Miniature MMIC Low Mass/Power Radiometer Modules for the 180 GHz GeoSTAR Array

Pekka Kangaslahti, Alan Tanner, David Pukala, Todd Gaier, Bjorn Lambrigtsen, Boon Lim, Xiaobing Mei* and Richard Lai*

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA

*Northrop Grumman Corporation, Redondo Beach, CA, 90278, USA

***Abstract* — We have developed and demonstrated miniature 180 GHz Monolithic Microwave Integrated Circuit (MMIC) radiometer modules that have low noise temperature, low mass and low power consumption. These modules will enable the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) of the Precipitation and All-weather Temperature and Humidity (PATH) Mission for atmospheric temperature and humidity profiling. The GeoSTAR instrument has an array of hundreds of receivers. Technology that was developed included Indium Phosphide (InP) MMIC Low Noise Amplifiers (LNAs) and second harmonic MMIC mixers and I-Q mixers, surface mount Multi-Chip Module (MCM) packages at 180 GHz, and interferometric array at 180 GHz. A complete MMIC chip set for the 180 GHz receiver modules (LNAs and I-Q Second harmonic mixer) was developed. The MMIC LNAs had more than 50% lower noise temperature (NT=300K) than previous state-of-art and MMIC I-Q mixers demonstrated low LO power (3 dBm). Two lots of MMIC wafers were processed with very high DC transconductance of up to 2800 mS/mm for the 35 nm gate length devices. Based on these MMICs a 180 GHz Multichip Module was developed that had a factor of 100 lower mass/volume (16x18x4.5 mm^3, 3g) than previous generation 180 GHz receivers.**

***Index Terms* — high electron mobility transistors (HEMTs), indium phosphide, millimeter wave field-effect transistor (FET) amplifiers, monolithic millimeter wave integrated low noise amplifier, MMIC receiver, I-Q receiver.**

I. Introduction

We developed 180 GHz radiometer technology for studies of the Global Water and Energy Cycle. The 180-GHz sounding band is used to obtain vertical profiles of water vapor (and to some extent liquid water). This requires a strong water absorption line, such as the one at 183.3 GHz. The sounding spectral channels are positioned in the flanks of this line (e.g. AMSU LEO instrument uses bands 2, 3, 7 and 17 GHz from the line), to provide a range of opacities and thus penetration depths into the atmosphere. By combining the measurements from different depths it is possible to reconstruct the vertical distribution of the absorbing/emitting water vapor. The better the sensitivity of the radiometers, the shorter integration time is needed to reach the typically required ΔT-0.3 K accuracy.

The current JPL built and commercial water vapor radiometers have mixer front ends and achieve NT=1500 to 2500 K (NF=7.0 to 9.8 dB) in double sideband (DSB) measurements [1],[2]. Recent mixer results show NT=500 to 600 K (NF=4.4 to 4.9 dB) DSB [3], which would indicate that they would perform better than most previously reported MMIC low noise amplifier (LNA) modules [4], [5]. This is based on the assumption that the 183 GHz water vapor line is symmetrical, and both sidebands can be observed. We reported LNA module results NT=390 to 550K (NF=3.7...4.6 dB) in this band, a significant improvement over the previous results, especially for our application where we need to separate the sidebands for correlation [6]. Recently we demonstrated a noise temperature of NT=400 to 450 K (NF=3.8..4.1) for a complete I-Q receiver [7]. This receiver operates with Pdc=24mW, weighs 3g and requires a local oscillator power of P_{LO}=+3dBm at 82.5 to 91.5 GHz LO frequency [7]. This is a breakthrough result for the GeoSTAR synthetic thinned aperture radiometer [8], a geostationary all-weather hurricane tracking instrument. It will enable GeoSTAR to provide humidity profiles of the sounding area every 15 minutes with a 25 km resolution.

II. LNA and Mixer Technology

The receiver development was based on a high performance 35 nm gate length InP HEMT [9,10]. The 35 nm InP HEMT has demonstrated superior d.c. performance, including extremely high transconductance over 2000 mS/mm, sharp pinchoff characteristics and reasonable output conductance. The devices demonstrate a reverse 2-terminal breakdown voltage typically greater than 2V and can also be operated at extremely low voltage and currents with useable device transconductance for MMW applications. The 35 nm InP HEMT has demonstrated f_T of over 550GHz and f_{max} over 1 THz. High frequency circuits based on the 35 nm InP HEMT are fabricated with two levels of metal, MIM capacitors and thin-film resistors on 2-mil thick InP substrates. 35 nm InP HEMTs have been used in sub-MMW integrated amplifier circuits operating as high as 350 GHz for the first time [11].

