Cryogenic MMIC Low Noise Amplifiers for W-Band and Beyond

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***Abstract*—We discuss results of low noise amplifier Monolithic Millimeter-wave Integrated Circuits (MMICs), which were designed for specific frequencies in the range of 70-200 GHz. We report on room temperature and cryogenic noise performance for a variety of circuits. The designs utilize Northrop Grumman Corporation's (NGC) 35 nm gate length InP HEMT technology. Some of the lowest reported noise figures to date have been observed with this process at cryogenic temperatures.**

***Index Terms*—MMIC LNAs, InP HEMT, cryogenic low noise amplifiers, multi-chip modules**

I. Introduction

In this work, we describe our recent results from cryogenic testing of low noise Monolithic Millimeter-wave Integrated Circuit (MMIC) amplifiers for a range of frequencies including 70-200 GHz. The MMICs were fabricated at Northrop Grumman Corporation (NGC) using 35 nm gate length InP HEMT technology on a 50 μm thick InP substrate. Some of the lowest reported cryogenic noise figures for any HEMT amplifiers have been observed with this process, including 22K noise at 85 GHz [1].

Unprecedented noise figures have been observed with this short gate length process, and this is due in part to the improvements made in device performance in terms of extremely high transistor cutoff frequencies. Major breakthroughs have been accomplished in the past few years in InP HEMTS and MMICs, permitting high gain MMIC amplifiers well over 400 GHz [2-5]. A very useful consequence of these high frequency transistors are their higher gain, and lower noise, found at lower frequencies such as W-Band (75-110 GHz), and G-Band (140-220 GHz).

InP HEMTs have extremely high electron mobilities, particularly when cooled to cryogenic temperatures. A factor of 7-10 improvement in noise temperature has been experimentally observed when cooling these HEMT MMIC amplifiers from 300K to 20K ambient. Advantages of MMIC LNA receivers include operation at 20K, well above the temperature required for superconducting detectors, which are a competing technology used for radio astronomy and remote sensing. Inexpensive cryocooler options are more readily available for 20K cooling as compared to 4K cooling. MMICs are also well-suited for large arrays.

Some examples of MMIC-based receivers incorporating front-end LNAs are the Q/U Imaging ExperimenT (QUIET) telescope, a 91 element, 90 GHz array which has operated in Chile for study of polarization of the cosmic microwave background radiation in astrophysics [6-8]. The CARMA [9] receivers in Owens Valley, CA utilize cryogenic MMIC amplifier front ends. MMIC amplifiers are being used and proposed for the Green Bank Telescope [10] for spectroscopic studies. The Planck receivers for the Low Frequency Instrument also utilize cryogenic MMIC low noise amplifiers [11].

II. Description of Circuits

A. Individual MMICs

The InP MMIC chip designs utilize microstrip transmission lines, on-chip metal-insulator-metal (MIM) capacitors, thin film resistors, and thru-substrate vias, and employ a common-source configuration. We will report on data from MMIC amplifiers having two and three gain stages. We packaged several MMIC amplifiers in waveguide housings and tested them at room temperature and at 20K ambient. A W-band design having two-stages of gain is shown in Fig. 1. Typical room temperature gain for this chip is about 10-15 dB from 75-105 GHz. A three-stage design reported in [1] has as much as 30 dB of gain at room temperature from 60-90 GHz. A third amplifier developed for G-Band was described in [12, 13], and has 15-20 dB of gain from 140-220 GHz. The G-Band amplifier chip photo is shown in Fig. 2.

B. Multi-Chip MMIC Receiver Module

We have also designed and fabricated a multi-chip MMIC receiver module for 140-180 GHz [14, 15]. The heterodyne module includes a waveguide RF input, MMIC LNAs, a GaAs

Manuscript received August 1, 2011. This work was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was sponsored in part by the W. M. Keck Institute for Space Studies. This work was also sponsored in part by NSF grant AST-090585.

