Cryogenically Cooled Performance of a Monolithic 44-GHz InP-Based HEMT Low-Noise Amplifier

Huei Wang, *Member, IEEE*, Dennis Chung-Wen Lo, Richard Lai, *Member, IEEE*, Cheng-Chih Yang, *Member, IEEE*, and John Berenz

***Abstract*—A monolithic 44-GHz low-noise amplifier using 0.1-μm pseudomorphic InAlAs/InGaAs/InP HEMT technology and its cryogenically cooled performance are reported. This single-stage MMIC amplifier has a measured noise figure of 2.5 dB with an associated gain of 8 dB at 44.5 GHz with 5-mW dc power consumption at room temperature. The noise temperature of this MMIC LNA decreases to 29 K (0.4-dB noise figure) and the associated gain increases to 10.3 dB when it is cooled down to 80 K under the same bias condition, which correspond to an average noise temperature reduction slope of 0.9 and a gain increase slope of 0.01 dB/°K. To our knowledge, this is the first reported cryogenically cooled noise performance of a monolithic amplifier at this frequency.**

I. Introduction

Ultra-low-noise front-end amplifiers are essential for the receivers in high sensitivity sensors and high-capacity communication systems. The InP-based high electron mobility transistors (HEMT's) have shown not only the lowest noise figures and highest gains among three-terminal devices operating at millimeter-wave frequencies [1]–[4], but also the on-current-collapse phenomenon as observed in GaAs-based HEMT's [5], [6]. In addition, InP-based HEMT MMIC technology has been successfully demonstrated via many MMIC chips at MMW frequencies from 35–140 GHz [7]–[13], which indicates the potential of low cost and high volume for these components.

In this letter, we report a monolithic single-stage 44-GHz low noise amplifier (LNA) using 0.1-μm pseudomorphic InAlAs/InGaAs/InP HEMT technology and its cryogenically cooled noise figure performance. This MMIC amplifier has a measured noise figure of 2.5 dB with an associated gain of 8 dB at 44.5 GHz under room temperature, with 5-mW dc power consumption. The noise temperature of this MMIC LNA decreases to 28 K (0.4-dB noise figure) and gain increases to 10.2 dB when it cooled down to 80 K under the same bias condition. To our knowledge, this is the first reported cryogenic-cooled noise performance of a monolithic amplifier at this frequency.

II. MMIC Fabrication and Design

Fig. 1 shows the chip photograph of this monolithic 44-GHz single-stage LNA. The chip size is 1.5×1.4 mm^2.

Manuscript received February 7, 1995.

The authors are with TRW Electronic Systems and Technology Division, Redondo Beach, CA 90278 USA.

IEEE Log Number 9413484.

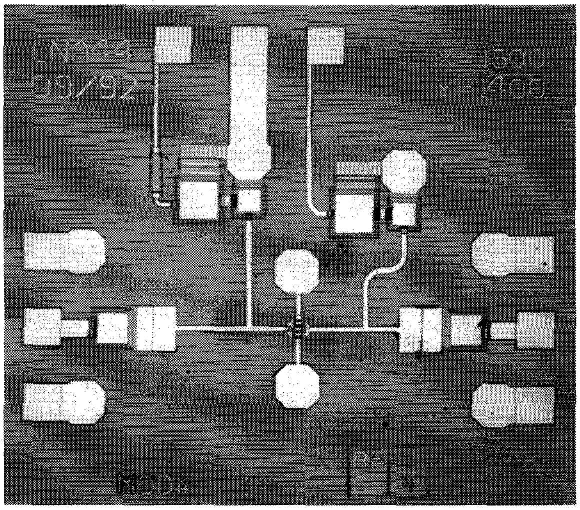
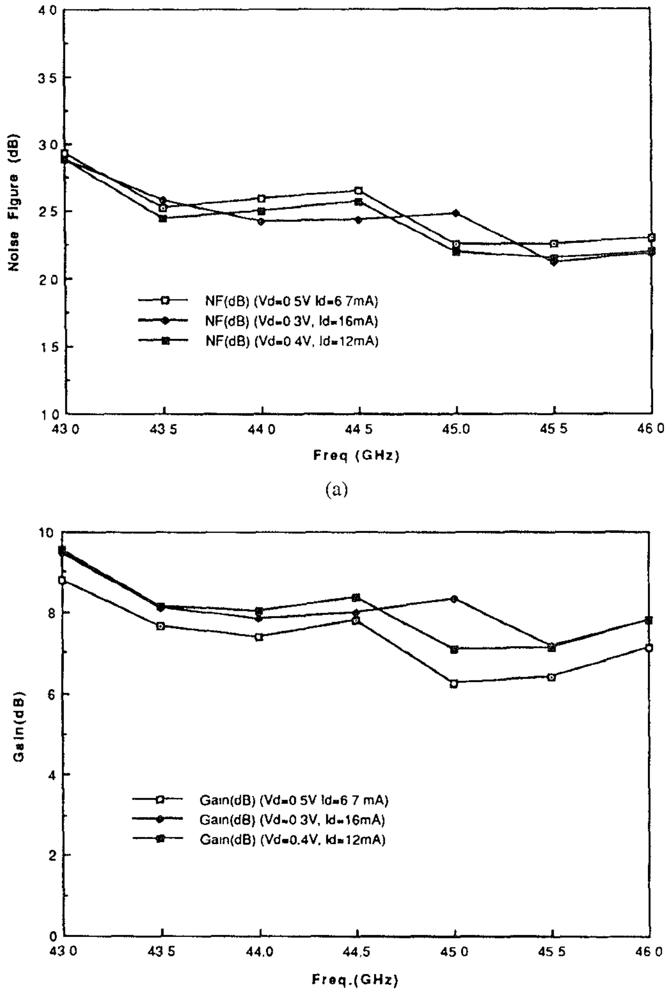