The noise temperature of the receiver is dictated by the first LNA MMIC. The configuration of the LNA is three transistor stages in common source configuration with interconnecting microstrip transmission lines on the 2 mil thick InP material. Fig. 1 shows a photograph of the MMIC LNA [7].

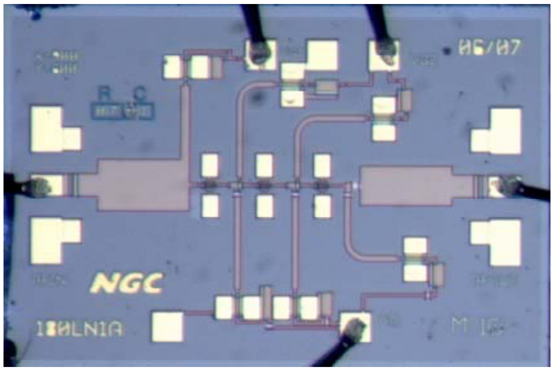

Fig. 1. The MMIC LNA designed and processed in 35 nm InP technology. Size of the MMIC is 900 x 600 um2. It is a three stage design, where each transistor has two gate fingers, for a total of 30 um gate periphery per device [7].

We screened a number of LNAs by on-wafer measurements (Fig. 2)[7]. The typical LNAs had a gain of G= 16 to 21 dB at the 165 to 183 GHz frequency band.

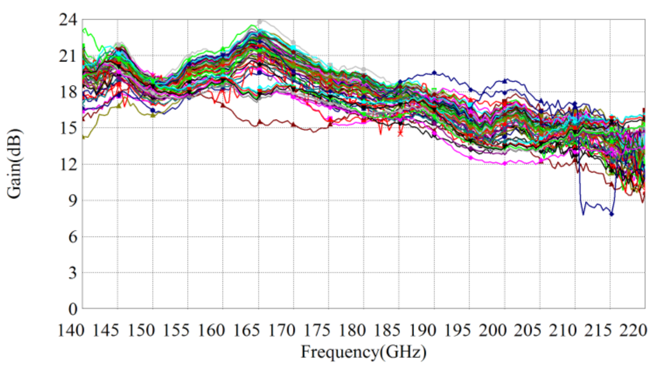

Fig. 2. The measured 140 to 220 GHz S-parameters were used to screen the LNA MMICs. The LNAs had 16…21 dB of gain over the operational frequency band [7].

The LNAs provided the low noise and sufficient gain to minimize the effect of the conversion loss of the mixer to the overall sensitivity of the receiver. The mixer MMIC was designed in the same 35 nm technology as the LNAs. The quadrature downconversion in the mixer was implemented with a 90 degree Lange coupler. This coupler improved the return loss of the mixer and achieved broadband 90 degree phase difference between the two unit mixers. The HEMTs of the mixers had dual gates for balanced LO feed and they operated biased to below channel pinch-off to maximize the second harmonic content in the channel conduction cycle. The RF signals were directed to the unbiased drains of the mixer HEMTs and the IF signals were low-pass filtered from the drain contacts. A compact and highly efficient power divider and balun was developed for the LO side. [7]. The low impedance CPW transmission line transforms the low resistive impedance of the mixer gates and balun match to the LO port. Fig. 3 shows a photograph of the mixer MMIC.

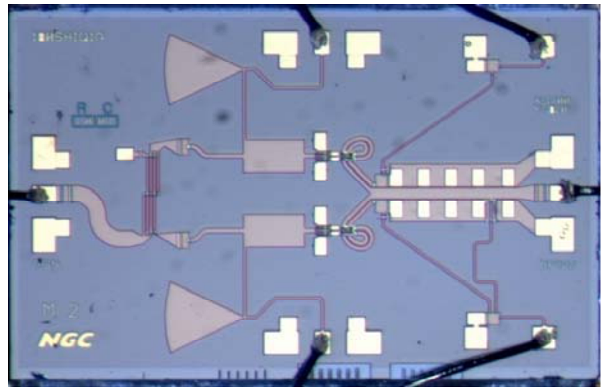

Fig. 3. The MMIC mixer designed and processed in 35 nm InP technology. Size of the MMIC is 1100 x 820 um2. The mixer has I and Q outputs and operates at second harmonic of the LO frequency [7].