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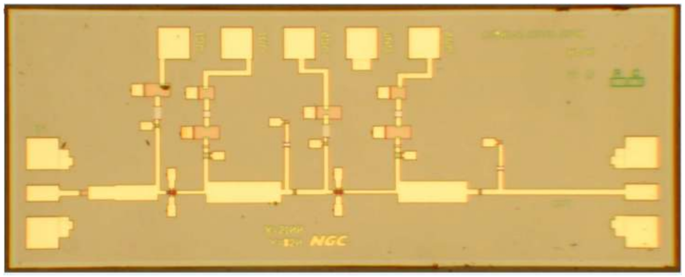

Fig. 1. MMIC LNA designed for W-Band having two gain stages in a common source configuration.

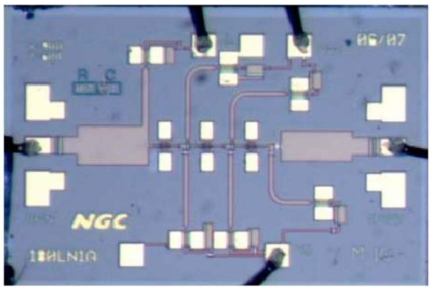

Fig. 2. MMIC LNA designed for G-Band having three gain stages (from [13]).

Schottky diode subharmonic mixer chip, and bandpass filters in a miniature compact waveguide housing suitable for scaling to large arrays. A photo showing the interior of the module, with the chip cavities, LNAs, mixer, filter, DC bias boards, DC feedthrus, and waveguide inputs and outputs is shown in Fig. 3. The split-block module is shown in Fig. 4, with the fully assembled multichip receiver module shown with a penny for scale. Cryogenic receivers built with these amplifiers may be useful for observations of the polarization of the cosmic microwave background and for spectroscopic surveys.

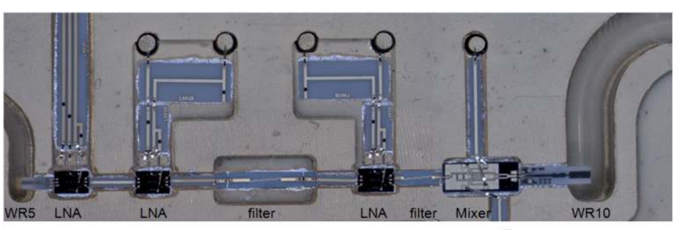

Fig. 3. Multi-chip MMIC module for G-Band, interior showing chips and waveguides.

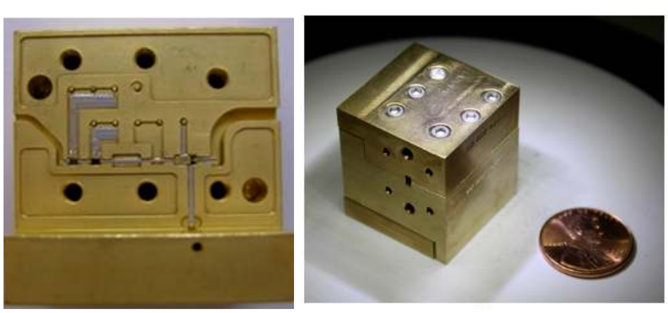

Fig. 4. Multi-chip MMIC Module for G-Band, split-block view at left, and fully assembled module with penny for scale at right.

III. Measured Results

A. Individual MMIC Modules: Results

We have performed room temperature and cryogenic noise testing of the MMIC modules using the Y-factor method, with a room temperature and a 77K load made of Eccosorb AN-72 (from Emerson & Cummings). In W-Band, we have measured the two-stage MMIC LNA of Fig. 1 to have a noise temperature of typically 220K-250K at room temperature. In the case of one LNA having HEMTs with an InAs channel composition, a minimum noise of 180 K is observed at 95 GHz, with gain greater than 15 dB up to 103 GHz. The data are shown in Fig. 5.

