35nm InP HEMT LNAs at E/W-Band Frequencies

Nicholas Estella, Lani Bui, Edmar Camargo, and James Schellenberg

QuinStar Technology, Inc., Torrance, CA 90505, USA

Abstract — This paper presents the design and performance of two millimeter-wave LNAs using 35nm InP HEMT device technology. First, a single-ended 3-stage LNA, operating over the 81-86 GHz band, is reported with a noise figure (NF) of 1.6-1.9 dB and a gain of 28 ±1 dB. This is the lowest reported noise figure for LNAs at this frequency. Secondly, a balanced LNA, operating over the 56-110 GHz band, is reported with a NF of typically 2.7 dB and a gain of greater than 20 dB. This amplifier represents an unprecedented combination of low noise, good input/output match, and broad bandwidth.

Index Terms — InP HEMT, low noise amplifier (LNA), noise figure (NF), millimeter wave, MMICs.

I. INTRODUCTION

Recent advances in sub-0.1 µm gate InP HEMT and mHEMT device technology have enabled the development of MMIC amplifiers operating at frequencies beyond 500 GHz [1-2]. This same device technology, when applied to lower millimeter-wave frequencies such as E-band (60-90 GHz) and W-band (75-110 GHz), is capable of producing LNAs with sub-2 dB noise figures [9]. Applications for these LNAs include radar and imaging, radio astronomy and remote sensing, satellite communications (SATCOM), and high data rate point-to-point communications.

Using this new device technology, this paper presents LNAs operating at E/W-band frequencies that establish new noise and bandwidth benchmarks. Specifically, we present (1) a single-ended, low-noise MMIC amplifier operating over the 81-86 GHz band and (2) a broadband balanced LNA covering the octave 55-110 GHz band.

II. MMIC TECHNOLOGY AND LNA DESIGN

The MMICs reported in this paper use Northrop Grumman's 35-nm InP HEMT process, with device f_T and f_{max} numbers of 480 GHz and 1.2 THz, respectively [3]. The process includes 600 pF/mm^2 metal-insulator-metal (MIM) capacitors, 20 and 100-ohm/sq. thin-film resistors (TFRs), two interconnect layers with an airbridge option, thru-substrate vias, and device passivation. The substrate thickness is 50 µm.

The singled-ended LNA, shown in Fig. 1, uses three gain stages. The 30 µm (2 x 15 µm) gate-width devices are biased at Vds = 1 V and a drain current of 300mA/mm or 9 mA. A common-source device configuration in a microstrip medium is used. The input is matched for lowest noise with a series high impedance line and shunt short circuit stub. Source inductance was added to the first two stages in an effort to

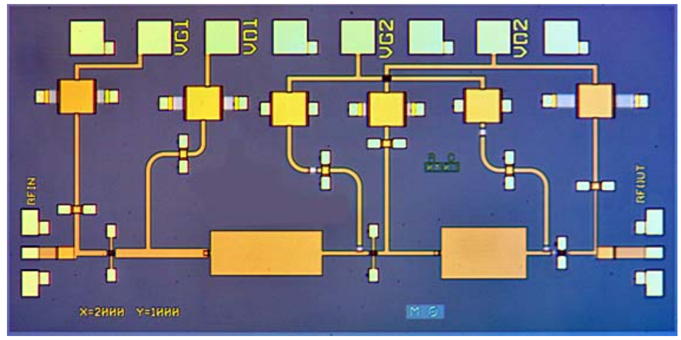

Fig. 1. 3-stage, single-ended LNA. Chip size: 2.0mm x 1.0mm.

achieve simultaneous noise and gain match and to improve the amplifier stability. A cascade connection of high and low impedance transmission lines are used for the interstage matching. The second and third stages are designed for gain flatness and good output return loss. Resistor-capacitor networks in the bias lines are used to ensure low-frequency and out-of-band stability. AWR's Axiem was used for electromagnetic (EM) simulation of the matching networks. The gate and drain pads of the second and third stages are connected together on the chip, while the first stage is biased independently to allow for noise optimization.

