A W-band HEMT based power amplifier module for millimeter-wave LO multipliers

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ABSTRACT

We report on the performance of power amplifiers as local oscillator drivers for millimeter and submillimeter-wave heterodyne receivers. The noise properties of the MMIC amplifier in multiplied local oscillator chains are characterized by pumping a low noise superconductor-insulator-superconductor double slot heterodyne mixer at 386 GHz in the laboratory. A more sensitive measurement of noise contribution from the amplifier was performed with a 278 GHz SIS waveguide receiver at the Caltech Submillimeter-Wave Observatory by means of astronomical observations. It is concluded that the MMIC amplifier does not add noise to the radiometer system.

1. INTRODUCTION

A critical component of all heterodyne receiver systems is the local oscillator (LO) source that enables the mixing device to produce the intermediate frequency (IF) signal. Traditionally, in submillimeter-wave receivers a Gunn diode oscillator followed by the appropriate frequency multiplier has been used to provide the LO source. While this combination has worked well and technology development of Gunn devices [1], multiplier devices[2], and multiplier circuits[3] continues to improve LO sources, there are compelling reasons to look beyond Gunn oscillators as the fundamental source of power in the LO chain. One inherent limitation of Gunn diode circuits and transit-time device circuits is the very limited achievable electronic tuning bandwidth. For space-borne applications, it is desirable to have all frequency tuning performed electronically, without the potential of mechanical failure. There has been some effort in extending voltage tuning bandwidth of Gunn devices at W-band, but this has resulted in severely degrading the output power. Voltage controlled W-band Gunn oscillators with 10% bandwidth have been demonstrated, with output power degraded to 10 mW [4]. Moreover, each Gunn diode oscillator circuit requires individual tuning making it difficult to produce them in large quantities.

Recent advances in the upper frequency limit and output power of three terminal devices have now made it possible to consider them as an alternative to fundamental oscillator sources [5,6,7]. 50 micron thick substrate, 0.1 micron GaAs high electron mobility transistor (HEMT) technology has now yielded state-of-the-art MMIC power amplifiers at W-band that have output power as high as 0.3W [8]. Use of this technology as the highest frequency power generation source in a LO chain, raises questions about the noise contributions of the amplifier to the receiver by means of the LO injected signal. We examine the noise properties of low noise receivers pumped by a W-band MMIC power amplifier.

2. TECHNOLOGY

The W-band power amplifier was fabricated with a 0.1 μm gate length pseudomorphic AlGaAs/InGaAs/GaAs HEMT MMIC process on a 50 μm thick GaAs substrate. The process details are described in references [5] and [6] for the 0.1 μm GaAs HEMT and 50 μm substrate processes, respectively. 0.1 μm GaAs HEMT devices achieve cutoff frequencies as high as 200 GHz and up to 10 dB small signal gain at 94 GHz, suitable for W-band power operation [8]. 50 μm GaAs substrate thickness improves thermal conductivity, reduces device source inductance and compacts devices cells and matching structures to minimize circuit losses. The power amplifier was designed with a 64 finger output device cell and a total output periphery of 1.28 mm. This amplifier also includes on-chip bias networks and was matched to 50 ohm input/output lines. A photograph of the chip is shown in Figure 1.

The chip, 2300x1800 μm^2 in size, has been packaged in a split-waveguide block housing, based upon a University of Massachusetts [9] design. E-plane probes are used for input and output coupling between the waveguide and microstrip. Simple wire-bonds are used to connect the probes, which are fabricated on 75 μm thick Teflon, to the chip. Appropriate bypass capacitors are used to enable biasing of the chip without oscillations. Figure 2 shows the lower half of the split block with the MMIC chip in place.

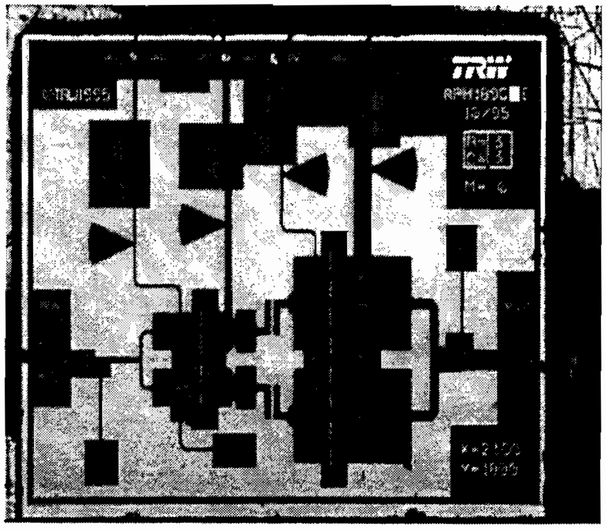


Figure 1: Photograph of the W-band monolithic power amplifier.