The schematic of the cryogenic test set, indicating the MMIC LNA modules inside a dewar at 20K, is shown in Fig. 6. The horn is separated from the load by a 1 mil thick mylar window. In addition to cryogenic measurements with a 295K and 77K load using the horn and window, we also employed a second method using a heated load, cooled in the dewar and having a hot and cold temperature of 50K and 30K, respectively. This was done to ensure that the noise power of the 295K load was not causing saturation effects in the LNAs in the horn and window method. Noise powers were measured after amplifying the signal from the mixer with IF amplifiers and a bandpass filter with a power meter. Both measurement methods agreed to within a few K.

When the two-stage LNA (having $In_{0.75}Ga_{0.25}As$ channel HEMTs) of Fig. 1 was cooled to 20K ambient temperature, we measured a receiver noise temperature T_{rec} of 36K at 90 GHz. Comparison between MMICs having $In_{0.75}Ga_{0.25}As$ channel HEMTs and InAs channel HEMTs for the same chip design showed improvement in noise temperature (T_{amp}) in the InAs case with less than 40K from 76-101 GHz as shown in Fig. 5. We calibrated our backend noise contribution to the LNA noise, and calculated the corrected amplifier noise temperature to be 27K at 90 GHz. The data from the two-stage LNAs, having both InAs channel HEMTs, and $In_{0.75}Ga_{0.25}As$ channel HEMTs, are plotted along with the data from the three-stage amplifier of Ref. 1, and the results are shown in Fig. 7.

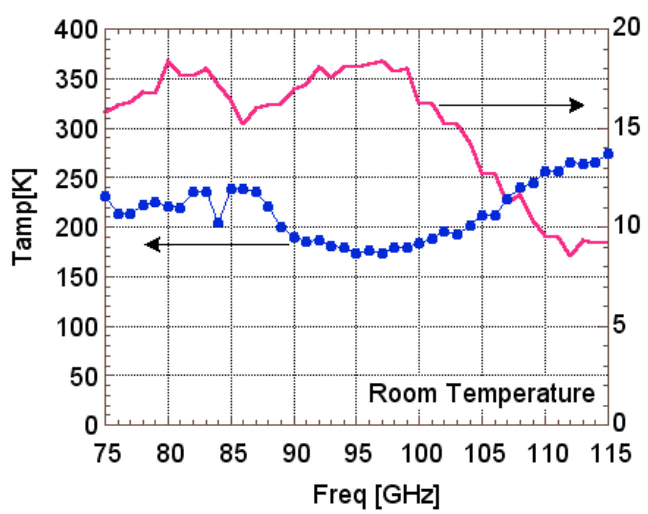

Fig. 5. Room temperature noise and gain measurement of the W-Band LNA shown in Fig. 1, having an InAs channel composition in the HEMTs.

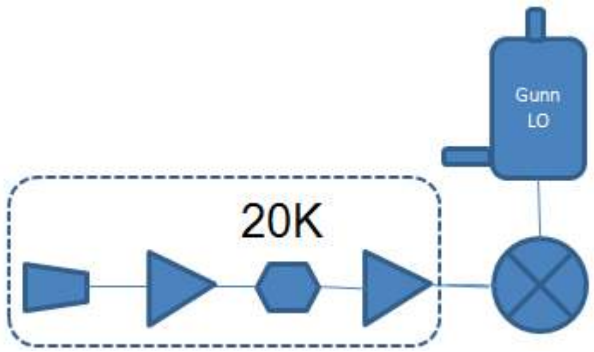

Fig. 6. Schematic of test set for noise figure measurements. Horn, LNA, cryogenic low-loss isolator, and second LNA are cooled to 20K in a dewar, while a room temperature mixer (with Gunn source for local oscillator) is used for down-conversion of the power signal in Y-factor measurements.