The balanced amplifier configuration is shown in Fig. 2. It also uses a 3-stage common-source topology, with 2 x 15 µm devices in the first and second stages and a 4 x 15 µm device in the third (output) stage. It was designed to cover the octave 55-110 GHz band. The balanced configuration produces good

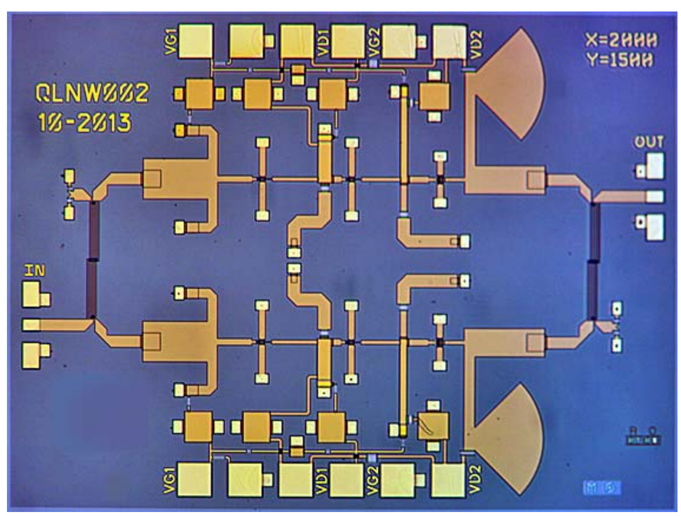

Fig. 2. Balanced LNA. Chip size: 2.0mm x 1.5mm.

input/output match and broad bandwidth at the cost of a slightly (~1 dB) higher NF. This increase in NF is due to losses in the Lange coupler and coupler imbalance, which allows some noise power from the coupler termination to reach the output port.

III. Measurements

A. On-Wafer Measurements

The MMICs were measured on-wafer using an Agilent 8510XF VNA. The results for the single-ended and balanced LNAs are shown in Figs. 3 and 4, respectively. For the single-ended LNA, the small-signal gain is 31.9 ± 1.1 dB over the 81-86 GHz band. The input return loss is in the range of 4.6-16.4 dB and the output return loss is better than 10 dB. The balanced LNA exhibits a broadband gain response with 20 dB minimum gain from 56-110 GHz and a small-signal gain of 29 ±0.4 dB in the 81-86 GHz band. The input and output return losses are nominally 18 dB from 50 to 110 GHz.

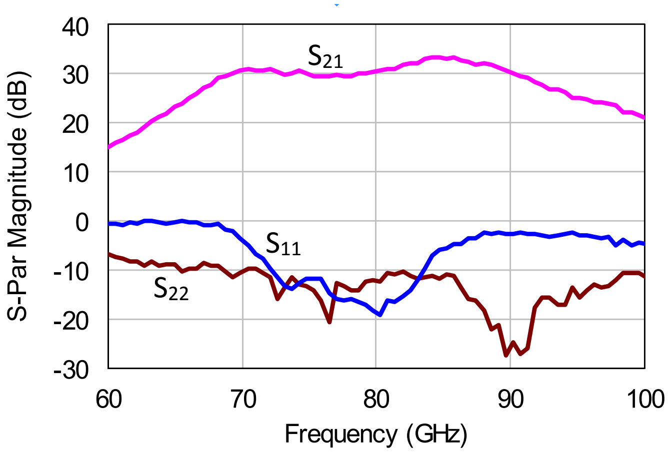

Fig. 3. On-wafer S-parameters of the single-ended 3-stage LNA at Vds = 1V, Ids = 27mA (300mA/mm for each device).