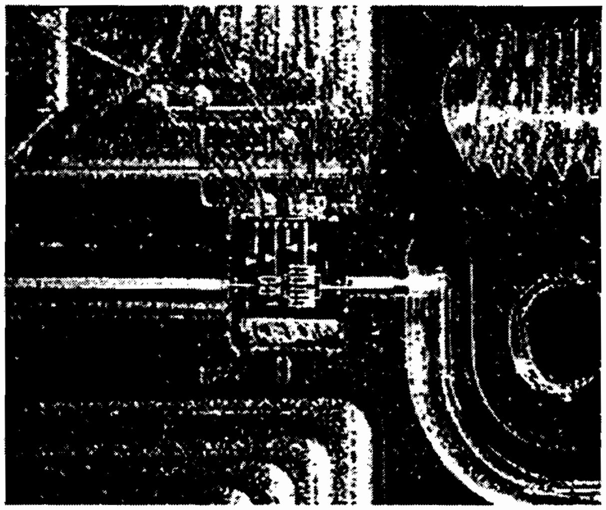


Figure 2: Photograph of the PA inside the lower half of the waveguide block.

The measured available small signal gain of the packaged PA is shown in Figure 3. The drains were biased at 3 volts with 280 mA of current while the gate voltages were held at 0 V for this particular measurement. The measurement was performed on a Hewlett-Packard 8510 vector network analyzer with custom millimeter-wave heads fabricated by Oleson Microwave labs.

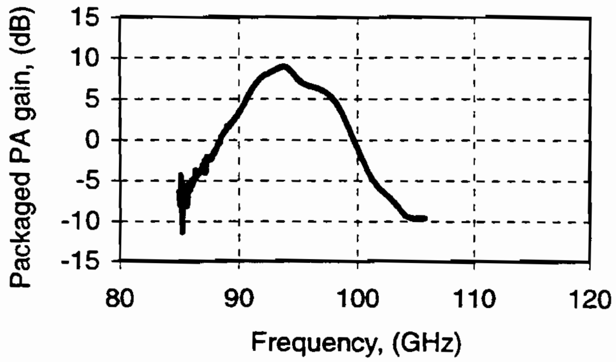


Figure 3: Measured small signal gain of the PA. Drain bias for both stages was 3 Volts at 280 mA total current. The gate voltage was 0 V.

A 75-110 GHz Backward Wave Oscillator (BWO) tube was used to provide an input signal to measure the frequency response of the PA under large signal conditions. The BWO was used because of the easy availability, wide bandwidth and high output power. However, for space borne applications a commercially available YIG based active multiplier will be used. The output power was measured with an Anritsu power meter and is shown in Figure 4.

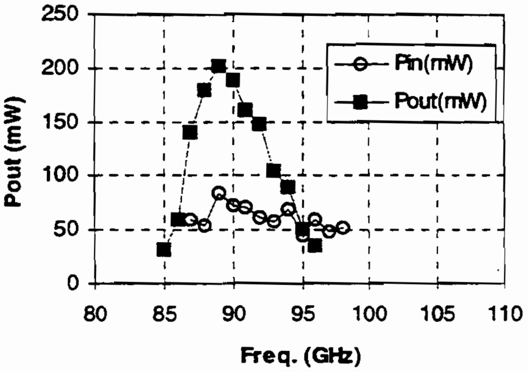


Figure 4: **Measured output power of the PA as a function of frequency. For maximum output power V_{d1}=1.5 V, I_{d1}=170 mA, V_{d2}=4 V and I_{d2}=400 mA.**

3. NOISE CHARACTERISTICS

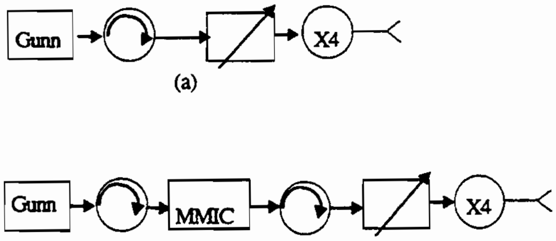
For low noise millimeter and submillimeter-wave radiometers, the noise added by the LO can cause serious degradation in the receiver sensitivity. Both AM and FM noise can be added by the LO source into the IF signal by means of the mixing process specifically, in the case of interferometers phase noise on the input of the mixer will result in degradation

The noise of HEMT transistors has been characterized as an input Johnson noise from input resistors at the quiescent operating temperature, and an output Johnson noise due to the drain-source resistance at an effective temperature proportional to the drain-source current density [10]. For the PA in the LO chain, both amplified input and output noises contribute to the total source noise. Typical values for the equivalent thermal noise at the output of the W-band PA could be higher than 5000 K. Propagation of this noise through the multiplication chain is difficult to calculate. A comparison of this noise relative to the noise of the high-Q cavity stabilized Gunn oscillator could be a critical design issue for low-noise receiver systems.