Fig. 1. Photograph of the monolithic 44-GHz single-stage InP-based HEMT low-noise amplifier.

The LNA utilizes a four-finger HEMT with 80 μm total gate periphery. The HEMT linear small signal equivalent circuit parameters are obtained from careful fit of the measured small signal S-parameters to 40 GHz under room temperature. The noise model parameters are obtained from fitting measured noise parameters to 26 GHz. The equivalent circuit model has been reported elsewhere [7], which provides a maximum available gain of 13 dB and a minimum noise figure of 1.2 dB at 44 GHz. The matching networks of the LNA are constructed by cascading high-low impedance microstrip lines on 70-μm-thick semi-insulating InP substrate. Metal-insulator-metal (MIM) capacitors are used for dc blocking RF bypass in matching and bias networks, while thin-film NiCr resistors are used in the bias networks for stability purpose. A wet chemical etching process is used to fabricate back side via holes through the InP substrated for grounding.

The MMIC chip is fabricated on a 2″ Fe-doped InP substrate grown by molecular beam epitaxy and employed 0.1-μm T-gate PM HEMT devices. The InAlAs/InGaAs/InP HEMT ($In_{0.6}Ga_{0.4}As$ channel) structure is same as the one reported in [2]. The In PHEMT MMIC fabrication process was adopted from the baseline MMIC fabrication process used for GaAs-based HEMT MMIC's [14]. The differences in the fabrication process steps include the device isolation process, the ohmic metallization, alloying conditions and the through substrate via hole etch.



(b)

Fig 2 The measured (a) noise figure and (b) associated gain of themonolithic 44-GHz low-noise amplifier tested in the specially designed test fixture from 43–46 GHz for three different bias conditions.

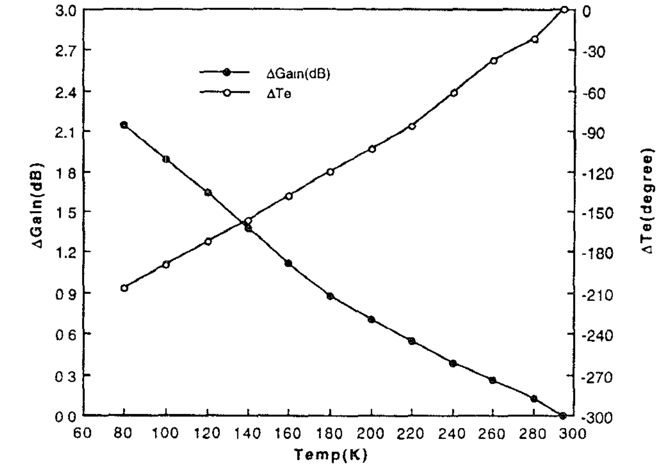


Fig. 3. The difference of noise temperature (ΔT_e in degree) and associated gain (ΔG in dB) from room temperature results as functions of testing temperature (K) at 44.5 GHz

III. Measured Circuit Performance

The monolithic LNA was first measured via on-wafer probing for noise figure and associated gain at room temperature for circuit functionality and selection purpose. A noise figure of 2.3 dB with an associated gain of 10 dB at 44 GHz was obtained 1-V drain bias with 10-mA drain current. The S-parameter of the LNA has also been tested via on-wafer probing, showing a consistent gain ($|S_{21}|$ in dB) performance. However, in the circuit simulation, a calculated noise figure of 1.8 dB was obtained, indicating half dB lower than the measured data.

