InP HEMT Integrated Circuits for Submillimeter Wave Radiometers in Earth Remote Sensing

*William R. Deal and Goutam Chattopadhyay**

Northrop Grumman Corporation
Redondo Beach, CA 90278
william.deal@ngc.com

*Jet Propulsion Laboratory, California Institute of Technology**
Pasadena, CA 91012
goutam.chattopadhyay@jpl.nasa.gov

***Abstract* — The operating frequency of InP integrated circuits has pushed well into the Submillimeter Wave frequency band, with amplification reported as high as 670 GHz. This paper provides an overview of current performance and potential application of InP HEMT to Submillimeter Wave radiometers for earth remote sensing.**

***Index Terms* —Submillimeter Wave, Indium Phosphide, HEMT**

I. Introduction

Nestled between the microwave and the optical ranges, the Submillimeter wave region (300 – 3000 GHz) has long been of interest to scientists and engineers due to its rich available bandwidth and spectral characteristics. However, due the lack of practical commercial component technologies at these frequency bands, the largest practical applications in the Submillimeter wave ranges continue to be science related in the areas of spectroscopy and remote sensing [1]. These applications use sensitive receivers, with the most common mixer front-end technologies being the SIS (Superconductor Insulator Superconductor), HEB (Hot Eletron Bolometers) and GaAs Schottky with choice of technology driven by required sensitivity, operating frequency and ability to cool the receiver. Efficient LO (Local Oscillator) generation is another challenge at Submillimeter wave frequencies. Traditionally, the most practical and efficient way for generating power at Submillimeter Wave frequencies has relied on chains of multipliers to reach the output frequency. This means the overall chain efficiency is very low compared to lower frequency sources.

However, advancements in the f_{MAX} of transistors promises to transform the types of components available in the Submillimeter Wave bands with InP HEMT transistors breaking the 1 THz barrier several years ago [2]. Amplification has now been reported as high as 670 GHz [3] using a 30 nm InP HEMT transistor (Fig. 1). Low Noise Amplifiers at these frequencies may reduce the noise contribution from mixers and IF amplifiers and power amplification could significantly improve LO efficiencies. Therefore, InP HEMT integrated circuits may be a viable front-end technology from a performance perspective.

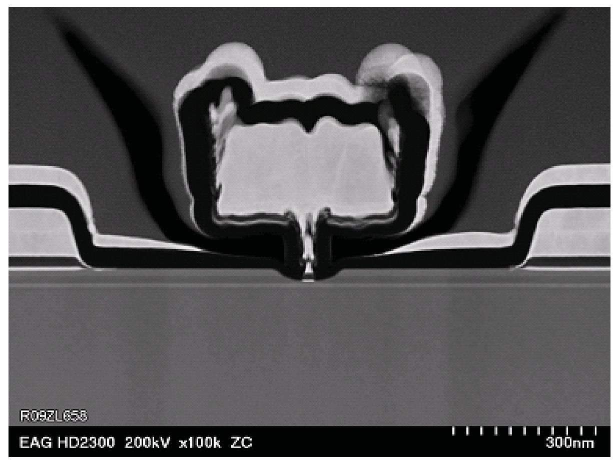

Fig. 1 STEM of 30 nm InP HEMT transistor.

The advent of integrated circuit technology may also prove successful in lowering cost and improving manufacturability of receivers at Submillimeter Wave frequencies as well. A variety of circuit functions can be realized in the same process, including mixing and multiplication [4]. This has the potential to realize the entire Submillimeter Wave receiver on a single chip.

This paper discusses the potential benefits of using InP HEMT integrated circuits for Submillimeter Wave radiometers for remote earth sensing. The paper begins with a brief overview of radiometer measurements in earth remote sensing. Later, state of art results for InP HEMT component performance in the Submillimeter Wave range is described.

