CHARACTERISTICS OF BROADBAND InP MILLIMETER-WAVE AMPLIFIERS FOR RADIOMETRY

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Abstract— **The performance of InP HEMT (High-Electron Mobility Transistor) amplifiers is characterized in a direct detection 3.8 mm receiver over a temperature range of 50 to 300 K. The effects of low frequency noise up-conversion are observed in the total power response. The measured spectrum of gain fluctuations at room temperature is characterized by $\delta g_n^2(f) \simeq (1\,\mathrm{Hz}/f)^{\alpha}\,\delta g_o^2$, with an index $\alpha \simeq 0.9$ and $\delta g_o^2 \simeq 6\times10^{-9}\,\mathrm{Hz}^{-1}$ per device used in the amplification chain. When the devices are cooled to 50 K, δg_o^2 increases by a factor of ~ 5. The measured receiver sensitivity is 3 mK $\mathrm{Hz}^{-1/2}$ at an ambient temperature of 300 K and 0.8 mK $\mathrm{Hz}^{-1/2}$ at 50 K. The measured sensitivity at room temperature is the best reported for a HEMT direct detection receiver in the 3 mm atmospheric window. At 50 K the observed receiver sensitivity is competitive with the performance of sub-Kelvin bolometric detectors or SIS junctions used for direct detection.**

Introduction

The modest cooling requirements of low-noise large-instantaneous bandwidth HEMT receivers have enhanced their desirability for radio astronomy applications. The continuation of this trend into the millimeter regime has opened interesting possibilities for the design of radiometric imaging systems. The primary objective of this study is the characterization of InP HEMT amplifier stability. The reported parameters are crucial in specifying the system requirements for the detection of broadband continuum radiation with these devices.

Similar investigations of amplifier stability with GaAs and InP/GaAs HEMTs at lower frequencies can be found in Jarosik (1996), Monnelly (1996), and Wollack (1995). Previous 3 mm HEMT direct detection radiometers with lower sensitivity are described in Gaier *et al.* (1996), Dow *et al.* (1996), Kane *et al.* (1995), and Lo *et al.* (1995).

Radiometer Noise and Stability

By design, the voltage response of a radiometer in the Rayleigh-Jeans limit is a linear function of the incident noise power,

$$V_{\mathrm{dc}} = (k_{\mathrm{b}}\,T_{\mathrm{sys}}\,\Delta\nu_{\mathrm{rf}})\;R\,G_{\mathrm{rf}}\,G_{\mathrm{video}} \qquad (1)$$

where $k_{\mathrm{b}} \simeq 1.4\times10^{-23}\,\mathrm{J/K}$, T_{sys} is the system temperature, and $\Delta\nu_{\mathrm{rf}}$ is the effective rf bandwidth. The rf gain G_{rf}, square-law detector responsivity R, and video gain G_{video} operate in their respective linear regimes. Sufficient rf gain and detector responsivity must be present for the first stage noise to dominate the contributions from the square-law detector and subsequent post-detection electronics. [1]

In the presence of gain fluctuations, we employ the following parameterization for the radiometer's voltage spectral density δV, in Volts $\mathrm{Hz}^{-1/2}$:

$$\frac{\delta V}{V_{\mathrm{dc}}} = \frac{\delta T}{T_{\mathrm{sys}}} = \kappa_o \left(\frac{2}{\Delta\nu_{\mathrm{rf}}} + \left(\frac{\Delta T_{\mathrm{offset}}}{T_{\mathrm{sys}}}\right)^2 \delta g^2(f) \right)^{1/2}, \qquad (2)$$

where κ_o is the demodulation efficiency (Dicke, 1946), $\Delta T_{\mathrm{offset}}$ is the offset from a balanced output, and $\delta g(f)$ is the radiometer's total noise spectral density of the gain fluctuations as a function of video frequency. A simple power law dependence with frequency is observed for the gain fluctuation in HEMTs $\delta g^2(f) \simeq (1\mathrm{Hz}/f)^{\alpha}\;\delta g^2$, where δg^2 is the amplitude and $\alpha \simeq 0.9$ is the spectral index (Wollack, 1995). After calibration, it is convenient to express the sensitivity in terms of the noise spectral density δT, in $\mathrm{mK\,Hz}^{-1/2}$.