III. MMIC MODULES

The LNA and mixer MMICs enabled us to design miniature planar receiver modules, a desirable feature for automated volume assembly. The microstrip to waveguide and interconnect microstrip circuits were designed on 3 mil alumina with matching of interconnect wirebonds. The high impedance transmission line of the bond wire and the end capacitances of the microstrip lines create a significant mismatch at 180 GHz. A commercial glass leadframe was used for the high density bias and IF interfaces [7].

The receiver is a cascade of two LNAs and the I-Q mixer that operates at the second harmonic frequency. At the RF input side there is a perpendicular transition from the WR-05 waveguide to microstrip. The two LNAs after the transition have a combined gain of about 35 to 40 dB, a sufficiently high gain to compensate for the conversion loss of the I-Q mixer. The LO side of the mixer is connected to a microstrip to WR-10 waveguide transition. The overall layout of the receiver module is presented in the photo in Fig. 3. The mass of the receiver module was only 3g [7].

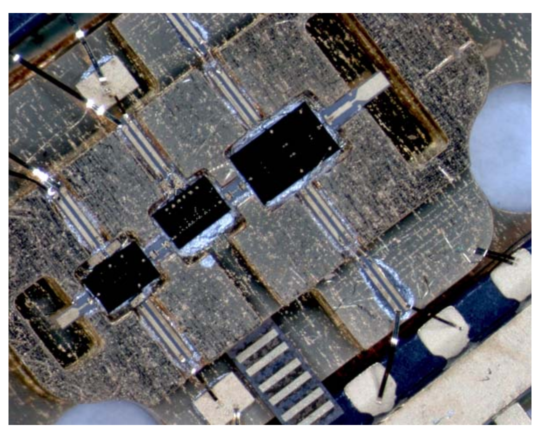

Fig. 3. Photo of the assembled receiver module [7].

The receiver module had to be mounted on a special testing platform to route the RF and LO signals to the respective waveguide connections, and to connect the bias and IF leads. The testing platform had a straight WR-05 through waveguide for the RF and two right angle waveguide corners to route the reduced height WR-10 LO waveguide. The testing platform and the mounted receiver module are shown in Fig. 4 [7].

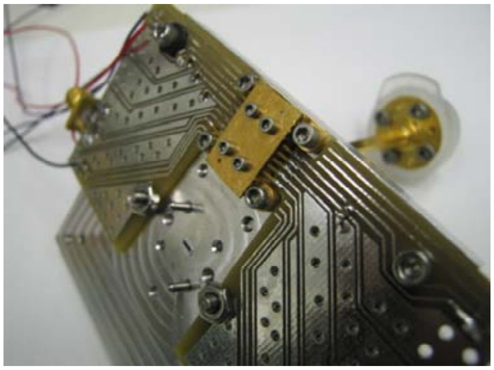

Fig. 4. The receiver module mounted on the testing platform. The 180 GHz RF signal is fed to the module through the platform, this photo shows an adapter mounted on the opposite side to connect from the special 6 mm diameter waveguide flange to the standard ¾" WR-05 waveguide flange. The LO waveguide flange is on the platform, and the bias and IF lines are on FR-4 PCB [7].

The development of the receiver was completed by design and fabrication of a horn antenna that has a matched beam pattern to the Earth's hemisphere from geostationary orbit (17 degrees), and fits in the required antenna to antenna spacing in the short baselines of the GeoSTAR array. A parabolic potter horn design had the advantage of broad frequency bandwidth and thin walls at the aperture with high horn to horn isolation in a tightly spaced interferometric receiver array [7]. The developed horn antenna is shown with the receiver module in Fig. 5.

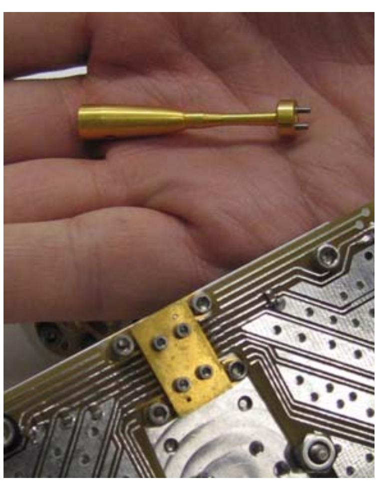

Fig. 5. The receiver module mounted on the testing platform and the parabolic potter horn antenna [7].