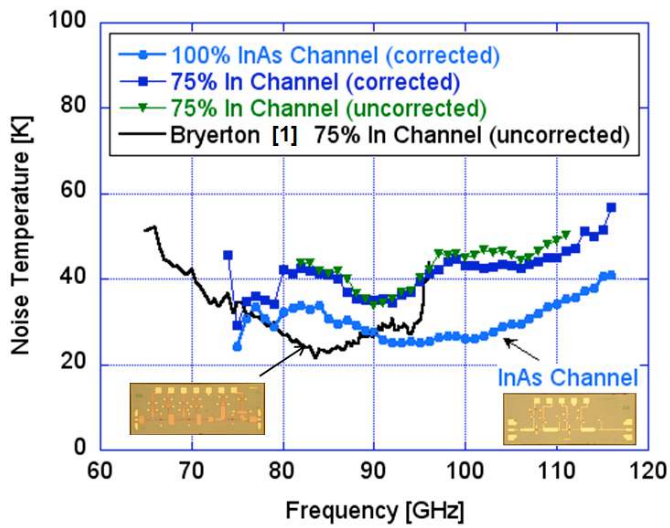

Fig. 7. Comparison of noise temperature in W-Band of different LNA blocks when cooled to 20K ambient temperature. Included are the design of Fig. 1 fabricated using InAs channel HEMTs, as well as $In_{0.75}Ga_{0.25}As$ channel HEMTs. Also included are the data from Bryerton *et al*. in Ref. 1 using $In_{0.75}Ga_{0.25}As$ channel HEMTs.

In addition to the W-Band results, we also measured the G-Band amplifier module discussed in Ref. 11, having the chip shown in Fig. 2. For the test, as in the schematic of Fig. 6, two LNAs were cooled in the dewar to 20K, with a WR5 horn in front of the first LNA. In this case, no low-loss cryogenic isolator was available between the LNAs. Using the same cryogenic test dewar with a 295K and 77K load, and 1 mil thick mylar window, we downconverted the noise power with an appropriate mixer for G-Band. The noise temperature of the G-Band amplifier of Fig. 2 is shown in Fig. 8. The amplifier noise was corrected for the backend noise contribution. We observed a minimum corrected amplifier noise temperature of 63K at 164 GHz. This result represents the lowest noise temperature obtained for a MMIC LNA module when cooled to 20K in G-Band to date.

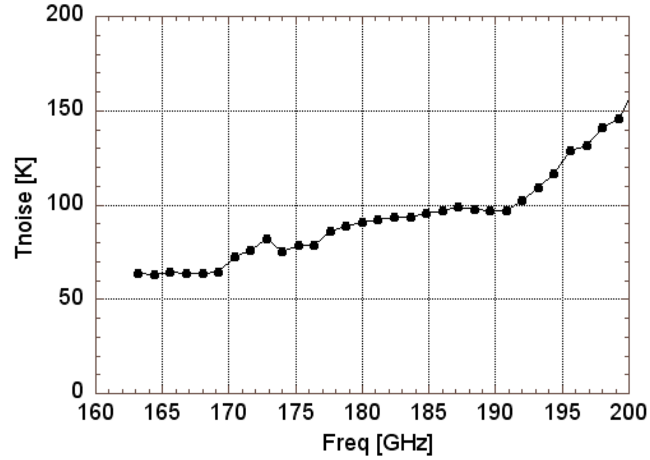

Fig. 8. Measured cryogenic noise of G-Band LNA from reference [12, 13].

B. Multi-Chip MMIC Receiver Module: Results

A photo of the G-Band multi-chip receiver module, described in Figs. 3 and 4, is shown in Fig. 9, with the local oscillator applied at the WR10 waveguide port, and a WR5 horn at the input. At room temperature, we have observed a receiver noise temperature of as low as 390K at 166 GHz. We have also performed cryogenic testing at 20K using a dewar with a 1 mil mylar window, and a 295K and 77K external load. Results from cryogenic testing indicate record performance for the HEMT MMIC superheterodyne receiver module: we have observed a receiver noise temperature of 58K at 166 GHz and less than 70 K between 162-174 GHz [15]. In Fig. 10, we plot the noise of the G-Band superheterodyne receiver module, alongside the G-Band amplifier module of Fig. 8 (which was corrected for backend noise contribution). The superheterodyne receiver module was not corrected for backend noise contribution from the mixer, since it contains an integrated mixer chip inside the module. The results of the two plots compare favorably, indicating that the receiver module has sufficient LNA gain to overcome the conversion loss of the mixer inside. The amplifier-only module has lower noise above 180 GHz than the multi-chip

Fig. 9. Photo of the G-Band receiver module, with local oscillator applied at room temperature.

receiver module. This is due to the bandpass filter in the multi-chip receiver module, which was intended to block out the H_20 line at 183 GHz for future measurements of the cosmic microwave background radiation.