II. Radiometer Measurements in Earth Remote Sensing

Resolution of critical outstanding questions in climate stability, weather and climate forecasting, and the long-range transport of air pollution in the Earth's atmosphere requires global measurements of upper tropospheric (8–16 km altitude) humidity, cloud ice, and composition with high spatial and temporal resolution. Radiometer based terahertz instruments are most suited to carry out these important measurements. Existing satellite-based instruments are not well-suited to observe deep convective processes, which typically have lifetimes of a few to several hours. This is rapid compared to the 12 hour repeat period of low-earth orbiting instruments, which typically can only take twice-daily snapshots of the atmosphere. While instruments on geostationary platforms can yield information with better temporal resolution, such nadir sounding measurements lack the vertical resolution needed for increased understanding of these systems. Furthermore, the study of these phenomena at infrared and ultraviolet wavelengths is difficult due to the impact of clouds on these measurements. In addition to the thick cumulonimbus clouds which characterize convective systems, the chemically important 'outflow' region that extends far beyond the region of convection is heavily populated with cirrus clouds, again ruling out the use of short-wavelength techniques. Microwave observations in the 100–600 GHz band, by contrast, can see through most cirrus clouds, allowing useful measurements of the underlying atmospheric composition in this critical region.

One of the poorly understood key factors controlling the vertical distribution of chemical species in the Earth's atmosphere is the transport of air into the upper troposphere

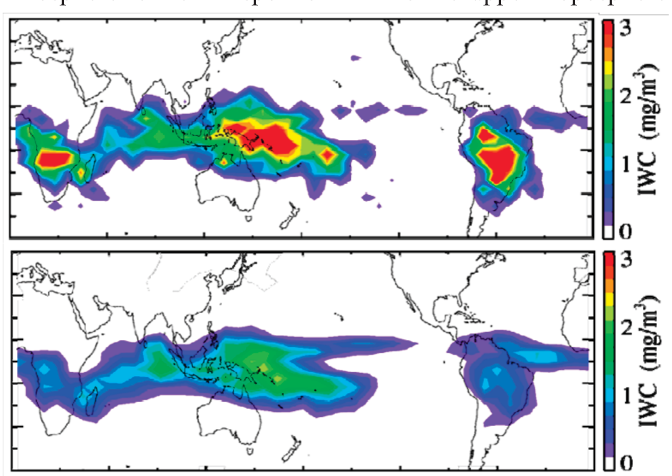

Fig. 2 Top: Aura MLS upper tropospheric cloud ice water content (IWC) January 2005 average. Bottom: ECMWF analyses for same period before model tunings justified by the MLS data [8].

by convective processes [5]. Ozone (one of the key components of air pollution) and its precursor species are very efficiently transported by deep convection. The high wind speeds in the upper troposphere, coupled with the longer ozone lifetime at these higher altitudes, lead to significant intercontinental transport of ozone-enriched air. Descent of this polluted air back to the boundary layer can have a significant impact on local and regional air quality [6], [7]. Radiometric observations of the upper troposphere give an unprecedented insight into the nature of these deep convective processes and the subsequent evolution of pollution plumes in the upper troposphere, furthering our understanding of boundary layer trace gas budgets. Remote sensing radiometers operating at the lower-end of the terahertz band improves our ability to weather and climate predictions. Measurements of cloud ice water contents at the upper troposphere play a critical role in this regard, as can be seen from Fig. 1. The 3-D mapping and high temporal resolution capability of the terahertz radiometer instruments provides the data needed for improving models and quantifying convective deposition. And cloud ice measurements indicate strength of convective events, while trace gas measurements quantify the amount of deposition.

III. SUBMILLIMETER WAVE INP HEMT TECHNOLOGY

In this sections, some highlights of InP HEMT integrated circuit technology as applied to Submillimeter Wave integrated circuits is described. A more detailed overview if the technology is provided in [4]. For InP HEMT to be a viable technology candidate at Submillimeter Wave frequencies, high gain levels must be available from the integrated circuits. Shown in **Fig. 3** is an integrated circuit designed for low noise amplification. At Submillimeter Wave frequencies, the 10-stage LNA area is only 0.25 mm^2. The amplifier itself has high gain, with a peak gain of approximately 30 dB reached at 670 GHz (**Fig.** 4).The amplifier has > 25 dB gain over a bandwidth of ~50 GHz