IV. Receiver Module Testing

The MMIC receiver testing was performed on the testing platform with the developed horn antenna as the input. This set-up for the noise figure measurement is shown in Fig. 6. We used an absorber termination as our hot and cold noise source in the Y-factor measurements. The hot temperature was the ambient (T= 295 K) and for cold load we dipped the absorber in liquid nitrogen (T=78 K) [7].

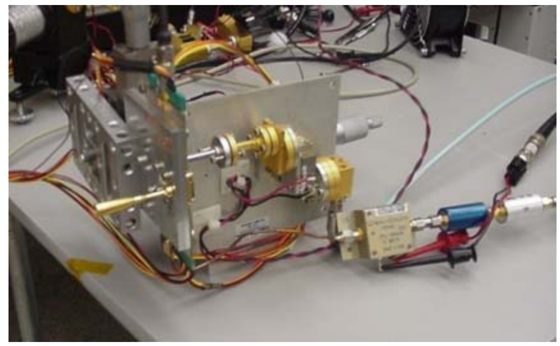

Fig. 6. Testing of the noise figure of the receiver [7].

The noise temperature results are shown in Fig. 7. The graph shows noise temperature and noise figure results from 160 to 190 GHz in addition to the gain of the receiver. These data include the horn and the testing platform; we did not remove their losses from the measurement results. The LNAs were biased to a drain voltage of V_d=0.75 V and the total drain current was I_d=32 mA for the two LNAs resulting in total power consumption of P_{dc}=24 mW for the receiver module [7]. The mixer was biased to below pinch-off, but the mixer gates did not draw current, as is typical for resistive mixers. These results were achieved with a local oscillator power of P_{LO}= +3dBm [7], which will result in significant power savings in the LO multiplication and distribution system of the GeoSTAR receiver array.

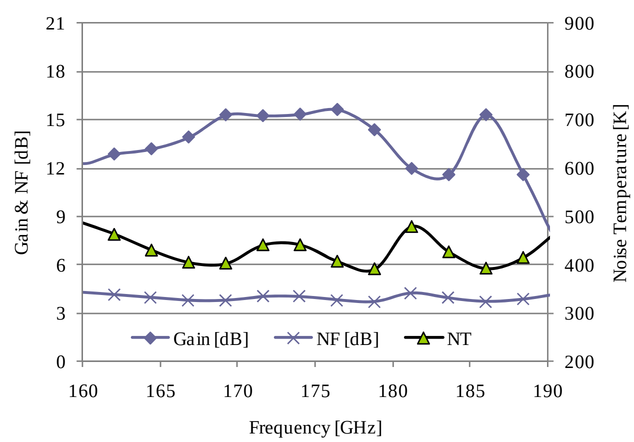

Fig. 7. Measured results for the MMIC receiver on the testing platform. The noise temperature is between 400 and 450 K over the 165 to 183 GHz frequency band [7].

The quadrature downconversion of the receiver was tested with a multiplied signal source connected to the adapter in Fig. 4. The IF frequency range of the system is from 10 MHz to 500 MHz. The receiver has a flat phase and amplitude response over this IF frequency range (see Fig. 8).

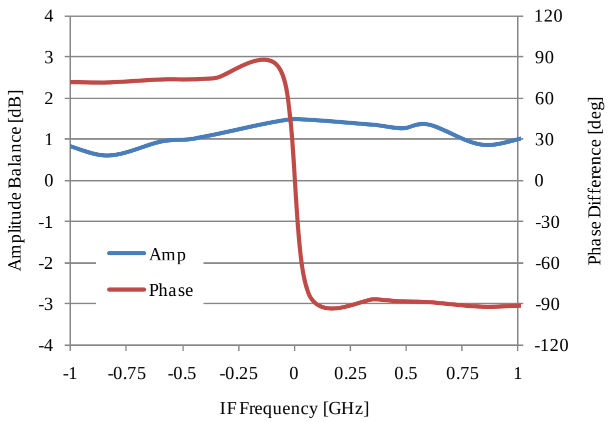

Fig. 8. Measured receiver quadrature response over the IF frequency range [7].