In addition to the thermal noise component, HEMT devices are well known to exhibit 1/f noise in the device transconductance. While unlikely, this noise can extend to high enough frequency to enter the receiver IF band (1-2 GHz or higher), fluctuations in the LO power could reduce the sensitivity of the receiver in an observing situation. The purpose of our initial investigation is to understand the noise properties of the MMIC PA applied to sensitive heterodyne receivers. Two experiments have been carried out.

In the initial experiment, a laboratory version of a superconductor-insulator-superconductor

(SIS) double slot antenna quasi optical mixer operating at 386 GHz was used [11]. The mixer LO utilizes a free running Gunn diode at 96.7 GHz followed by a Schottky diode quadrupler. The mixer noise temperature was measured with two different LO configurations as shown in Figure 5.



(a)

(b)

Figure 5: LO chain configuration (a) with the Gunn diode oscillator, (b) with the MMIC PA inserted into the LO chain.

In both cases, the pumped current through the SIS junction was monitored and kept constant. In configuration (a), the standard operating mode, a receiver noise temperature of 219-222 K was measured. In configuration (b), inserting the PA with level setting attenuators and isolators between the Gunn oscillator and multipliers, a noise temperature of 217-214 K was measured. Additionally, in a third configuration, a waveguide bandpass filter (92-96 GHz) was added between the MMIC amplifier and the second isolator for the purposes of limiting the amplifier noise available to the RF passband. This resulted in a possible marginal reduction in the noise temperature, measured to be 208-210 K. In either case, the application of a driver amplifier does not appear to degrade the noise temperature of the SIS receiver. In fact we consistently measured (by going back and forth between A and B) a very slight receiver noise reduction when the power amplifier is inserted.

With this encouraging result we continued our investigation with a more sensitive waveguide receiver at the Caltech submillimeter-wave observatory at Mauna Kea, Hawaii. This also provided us the opportunity to examine the effect of putting an amplifier in the LO chain for astronomical observations. A 278 GHz SIS receiver [12] was used to observe the Methanol (CH_3OH) line in the Orion-South Nebula. The initial LO chain configuration is shown in Figure 6 (a). The Gunn was phase locked and a receiver noise temperature of 22.5 K +/- 1 K (double side band) was measured using hot and cold loads. The observation was done with an integration time of 400 seconds and a number of scans were taken for accuracy. The telescope was then pointed off the source for calibration and to get a measure of the noise floor. The MMIC amplifier was then inserted into the LO chain as shown in Figure 6 (b). The measured noise temperature of the receiver was 21.3 K +/- 1K double side band while keeping identical SIS current to the measurement with the Gunn diode. The same observation of the Orion Nebula with identical integration time and scans was carried out. Figure 7 shows the measurement of the Methanol line, both with and without the power amplifier. As can be seen there is no discernible line broadening and the noise floor in both cases is the same. Figure 8 shows the noise floor fluctuations from the two different LO configurations, again indicating no major discrepancy.

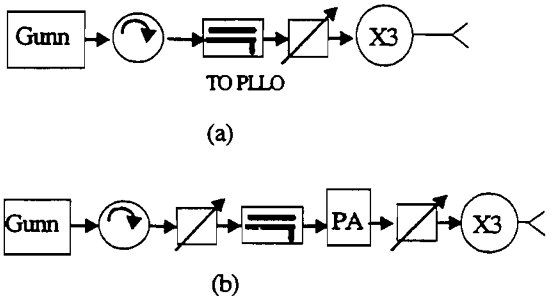


Figure 6: LO chain configuration at the CSO with and without the PA. A second isolator between the PA and the multiplier would have been desirable since some standing wave problems were observed. However given the mounting mechanics, we were unable to do so.

4. CONCLUSION

Sensitive heterodyne receivers have been used to investigate the noise properties of an HEMT based power amplifier as a driver for LO chains. Based on the measured receiver noise temperatures and the amplitude and shape of the measured signal from the Orion Nebula it is concluded that the noise added to the local oscillator chain by the use of a MMIC solid state power amplifier is insignificant for single dish operation.