For a direct detection receiver, $\kappa_o \equiv 1$ and $\Delta T_{\mathrm{offset}}/T_{\mathrm{sys}} = 1$. From Equation 2, one notes that for such a receiver in the narrow bandwidth limit the ratio of spectral density to the mean signal output approaches a constant magnitude, $\delta V/V_{\mathrm{dc}} = \sqrt{2/\Delta\nu_{\mathrm{rf}}}$. In the wide bandwidth limit, the radiometric offset and gain stability determine the effective spectral density, $\delta V/V_{\mathrm{dc}} = (1\mathrm{Hz}/f)^{\alpha/2}\,\delta g$. The so-called "knee" or "corner" frequency in the radiometer response, $f_{\mathrm{knee}} \sim (\Delta\nu_{\mathrm{rf}}\,\delta g^2/2)^{1/\alpha}$, occurs at the transition between these two regimes.

Measured Radiometer Performance

A direct detection receiver was fabricated with cascaded E- and W-band amplifiers mounted on the 50 K stage of a CTI 1020 refrigerator (see Figure 1 for the receiver configuration). Both amplifiers were five stage $0.1\times50\mu\mathrm{m}^2$ un-passivated T-gate InP HEMTs. A detailed description is given in Pospieszalski *et al.* (1995, 1997) and Nguyen *et al.* (1993). The bandpass was defined by a filter external to the dewar. The effective bandwidth of the three configurations tested, 3, 6, and 20 GHz, was determined by measurement

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[1] In addition, it is assumed that any voltage offset in the video frequency electronics is small compared to radiometer output voltage and stable in time. In practice, this condition is readily achievable.

of the individual components in the system with a scalar network analyzer. A Millitech DXP-10 zero bias detector was used for square-law detection with $R \simeq 1100\,\mathrm{mV/mW}$ (input rf power level: $-20\,\mathrm{dBm}$).

The system temperature was measured with a feed horn viewing a hot/cold load through a mylar vacuum window. The voltage offset due to the diode video preamp was $< 10^{-3}$ of V_{dc} and stable. The measured receiver noise was $300 \pm 10\,\mathrm{K}$ at room temperature and $80 \pm 10\,\mathrm{K}$ when cooled to a physical temperature of 50 K. The measured receiver sensitivity was $3\,\mathrm{mK\,Hz^{-1/2}}$ at an ambient temperature of 300 K and $0.8\,\mathrm{mK\,Hz^{-1/2}}$ at 50 K for video frequencies $\gg$ 10 KHz and an effective rf bandwidth of 20 GHz. In all three configurations tested, the noise at a video frequency of 100 KHz was within $\sim 5\%$ and consistent with the measurement uncertainty of the magnitude computed from the system temperature and effective bandwidth.

A waveguide termination was instrumented with a silicon temperature sensor, a nichrome heater resistor, and a weak thermal link to the 15 K cold station. This arrangement provides a stable source for system gain stability and system temperature measurement. The cold load was attached to the input amplifier flange via a 4 cm section of stainless steel waveguide (attenuation: $0.55 \pm 0.1\,\mathrm{dB}$). Broadband measurements of T_{sys} were repeated in this configuration. The observed increase mean receiver noise power was consistent with the measured attenuation and the computed temperature distribution under the assumption that the loss is uniformly distributed along the guide.

The radiometer's low frequency power spectrum was characterized with a Hewlett Packard 3561A Dynamic Signal Analyzer and the results are shown in Figure 2. The observed magnitude of the spectral density of gain fluctuations is independent of the rf bandwidth. The noise floor of the test set was characterized in the following states: 1) the rf receiver power off and the video preamp connected to the diode, 2) the preamp terminated in the video detector impedance, and 3) a typical diode output level and video impedance simulated with a mercury battery and resistor. The test set's noise power was, within the measurement error, the same in all three states.

A correction, dependent on video frequency, of $<$ 0.5 dB was applied to the recorded data to account for the frequency response of the video frequency preamp. For frequencies $> 1\,\mathrm{Hz}$, the spectral measurements were repeated with the radiometer output ac coupled to the analyzer. The results agree within the statistical error of the measurement. Variations in the HEMT bias, LED illumination, and thermal environment have an insignificant contribution to $\delta g^2(f)$ over the range of parameters investigated. The spectral density of gain fluctuations observed as a function ambient temperature is plotted in Figure 3.