For the measurement of cryogenically cooled performance, the MMIC LNA is diced and mounted in a Q-band test-fixture, which has a transition loss of between 0.8 and 1 dB and return loss of better than 15 dB from 43 to 46 GHz. The dc bias wire is bonded to the designated bias pads on the MMIC through a shunt chip capacitor of 0.1 μF for amplifier stability under cryogenically cooled temperature condition.

The LNA mounted in the fixture is first measured at room temperatureunder very low bias conditions (less than 5-mW dc power consumption, i.e., $V_d = 0.5$ V, $I_d = 6.7$ mA; $V_d = 0.3$ V, $I_d = 16$ mA; $V_d = 0.4$ V, $I_d = 12$ mA). The noise temperature and associated gain from 43–46 GHz are plotted in Fig. 2(a) and (b). It shows a measured noise figure of 2.5 dB with an associated gain of 8 dB at 44.5 GHz at the bias conditions of $V_d = 0.3$ V, $I_d = 16$ mA. All of the results stated here have been corrected for the transition losses.

The LNA is then cryogenically cooled down to 80 K. The noise temperature and associated gain under $V_d = 0.3$ V, $I_d = 16$ mA at 44.5 GHz are measured with 20-K step from room temperature (300 K) to 80 K. The difference of noise temperature (ΔT_e in degree) and associated gain (ΔG in dB) from room temperature results as functions of testing temperature (in degree K) are plotted in Fig. 3. The noise temperature of this MMIC LNA decreases to 29 K (0.4-dB noise figure) and gain increases to 10.3 dB when it is cooled down to 80 K under the same bias condition, which correspond to an average noise temperature reduction slope of 0.9 and a gain increase slope of 0.01 dB/i°K. The cryogenically cooled data of the LNA are similar for the other two bias conditions. It is noted that this MMIC LNA was designed for low noise at room temperature. The cooled noise performance is expected to be better if designed with adequate HEMT noise model at low temperature, as those MIC reported in [4]. The LNA measured results were repeatable after a few temperature cycles, showing that the MMIC was not damaged during the cryogenic operation. This is similar to the MMIC demonstrated in [15].

IV. Summary

We have demonstrated a monolithic single-stage 44-GHz low noise amplifier using 0.1-μm pseudomorphic InAlAs/InGaAs/InP HEMT technology and its cryogenic-cooled noise figure performance. This MMIC amplifier shows 2.2-dB increase in gain and 205° reduction in noise temperature when it is cooled down to 80 K with less than 5-mW dc power consumption, which correspond to an average noise temperature reduction slope of 0.9 and a gain increase slope of 0.01 dB/°K. This is the first reported cryogenically cooled noise performance of the monolithic amplifiers at this frequency.

ACKNOWLEDGMENT

The authors would like to thank S. Chen, S. Kam, D. C. Yang, E. Barnachea, G. S. Dow, K. L. Tan, R. Dia, L. Go, D. Streit, J. Velebir, P. H. Liu, and the members of RF Product Center of TRW for their support and help to this work.

REFERENCES

[1] K. H. G. Duh *et al.,* "A super low-noise 0.1 μm T-gate InAlAs-InGaAs-InP HEMT," *IEEE Microwave and Guided Wave Lett.,* vol. 1, no. 5, pp. 114–116, May 1991.

[2] K. L. Tan *et al.,* "140 GHz 0.1 μm gate-length pseudomorphic $In_{0.52}Al_{0.48}As/In_{0.60}Ga_{0.40}As$/InP HEMT," in *IEEE Int. Electronic Device Meet. Dig.,* Washington DC, Dec. 1991, pp. 239–242.