5. ACKNOWLEDGMENTS

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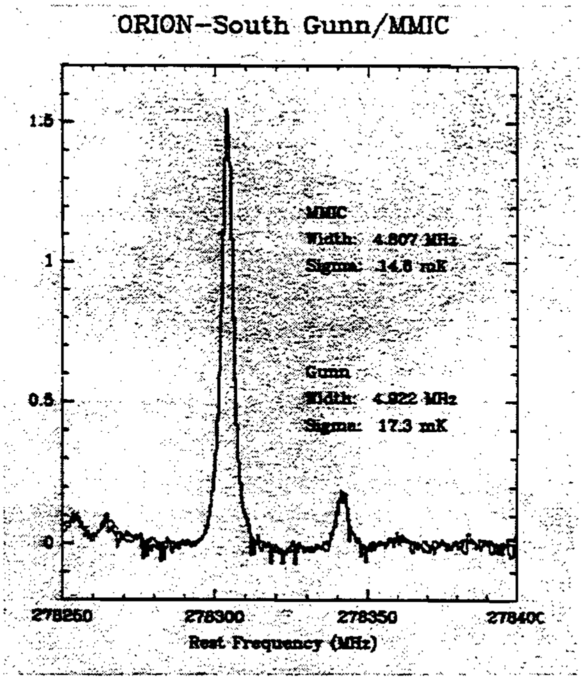

Figure 7: Observation of the Methanol line in the Orion Nebula with the two different LO chains as shown in Figure 6. Addition of the PA does not deteriorate the observation.

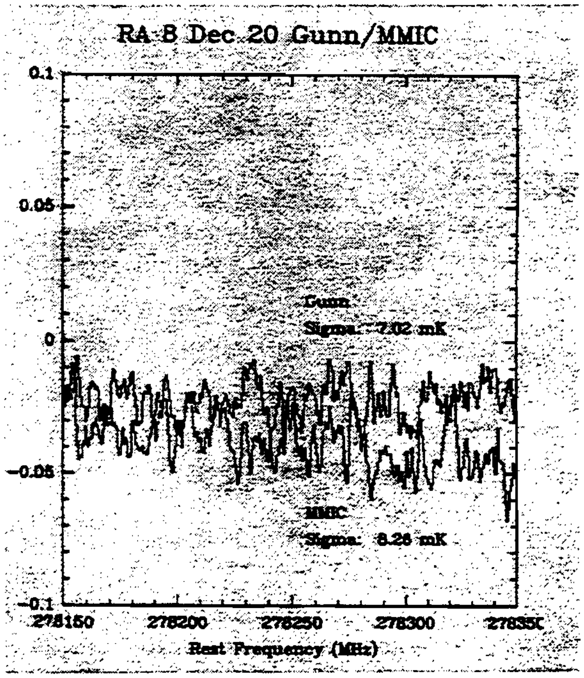

Figure 8: The above signals are obtained when the telescope is pointed to a dark sky target.

6. REFERENCES

1. H. Eisele and G. I. Haddad, "Two-Terminal Millimeter-Wave Sources, " to appear in MTT-46, 1998.
2. R. Peter Smith, et. al, "Advances in Submillimeter Wave semiconductor-based device designs and processes at JPL," 8th International Space Terahertz Symposium, Boston 1997.
3. N. Erickson, work to be presented at the 9th International Space Terahertz Symposium, Pasadena, 1998.
4. N. N. (Watkins-Johnson Co.): "W-band Varactor-Tuned Oscillators with 10 GHz Bandwidth", Microwave Journal, Vol. 33, no. 10, 1988, pp. 137-140.
5. M. D. Biedenbender et al., "A 0.1-um W-band HEMT production process for high yield and high performance low noise and power MMIC's," in 16th Annul. IEEE GaAs IC Symposium Digest, Philadelphia, PA, Oct. 1994, pp. 325-328.
6. R. Lai et. al. "A High Efficiency 0.15 μm 2-mil Thick InGaAs/AlGaAs/GaAs V-band Power HEMT MMIC", IEEE GaAs IC Symposium Digest, pp. 225-227, Orlando, FL, Nov. 1996.
7. H. Wang et al., "A W-band monolithic 175 mW power amplifier," in 1995 IEEE MTT-S Int. Microwave Symposium Digest, Vol. 2, Orlando, FL, pp. 419-421.
8. P. P. Huang, et. al, "A 94-GHz 0.35-W Power Amplifier Module," IEEE-MTT vol. 45, no. 12, December 1997, pp. 2418-2423.
9. Y. C. Leong and S. Weinreb, "Design and simulation of W-band microstrip-waveguide transition using HFSS and MDS," University of Massachusetts technical report, May 30th, 1997.
10. M W. Pospieszalski, "Modeling of Noise Parameters of MESFET's and MODFET's and their frequency and temperature dependence," IEEE-MTT Vol. 37, number 9, September 1989, p. 1340.
11. J. Zmuidzinas and H. G. LeDuc, "Quasi-Optical Slot Antenna SIS Mixers," IEEE MTT-40, No. 9, September 1992.
12. J. Kooi, M. Chan, B. Bumble, H. G. LeDuc, P. Schaffer, and T. Phillips, "230 and 492 GHz Low-noise SIS wave-guide receivers employing tuned Nb/AlOx/Nb Tunnel-junctions," International Journal of Infrared and Millimeter Waves, v16 912), pp. 2049-2068, December 1995.