Discussion

The modulation rate required to achieve the thermal or "white" noise limit in the presence of gain fluctuations can be readily computed from Equation 2. The result for the radiometer chain operating at $\sim 50\,\mathrm{K}$ is summarized in Figure 4. It is important to note that the overall stability of the amplification chain can be improved by a factor of a few by appropriate device bias and proper distribution of gain between cryogenic and room temperature amplifiers.

From a system perspective, substantial improvement in stability can be achieved through the design of the receiver architecture. Since the maximum switch rate in many practical implementations is essentially predetermined (a quasi-optical modulator the switch rate is typically $< 100\,\mathrm{Hz}$, *etc.*) operating the receiver in a balanced configuration is desirable. A true rf multiplier (*e.g.,* a correlation-type receiver) with post-detection offset small compared to the system noise is preferred to a differencing-type or Dicke receiver in mitigating the effects of gain fluctuations. This can be seen by considering the effective noise produced by variations in the gain acting on the mean radiometric offset. For similar reasons, rapid calibration and pilot signal stabilization schemes present difficulties in achieving substantial stability improvements.

Conclusions

The stability and noise of InP HEMT amplifiers for use in a radiometric detector are presented. The measured room temperature sensitivities are the best reported for a direct detection receiver employing this technology in the 3 mm atmospheric window. At a physical temperature of 50 K, the measured receiver sensitivity is competitive with the cryogenic performance of sub-Kelvin bolometric detectors or SIS (Superconductor-Insulator-Superconductor) junctions used in a direct detection mode.

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References

[1] Dicke, R., "The Measurement of Thermal Radiation at Microwave Frequencies," 1946, *Rev. Sci. Instrum.* vol. 17, no. 7, pp. 268–275.

[2] Dow, G.S., *et al.,* "Large Scale W-Band Focal Plane Array for Passive Radiometric Imaging," June 1996, *IEEE MTT-S Int. Microwave Symp. Digest*, San Francisco, California, pp. 369-372.

[3] Gaier, T., *et al.,* "Noise Performance of a Cryogenically Cooled 94 GHz InP MMIC Amplifier and Radiometer," *1996 Proc. SPIE Conf.*, vol. 2842, pp. 46-54.

[4] Jarosik, N.C., "Measurement of the Low-Frequency-Gain Fluctuations of a 30-GHz High-Electron-Mobility-Transistor Cryogenic Amplifier," 1996, *IEEE Trans. Microwave Theory Tech.*, vol. 44, no. 2, pp. 193–197.

[5] Kane, B., Weinreb, S., Fischer, E., and Byer, N., "High-Sensitivity W-Band MMIC Radiometer Modules," May 1995, *IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Digest*, Orlando, Florida, pp. 59–62.
[6] Lo, D.C.W., *et al.,* "MMIC-Based W-Band Dicke Switched Direct-Detection Receiver," 1995, *IEEE GaAs IC Symp. Digest*, San Diego, California, pp. 226–229.
[7] Monnelly, G.P., "An Instrument for Investigation of the Angular Power Spectrum of Anisotropies in the Cosmic Microwave Background," 1996, Thesis, Princeton University, Physics Department.
[8] Nguyen, L.D., *et al.* "Manufacturability of 0.1-μm Millimeter-Wave Low-Noise InP HEMT's," *Proc. 1993 IEEE MTT-S Int. Microwave Symp.*, Atlanta, GA, pp. 345–347.
[9] Pospieszalski, M.W., *et al.,* "Q and E Band Cryogenically Coolable Amplifiers Using AlInAs/ GaInAs/InP HEMT's," May 1995, *Proc. IEEE MTT-S Int. Microwave Symp. Digest*, Orlando, FL, pp. 1121–1124.
[10] Pospieszalski, M.W., *et al.,* "Millimeter Wave Waveguide Bandwidth Cryogenically-Coolable InP HEMT Amplifiers," June 1997, *IEEE MTT-S Int. Microwave Symp. Digest*, Denver, CO, pp. 1285-1288.
[11] Wollack, E.J., "High-Electron-Mobility Transistor Gain Stability and its Design Implications for Wide Band Millimeter Wave Receivers," 1995, *RSI*, vol. 66, no. 8, pp. 4305–4312.