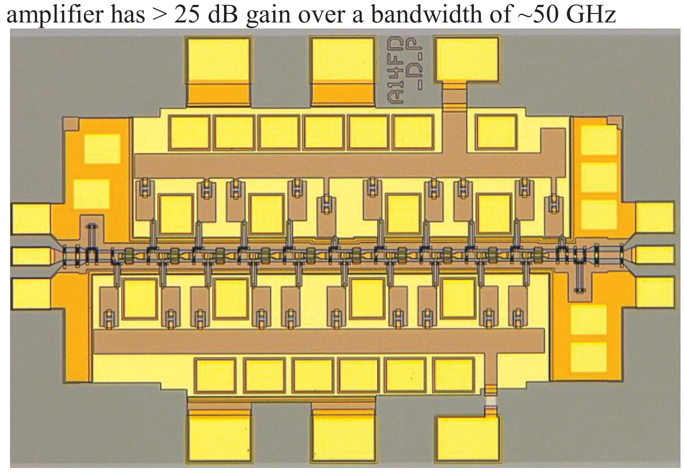

Fig. 3 Microphotograph of 10-Stage LNA designed to operate at 670 GHz.

A noise figure trend chart is shown in Fig. 5. This is similar to the chart in [4], with more recent noise temperature data added at the high end. Note that all of this data is taken on packaged InP HEMT amplifiers. In the range of 600-700 GHz, the noise temperature is ~ 4400 K measured at room temperature. Cooling will significantly improve noise temperature performance. Note that the noise temperature for these first generation InP HEMT low noise amplifiers is roughly

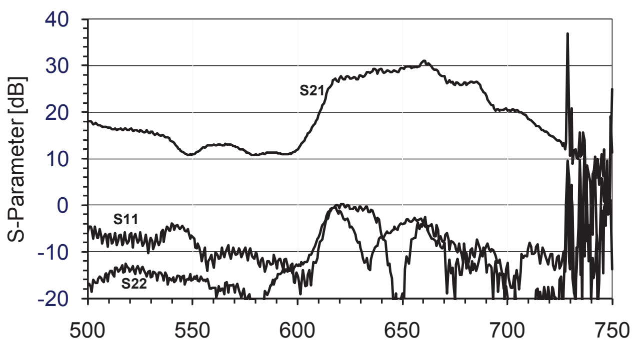

Fig. 4 Measured gain of 10-stage amplifier

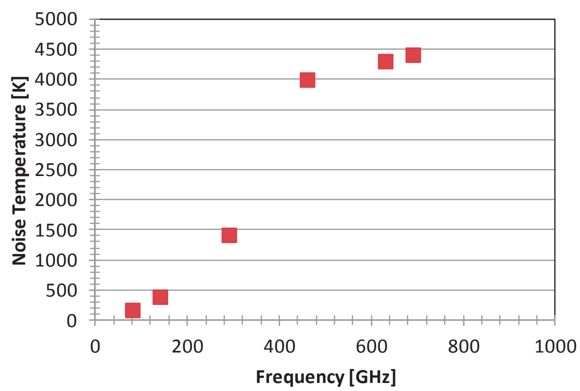

Fig. 5 Measured Noise Temperature of NGAS LNA's

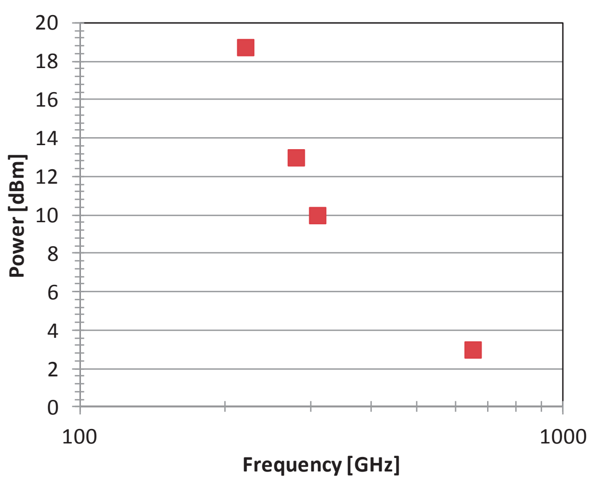

Fig. 6 Measured output power of packaged NGAS amplifiers.

comparable to GaAs Schottky mixers at the higher band. We expect additional improvements as the technology continues to advance.