Both of the G-Band modules contained MMIC LNAs having $In_{0.75}Ga_{0.25}As$ channel HEMTs. We hope to achieve even better performance using InAs channel HEMTs. Testing is currently underway of new MMIC amplifiers having InAs channel HEMTs.

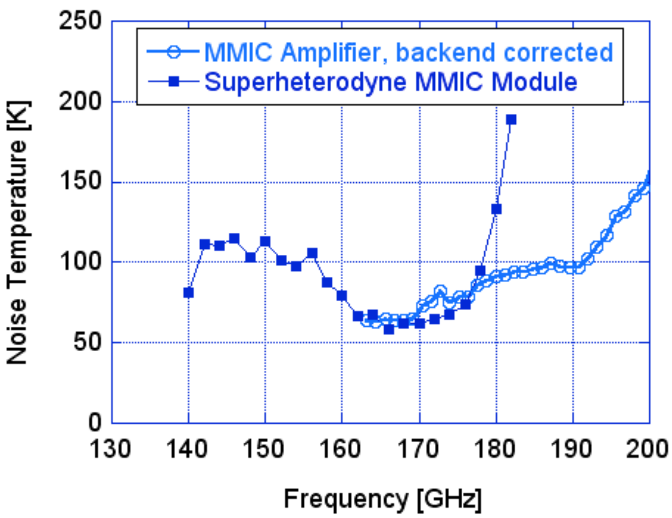

Fig. 10. Cryogenic noise performance vs. frequency for the multi-chip MMIC super heterodyne receiver module, plotted with the data for a single LNA module (from Fig. 8), obtained at 20K ambient temperature. A minimum noise temperature of 62K is achieved at 164 GHz.

IV. Conclusion

In summary, we have designed several LNAs to cover various parts of W-Band. Wafers with InAs channel HEMTs and those with $In_{0.75}Ga_{0.25}As$ channel HEMTs were fabricated alongside, and we have measured identical chip designs from both wafers. A noise temperature of less than 40K is possible across W-Band with a two-stage LNA design, and a minimum noise in the mid-20K range was observed experimentally. In addition, we have tested a G-Band LNA and a multichip G-Band receiver module. Both G-Band modules obtained record performance of approximately 62K at 164 GHz.

Acknowledgment

We would like to acknowledge the expertise of Ms. Mary Soria and Ms. Heather Owen for amplifier and module micro-assembly. We would also like to thank Drs. Sander Weinreb and Anthony Readhead of the California Institute of Technology, Drs. Michael Seiffert and Charles Lawrence of the Jet Propulsion Laboratory, and Dr. Eric Bryerton of the National Radio Astronomy Observatory for helpful discussions.

References

[1] 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," *2009 IEEE MTT-S Int. Microwave Symp. Dig.*, June 2009, Charlottesville, VA, pp. 681-684.

[2] L. Samoska, A. Fung, D. Pukala, P. Kangaslahti, R. Lai, S. Sarkozy, X. B. Mei, and G. Boll, "On-Wafer Measurements of S-MMIC Amplifiers from 400-500 GHz," *2011 IEEE MTT-S Int. Microw. Symp. Dig.*, Baltimore, MD, June, 2011.

[3] W. R. Deal, K. Leong, X. B. Mei, S. Sarkozy, V. Radisic, J. Lee, P. H. Liu, W. Yoshida, J. Zhou, and M. Lange, "Scaling of InP HEMT Cascode Integrated Circuits to THz Frequencies," *IEEE Compound Semiconductor IC Symp.*, Oct., 2010, pp. 1-4.