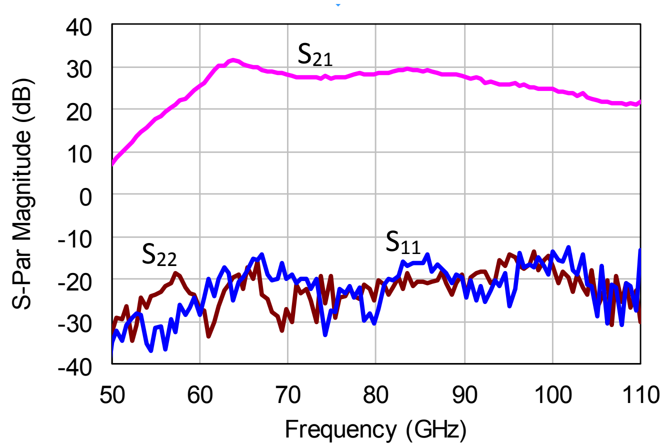

Fig. 4. On-wafer S-parameters of the balanced LNA. Bias conditions are [Vd1, Vd2, Vd3] = [0.8, 0.9, 1.0] V, [Id1, Id2, Id3] = [4.5, 9, 18] mA. The total chip current is 63 mA.

B. Packaged Amplifier Measurements

The LNAs were mounted in WR-10 waveguide modules for noise characterization. The noise figure was measured using the Y-factor method with a WR-10 solid-state noise source. This was confirmed with hot/cold noise sources. Noise Figure measurements were made relative to the input/output waveguide (WG) flanges and then de-embedded to the chip by subtracting the loss of the fixture. This resulted in a correction of 0.3 dB on each end. The chip-level results are plotted in Fig. 5 and also included in Table 1. The noise figure ranges from 1.6-1.9 dB over the 81-86 GHz band with an associated gain of 28 ±1.0 dB.

The performance of this amplifier is compared to other reported results in Table 1. All the results in this table are chip-level data. This work has produced the lowest noise figure of any of the MMICs listed, and clearly, the best noise performance in the 81-86 GHz band.

Our chip-level measurements for the balanced LNA are shown in Fig. 6. The NF is typically 2.7 dB from 75-100 GHz with gain ranging from 20-28 dB.

In order to verify the results obtained with the solid-state noise source, we also measured the single-ended amplifier using hot and cold loads as the noise source. For the cold load,

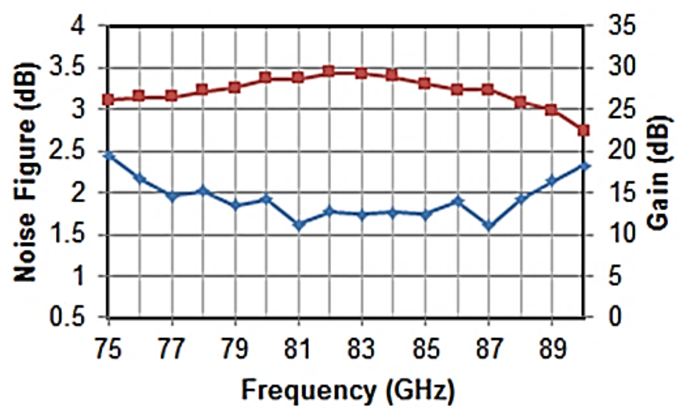

Fig. 5. Measured chip-level noise figure and gain of the single-ended LNA. Bias: Vds = 0.6 V, Ids = 3.8mA per stage.

Table 1. Best reported E and W-band MMIC LNA results.