Power amplification is another potential benefit in realizing efficient local oscillators. Currently, most LO multiplier chains use power amplifiers at or below W-Band. The power is then successively multiplied up to reach the requisite output frequency. By pushing power amplification considerably higher in frequency, the overall chain efficiency can be considerably improved. Shown in Fig. 6 measured output power of packaged amplifiers similar to the plot in [4]. Note that power at 220 GHz [9] and 640 GHz [10] has been added to the plot. A peak output power of 3 dBm has been demonstrated at 640 GHz. Taken with the low noise amplification, this shows that InP HEMT is a competitive front-end technology to ~650 GHz. With ongoing transistor scaling efforts, we expect both performance and frequency increases in the coming years.

Acknowledgement

This work was supported by the DARPA THz Electronics Program and Army Research Laboratory under the DARPA Contract no. HR0011-09-C-0062. The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. Approved for Public Release, Distribution Unlimited. The authors would like to thank Dr. John Albrecht and Dr. Mark Rosker of DARPA, and Dr. Alfred Hung of ARL. The second author acknowledges that some part of the work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, under a contract with the National Aeronautics and Space Administration.

References

[1] P. Siegel, "Terahertz Technology," *IEEE Trans. on Micr. Theo and Techn.*, vol. 50, no. 3, March 2002 pp. 910-928.
[2] R. Lai, X.B. Mei, W.R. Deal, W. Yoshida, Y.M. Kim, P.H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, A. Fung, "sub 50 nm InP HEMT device with Fmax greater than 1 THz," IEEE 2007 IEDM Conf. Dig., pp. 609-611, Dec. 2007.
[3] W.R. Deal, K. Leong, V. Radisic, S. Sarkozy, B. Gorospe, J. Lee, P.H. Liu, W. Yoshida, J. Zhou, M. Lange, R. Lai, X.B. Mei, "Low Noise Amplification at 0.67 THz Using 30 nm InP HEMTs," *IEEE MWCL*, Vol, 21, No. 7, pp. 368-370, Jul. 2011.
[4] W.R. Deal, X.B. Mei, K. Leong, V. Radisic, S. Sarkozy, R. Lai, "THz Monolithic Integrated Circuits Using InP High Electron Mobility Transistors," *IEEE Trans. THz Sci. and Techn.*, Vol, 1, No. 1, pp. 25-32, Sep. 2011.
[5] V. Ramaswamy, et al., "Radiative Forcing of Climate Change," Chapter 6 of Climate Change 2001: *The Scientific Basis, Cambridge University Press,* ISBN 0521 01495 6, 2001.
[6] D. J. Jacob, J.A. Logan, and P.P. Murti, "Effect of rising Asian emissions on surface ozone in the United States," *Geophys. Res. Lett.*, 26(14):2175-2178, 1999.
[7] O. Wild and H. Akimoto, "Intercontinental transport of ozone and its precursors in a three-dimensional CTM," *J. Geophys. Res.*, 106(D21):27,729-27,744, 2001.
[8] Li, J., H. L. Huang, C. Y. Liu, P. Yang, and T. J. Schmit, "Retrieval of cloud microphyiscal properties from MODIS and AIRS," J. *Appl. Meteorol.,* 44(10), 1526– 1543, 2005.
[9] V. Radisic, K.M.K.H. Leong, S. Sarkozy, X.B. Mei, W. Yoshida, P.H. Liu, and R. Lai "A 75 mW 210 GHz Power Amplifier Module," *IEEE CSIC Digest*, October, 2011.
[10] V. Radisic, K. M.K.H. Leong, X.B. Mei, S. Sarkozy, W. Yoshida, and W.R. Deal, "Power Amplification at 0.65 THz using InP HEMTs," to appear in *IEEE Transactions on Microwave Theory and Techniques.*