[4] A. Tessmann, A. Leuther, R. Loesch, M. Seelmann-Eggebert, H. Massler, "A Metamorphic HEMT S-MMIC Amplifier with 16.1 dB Gain at 460 GHz," *IEEE Compound Semiconductor IC Symp.*, Monterey, CA, Oct., 2010, pp. 1-4.

[5] L. A. Samoska, "An Overview of Solid State Integrated Circuit Amplifiers in the Submillimeter-wave and THz Regime," to appear in *IEEE Transactions on Terahertz Science and Technology*, Vol. 1, Sept. 2011.

[6] C. Bischoff, A. Brizius, I. Buder, Y. Chinone, K. Cleary, R. N. Dumoulin, A. Kusaka, R. Monsalve, S. K. Ness, L. B. Newburgh, R. Reeves, K. M. Smith, I. K. Wehus, J. A. Zuntz, J. T. L. Zwart, L. Bronfman, R. Bustos, S. E. Church, C. Dickinson, H. K. Eriksen, P. G. Ferreira, T. Gaier, J. O. Gundersen, M. Hasegawa, M. Hazumi, K. M. Huffenberger, M. E. Jones, P. Kangaslahti, D. J. Kapner, C. R. Lawrence, M. Limon, J. May, J. J. McMahon, A. D. Miller, H. Nguyen, G. W. Nixon, T. J. Pearson, L. Piccirillo, S. J. E. Radford, A.C. S. Readhead, J. L. Richards, D. Samteben, M. Seiffert, M. C. Shepherd, S. T. Staggs, O. Tajima, K. L. Thompson, K. Vanderlinde, R. Williamson, and B. Winstein, "First Season QUIET Observations: Measurements of CMB Polarization Power Spectra at 43 GHz in the Multipole Range 25 $\leq l \leq 475$," submitted to *Astrophysical Journal*, 2010.

[7] Todd Gaier, Charles R. Lawrence, Michael D. Seiffert, Mary M. Wells, Pekka Kangaslahti, Douglas Dawson "Amplifier arrays for CMB polarization," *New Astronomy Reviews*, 47, 1167 (2003).

[8] P. Kangaslahti, T. Gaier, M. Seiffert, S. Weinreb, D. Harding, D. Dawson, M. Soria, C. Lawrence, B. Hooberman, A. Miller, "Planar Polarimetry Receivers for Large Imaging Arrays at Q-band", *IEEE MTT-S, International Microwave Symposium Digest*, 89 (2006).

[9] CARMA website: http://www.mmarray.org/

[10] Green Bank Telescope website: http://www.gb.nrao.edu/

[11] Bersanelli, M., …, Seiffert, M., et al. (113 co-authors), "Planck pre-launch status: Design and description of the Low Frequency Instrument," *Astronomy & Astrophysics*, 520, A4 (2010).

[12] P. Kangaslahti, D. Pukala, T. Gaier, W. Deal, X. Mei, R. Lai, "Low Noise Amplifier for 180 GHz Frequency Band," *2008 IEEE MTT-S Int. Microwave Symp. Dig.*, June 2008, Charlottesville, VA, pp. 681-684.

[13] P. Kangaslahti, "Recent developments in 180 GHz MMIC LNA and receiver technology" *Proc. 11th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment MicroRad2010 ,* March, 2010. pp 272 – 275.

[14] P. Voll, J. M. Lau, M. Sieth, S. E. Church, L. A. Samoska, P. Kangaslahti, T. C. Gaier, D. Van Winkle, and S. Tantawi, "Development of a 150 GHz MMIC Module Prototype for Large-Scale CMB Radiation Experiments," *Proc. of SPIE Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V*, Vol. 7741, June, 2010, San Diego, CA, pp. 77412J-77412J-10.

[15] P. Voll, L. Samoska, S. Church, J. Lau, M. Sieth, T. Gaier, P. Kangaslahti, M. Soria, S. Tantawi, and D. Van Winkle, "A G-Band Cryogenic MMIC Heterodyne Receiver Module for Astrophysical Applications," to be presented at the *European Microwave Conference*, Manchester UK, Oct., 2011.