Reference	Technology	Freq (GHz)	NF (dB)	Gain (dB)	NF* (dB)
Mei [4]	100nm InP HEMT	94	2.5	19	2.5
Bryerton [5]	35nm InP HEMT	78	2.45	28	2.6-2.9
Leuther [6]	50nm GaAs MHEMT	94	1.9	20	1.9
Byk [7]	100nm GaAs PHEMT	86	2.8	20	2.8-3.4
Thome [8]	50nm GaAs MHEMT	80	2.1	18	2.1-2.4
Smith [9]	50nm GaAs MHEMT	79	1.8	27	1.8-2.3
This work	35nm InP HEMT	81	1.6	28	1.6-1.9

*Noise figure at 81-86 GHz

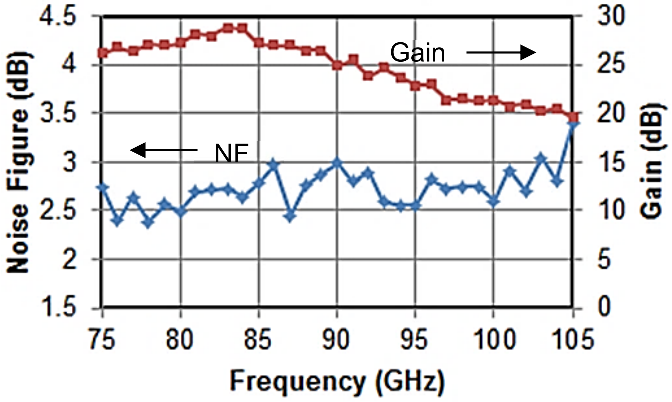

Fig. 6. Measured chip level noise figure and gain of the balanced LNA. Bias conditions for each unit amplifier are [Vd1, Vd2, Vd3] = [0.8, 0.9, 1.0] V, [Id1, Id2, Id3] = [4.5, 9, 18] mA.

we used a WG termination immersed in liquid nitrogen. For the hot load, we simply used a room-temperature WG termination. The results comparing these hot/cold load results to the solid-state source measurements are shown in Fig. 7. Note that a different MMIC sample was used for the two measurements. In spite of this, the agreement between the solid-state and hot/cold load methods is generally good. The hot/cold load method indicates a noise figure 0.2-0.4 dB higher than the solid-state noise source in the 81-86 GHz range. This difference is within measurement uncertainty.

The single-ended LNA module (MMIC plus fixture) was characterized for output power and third-order intercept. It exhibits a P_{1dB} of typically 0 dBm and a saturated output power, Psat, of 1.8-2.0 dBm. At 85 GHz, using a 10 MHz tone spacing, the third-order intercept point referenced to the output, OIP3, was +5 dBm. The balanced LNA module has a typical P_{1dB} of 7 dBm and a Psat of 9 dBm.

The input power damage level was also measured for the single-ended packaged LNA. A step stress test, 1 minute in duration, was performed in which the input power was incrementally increased until failure. The failure criteria was set at a 10% change in the quiescent drain current or a 1.0 dB decrease in the small-signal gain. Based on this criterion, measurements indicated an input power damage level of +14 dBm.

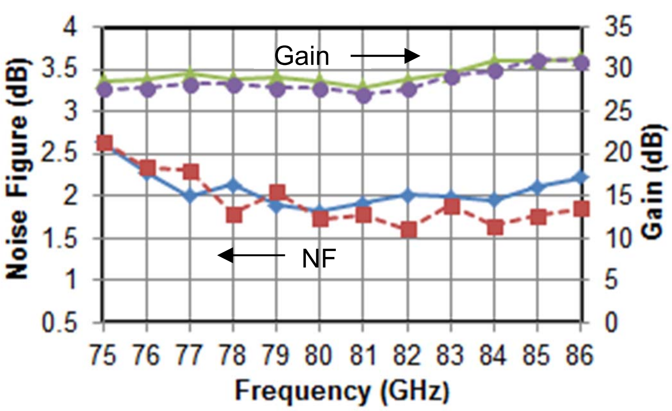

Fig. 7. Chip level results using solid-state noise source and hot/cold load. Bias condition is Vds = 0.6V, Ids = 13mA. Solid blue line with diamonds: hot/cold NF; solid green line with triangles: hot/cold gain; dashed red line with squares: solid-state NF; purple dashed line with circles: solid-state gain.

