circuit. It illustrates the less influence of the compensation circuit on LNAs.

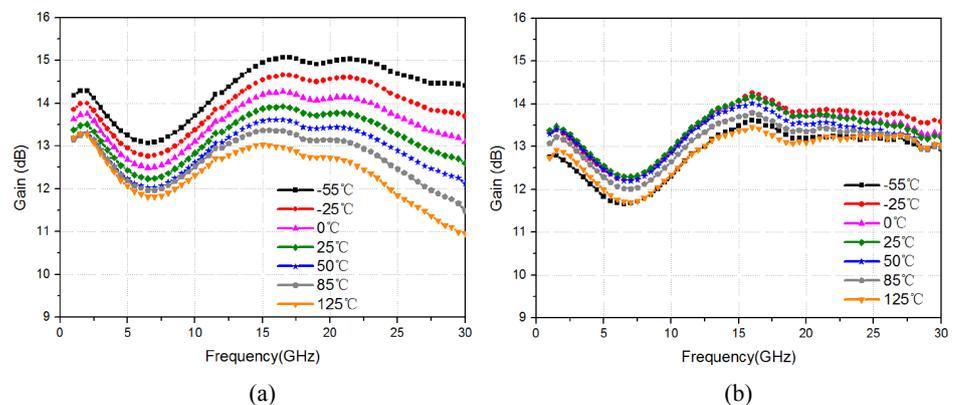


Fig. 4. Temperature dependencies of gains for (a) without and (b) with the temperature-compensation circuit.

Fig. 5(a) shows the measured the input and output reflection coefficients S_{11} , S_{22} of the UWB-LNAs with and without the on-chip temperature-compensation circuit at 25°C . For both amplifiers, the measured $|S_{11}|$ is better than -7 dB in the frequency range of 1–30 GHz, and $|S_{22}|$ is better than -7 dB in the frequency range of 2.5–30 GHz. Fig. 5(b) shows the measured NF and the Output P1dB of the amplifier with and without the on-chip temperature-compensation circuit at 25°C . Both of them achieve NF of around 1.9–3.1 dB and Output P1dB of about 14 dBm, respectively. These results indicate that the temperature-compensation circuit seldom has an influence on S-parameters, NF and Output P1dB of UWB-LNAs.

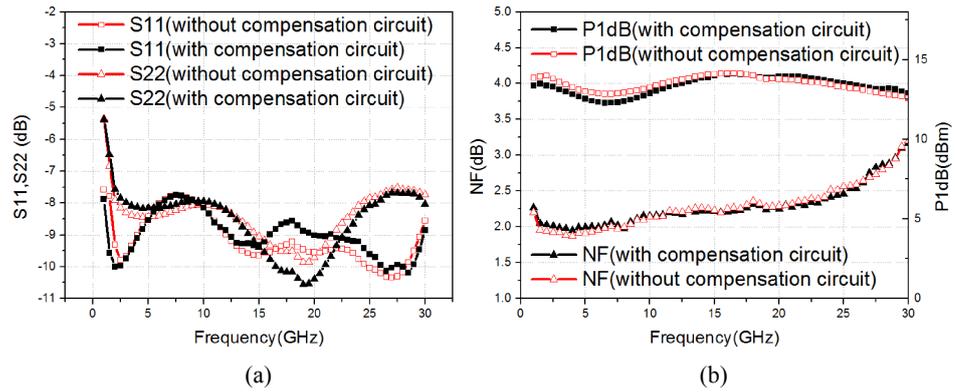


Fig. 5. Measurement of (a): S_{11} and S_{22} (b): Output P1dB and NF for with and without the temperature-compensation circuit at 25°C.

Table II gives the comparison of the performance between our work and the state-of-the-art wideband GaAs pHEMT LNAs. To the best of our knowledge, our work has the widest bandwidth for the LNA with the proposed temperature-compensation circuit yielding the lowest gain variation at the temperature ranging from -55°C to 125°C , while it still features excellent RF performance.