V. Conclusion

The developed MMIC receiver has the lowest reported noise figure at 180 GHz frequency band of I-Q receivers operating at ambient temperature. The receiver has miniature size and very low power consumption and mass, all desirable features for large arrays. Furthermore, the local oscillator power requirements were very low, which will simplify the LO system development and reduce its power requirements. These developed MMIC receivers are an enabling technology for the geostationary thinned array radiometer (GeoSTAR) instrument for humidity sounding of the atmosphere, and when combined with the 50 or 118 GHz array, both humidity and temperature sounding at unprecedented temporal coverage. The LNA and mixer MMICs will be used immediately in the ESTO IIP-07 tasks "GeoSTAR technology development and risk reduction for PATH" and “Ka-band SAR Interferometry Studies for the SWOT Mission”. The developed LNAs were also integrated in the airborne “High Altitude MMIC Sounding Radiometer (HAMSR)” that was developed under the IIP-98 and currently is funded to be installed onto the Global Hawk UAV for participation in NASA's Genesis and Rapid Intensification Processes (GRIP) hurricane field experiment in the summer of 2010.

Acknowledgement

This work was supported by the by the NASA Earth Science Technology Office Advanced Component Technologies ACT-05 program. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration.

References

[1] S. Brown, B. Lambrigtsen, et. al., “Observations of tropical cyclones with a 60, 118 and 183 GHz microwave sounder,” *Proc. IEEE Geoscience and Remote Sensing Symposium*, 23-28 July 2007, Barcelona, Spain, pp. 3317 - 3320.

[2] A. L. Pazmany, M. Wolde, “A compact airborne G-band (183 GHz) water Vapor Radiometer and retrievals of liquid cloud parameters from coincident radiometer and millimeter wave radar measurements,” *Proc. IEEE MicroRad 2008*, 11-14 March 2008, Firenze, Italy, pp. 1-4.

[3] J. L. Hesler, D. W. Porterfield, et. al., “Development of compact broadband receivers at submillimeter wavelengths,” *Proc. IEEE Aerospace Conf.*, 6-13 March 2004, Big Sky, MO, pp. 735-740.

[4] A. Tessmann, A. Leuther, et. al. “220 GHz Low-Noise Amplifier Modules for Radiometric Imaging Applications,” *Proc. IEEE European Microwave Conference*, 10-13 Sept. 2006, Manchester, United Kingdom, pp. 137 - 140.

[5] R. Raja, M. Nishimoto, et. al. “A 183 GHz low noise amplifier module with 5.5 dB noise figure for the conical-scanning microwave imager sounder (CMIS) program,” *Proc. IEEE IMS-01*, 20-25 May 2001, Phoenix, AZ, pp. 1955 - 1958.

[6] P. Kangaslahti, D. Pukala, T. Gaier, W. Deal, X. Mei, R. Lai, “Low noise amplifier for 180 GHz frequency band,” *Proc. IEEE IMS-08*, 15-20 June 2008, Atlanta, GA, pp. 451 - 454.

[7] P. Kangaslahti, D. Pukala, T. Gaier, A. Tanner, W. Deal, B. Lambrigtsen, X. Mei, R. Lai, “Miniature Low Noise G-band I-Q Receiver,” *Proc. IEEE IMS-10*, 21-26 May 2010, Anaheim, CA.

[8] B. Lambrigtsen, A. Tanner, T. Gaier, P. Kangaslahti and S. Brown, “Prototyping GeoSTAR for the PATH Mission” *Proc. NASA Science Technology Conference*, June 19-21, 2007, University of Maryland University College, Adelphi, MD

[9] X.B. Mei, W. Yoshida, et. al., “35-nm InP HEMT SMMIC Amplifier With 4.4-dB Gain at 308 GHz” *IEEE Electron Device Letters*, vol. 28, Issue 6, pp. 470 – 472, June 2007.

[10] X.B. Mei, W. Yoshida, et. al., “35nm InP HEMT for Millimeter and Sub-Millimeter Wave Applications” *Proc. IEEE 19th Int. Conf. on Ind. Phosph. & Rel. Mat.*, 14-18 May 2007, pp. 59 - 62

[11] R. Lai, X., B. Mei., et. al., “Sub 50 nm InP HEMT Device with Fmax Greater than 1 THz” *Proc. IEEE Electron Devices Meeting*, 10-12 Dec. 2007, Washington, DC, pp. 609 - 611.

[12] M Varonen, M. Kärkkäinen, et. al. “Resistive HEMT Mixers for 60 GHz Broadband Telecommunication”, *IEEE Trans. Microwave Theory Tech*, vol. 53, pp. 2403-2408, April 2005.