[3] R. Lai *et al.,* "An ultra low noise cryogenic Ka-band InGaAs/InAlAs/InP HEMT front-end receiver," *IEEE Microwave and Guided Wave Lett.,* vol. 4, no. 10, pp. 329–331, Oct. 1994.

[4] M. W. Pospieszalski *et al.,* "Millimeter-wave cryogenically-coolable amplifiers using AlInAs/GaInAs/InP HEMT's," in *1993 IEEE MTT-S Int. Microwave Symp. Dig.* Atlanta GA, June 1993, vol. 2, pp. 515–518.

[5] R. Lai, B. Allen, C. C. Yang, L. Shaw, D. Brunone, K. L. Tan, D. C. Streit, and P. H. Liu, "Cryogenic noise performance of InGaAs/InAlAs/InP HEMT's," in *Proc. Fourth Int. Conf. Indium Phosphide and Related Materials (IPRM),* Newport, RI, Apr. 1992, pp. 507–510.

[6] R. Lai *et al.,* "Characteristics of 0.8 and 0.2 μm gate length AlInAs/GaInAs/InP ($0.53 \leq x \leq 0.7$) modulated doped field effect transistors at cryogenic temperatures," *IEEE Trans. Electron Dev.,* vol. 39, p. 2206, 1992.

[7] D. C. W. Lo, H. Wang, B. R. Allen, G. S. Dow, K. W. Chang, M. Biedenbender, and R. Lai, "Novel monolithic multi-functional balanced switching low noise amplifiers," *IEEE Trans. Microwave Theory Tech.,* vol. 42, no. 12, Dec. 1994.

[8] D. C. W. Lo, R. Lai, H. Wang, K. L. Tan, R. Dia, D. Streit, P. Liu, J. Velebir, B. Allen, and J. Berenz, "A high performance monolithic Q-band InP-based HEMT low noise amplifier," *IEEE Microwave and Guided Wave Lett.,* vol. 3, no. 9, pp. 299–301, Sept. 1993.

[9] K. W. Chang, H. Wang, R. Lai, D. C. W. Lo, and J. Berenz, "A V-band monolithic InP HEMT downconverter," in *15th Annual IEEE GaAs IC Symp. Dig.,* San Jose, CA, Oct. 1993, pp. 211–214.

[10] H. Wang, T. N. Ton, R. Lai, D. C. W. Lo, S. Chen, D. Streit, G. S. Dow, K. L. Tan, and J. Berenz, "Low noise and high Gain 94 GHz monolithic InP-based HEMT amplifiers," in *IEEE Int. Electronic Device Meet. Tech. Dig.,* Washington DC, Dec. 1993, pp. 239–242.

[11] H. Wang, R. Lai, S. Chen, and J. Berenz, "A monolithic 75–110 GHz balanced InP-based HEMT amplifier," *IEEE Microwave and Guided Wave Lett.,* vol. 3, no. 10, pp. 381–383, Oct. 1993.

[12] R. Lai, H. Wang, K. L. Tan, G. I. Ng, D. C. Streit, P. H. Liu, J. Velebir Jr., S. Chen, J. Berenz, and M. W. Pospieszalski, "A monolithically integrated 120 GHz InGaAs/InAlAs/InP HEMT amplifier," *IEEE Microwave and Guided Wave Lett.,* vol. 4, no. 6, pp. 194–195, June 1994.

[13] H. Wang, R. Lai, D. C. W. Lo, D. C. Streit, M. W. Pospieszalski, and J. Berenz, "A 140-GHz monolithic low noise amplifier," in *IEEE Int Electronic Device Meet. Tech. Dig.,* San Francisco, Dec. 1994.

[14] K. L. Tan, P. H. Liu, D. C. Streit, R. Dia, A. C. Han, A. Freudenthal, J. Velebir, K. Stolt, J. Lee, M. Biedenbender, R. Lai, H. Wang, and B. Allen, "A high performance 0.1 μm pseudomorphic AlGaAs/InGaAs HEMT process for W-band MMIC's," in *14th Annual IEEE GaAs IC Symp. Dig.,* Miami, FL, Oct. 1992, pp. 251–254.

[15] C. C. Yang, B. L. Nelson, B. R. Allen, W. L . Jones, and J. B. Horton, "Cryogenic characteristics of wide-band pseudomorphic HEMT MMIC low-noise amplifiers," *IEEE Trans. Microwave Theory Tech.,* vol. 41, nos. 6 and 7, pp. 992–997, June/July 1993.