IV. Conclusion

Using 35nm InP technology, we have demonstrated two new LNAs with state-of-the-art performance. The single-ended LNA, operating at 81-86 GHz, has demonstrated a noise figure of 1.6-1.9 dB. This is the lowest noise figure for any reported LNA operating at E-band frequencies. The balanced LNA achieves a wideband gain response covering the 56-110 GHz range with 20 dB minimum gain and a typical NF of 2.7 dB. In addition, it provides an excellent broadband input/output match.

References

[1] W. R. Deal, X. B. Mei, K. M. K. H Leong, V. Radisic, S. Sarkozy, and R. Lai, "THz Monolithic Integrated Circuits Using InP High Electron Mobility Transistors," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 1, pp. 25-32, Sep. 2011.

[2] A. Tessmann, A. Leuther, V. Hurm, I. Kallfass, H. Massler, M. Kuri, M. Riessle, M. Zink, R. Loesch, M. Seelmann-Eggebert, M. Schlechtweg and O. Ambacher, "Metamorphic HEMT MMICs and Modules Operating Between 300 and 500 GHz," *IEEE J. Solid-State Circuits*, vol. 46, no. 10, pp. 2193-2202, Oct. 2011.

[3] R. Lai, W. R. Deal, X. B. Mei, W. Yoshida, J. Lee, L. Dang, J. Wang, Y. M. Kim, P. H. Liu, V. Radisic, M. Lange, T. Gaier, L. Samoska and A. Fung, "Fabrication of InP HEMT Devices with Extremely High Fmax," *Int. Conf. on InP & Related Materials*, May 2008, pp. 1-3.

[4] X. B. Mei, C. H. Lin, L. J. Lee, Y. M. Kim, P. H. Liu, M. Lange, A. Cavus, R. To, M. Nishimoto and R. Lai, "A W-band InGaAs/InAlAs/InP HEMT Low-Noise Amplifier MMIC with 2.5dB Noise Figure and 19.4 dB Gain at 94GHz," *Int. Conf. on InP & Related Materials*, May 2008, pp. 1-3.

[5] E. W. Bryerton, X. B. Mei, Y. M. Kim, W. Deal, W. Yoshida, M. Lange, J. Uyeda, M. Morgan and R. Lai, "A W-Band Low Noise Amplifier with 22K Noise Temperature," *IEEE Int. Microwave Symp. Dig.*, June 2009, Boston, MA, pp. 681-684.

[6] A. Leuther, A. Tessmann, I. Kallfass, R. Losch, M. Seelmann-Eggebert, N. Wadefalk, F. Schafer, J. Gallego Puyol, M. Schlechtweg, M. Mikulla and O. Ambacher, "Metamorphic HEMT technology for low-noise applications," *Int. Conf. on InP & Related Materials*, May 2009, pp. 188-191.

[7] E. Byk, A. M. Couturier, M. Camiade, C. Teyssandier, M. Hosch, H. Stieglauer and P. Fellon, "An E-band Very Low Noise Amplifier with Variable Gain Control on 100 nm GaAs pHEMT Technology," *Proc. of the 7th European Microwave Integrated Circuits Conference*, Oct. 2012, pp. 111-114.

[8] F. Thome, H. Massler, S. Wagner, A. Leuther, I. Kallfass, M. Schlechtweg and O. Ambacher, "Comparison of Two W-Band Low-Noise Amplifier MMICs with Ultra Low Power Consumption Based on 50 nm InGaAs mHEMT Technology," *IEEE Int. Microwave Symp. Dig.*, June 2013, Seattle, WA.

[9] P. M. Smith, M. Ashman, D. Xu, X. Yang, C. Creamer, P. C. Chao, K. Chu, K. H. Duh, C. Koh and J. Schellenberg, "A 50nm MHEMT Millimeter-Wave MMIC LNA with Wideband Noise and Gain Performance," *IEEE Int. Microwave Symp. Dig.*, June 2014, Tampa, FL.