Table II. Performance comparison

Ref.	Freq. (GHz)	Gain (dB)	NF (dB)	ΔGain (dB/ $^{\circ}\text{C}$)	ΔGain (dB/ $^{\circ}\text{C}/\text{stage}$)	Operate Temp. ($^{\circ}\text{C}$)
[2]	4–20	24	1.6	0.014	0.0046	$-55\sim 125$
[8]	6–18	19	1.6	0.013	0.0065	$-55\sim 85$
[9]	2–18	20	2.9	0.020	-	$-40\sim 85$
[10]	8–16	16	2.5	0.01	0.005	$-25\sim 75$
This work	1–30	13.4	<3.1	0.0044	0.0022	$-55\sim 125$

For the 0.1- μm GaAs pHEMT technology we used, the variation of GaAs mesa resistors value is $\pm 6\%$ and the variation of Ni/Cr thin-film resistors is $\pm 2\%$. Regarding the effects of resistance variation on the LNA, the following analysis is based on the worst case. In other words, the variations of Ni/Cr thin-film resistors and GaAs mesa resistors are assumed to be -2% and $+6\%$ (or $+2\%$ and -6%), respectively. Therefore, the gate voltage V_{g1} , V_{g2} reaches the maximum variation. According to the principle of resistive divider, the variation of both V_{g1} and V_{g2} is about ± 0.04 V. Through the measured gain characteristics of the LNA without the temperature-compensation circuit at different temperature points, we can calculate the maximum gain variations with temperature, as shown in Fig. 6. It is confirmed that the gain variation is about 0.006 dB/ $^{\circ}\text{C}$ in the temperature range from -55°C to 125°C at the maximum resistance variation. Furthermore, the maximum gain variation due to gate voltage variation is about ± 0.3 dB. Therefore, the effect of resistance variations on the gain of the LNA is relatively small.

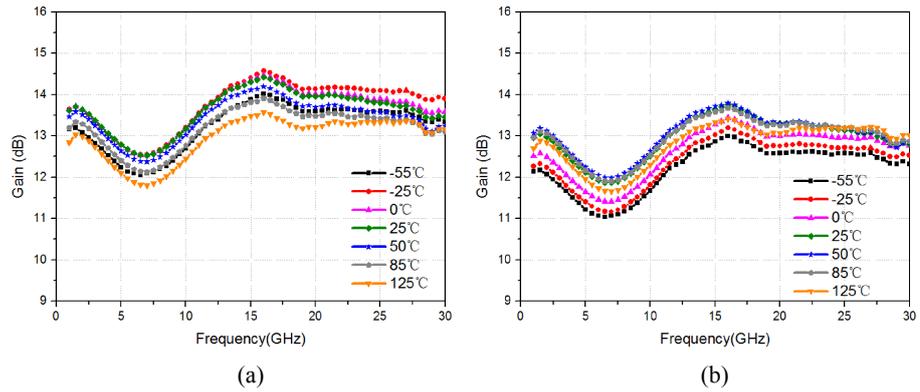


Fig. 6. The calculated gain variations with temperature for (a) the variation of Ni/Cr thin-film resistors is assumed to be -2% and the variation of GaAs mesa resistors is assumed to be $+6\%$ (b) the variation of Ni/Cr thin-film resistors is assumed to be $+2\%$ and the variation of GaAs mesa resistors is assumed to be -6% .

5 Conclusion

In this paper, a 1–30 GHz ultra-wideband LNA MMIC with a simplified on-chip temperature-compensation circuit composed of a few GaAs mesa resistors and Ni/Cr thin-film resistors has been presented. It was found that the gain variation can be significantly reduced in the temperature range between -55°C and 125°C from 3.4 dB to 0.8 dB by using the temperature-compensated circuit. To the best of our knowledge, it is the lowest the gain variation ($0.0022\text{ dB}/^{\circ}\text{C}/\text{Stage}$) for UWB LNAs with temperature ever reported. It was also found that the present temperature-compensation circuit neither degrades other aspects of the circuit performance nor increases the area of the original amplifier chip. The proposed temperature-compensated UWB-LNA can be further applied to the modern high-speed data communications in a wide temperature range.

Acknowledgments

This work was supported by the key Program of National Natural Science Foundation of China under Grant 61434006 and the National Natural Science Foundation of China under Grant 61674117.