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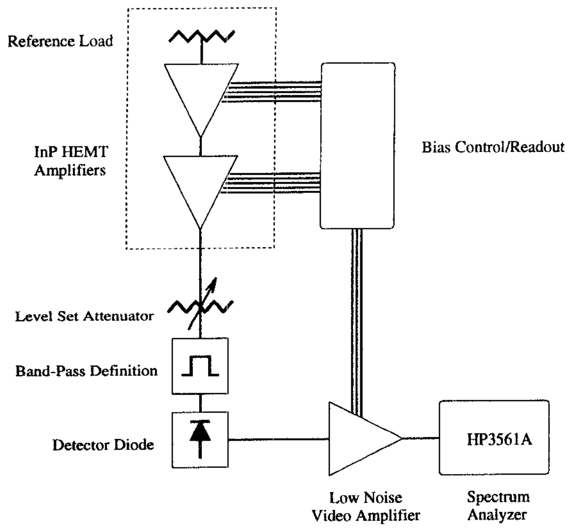

Fig. 1. Receiver stability test configuration. The InP amplifiers and the reference load are thermally isolated and cooled by a closed-cycle He refrigeration system. The reference load provides a stable input signal for the receiver; its temperature can be monitored and varied to determine the system noise. The attentuator is used to maintain a constant power level at the square-law-detector as the reference temperature and system bandwidth are varied.

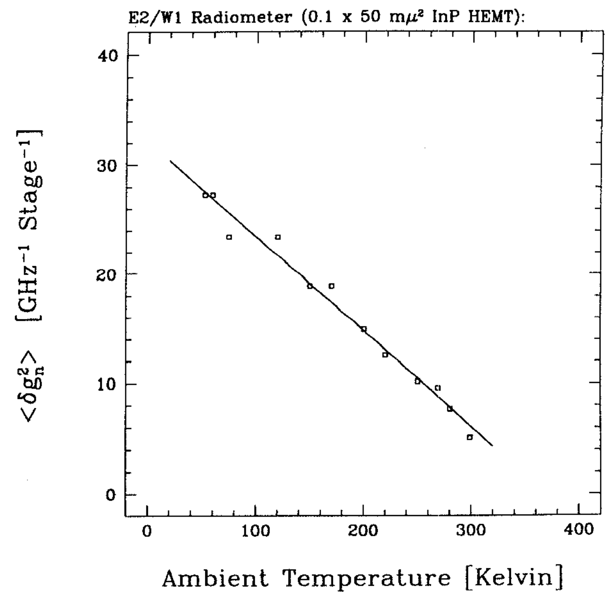

Fig. 3. Low noise bias device gain stability as a function of ambient temperature.

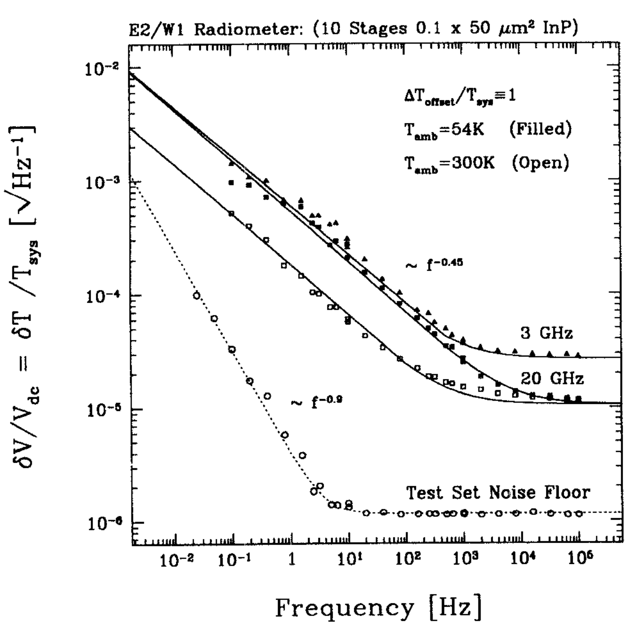

Fig. 2. The power spectra of the radiometer output. The filled symbol data were taken at a physical temperature of 54 K, the indicated effective rf bandwidths, and a low noise bias. The open symbol data were taken at a physical temperature of 300 K, a 20 GHz rf bandwidth, and devices biased for maximum g_m. The dashed line and open circles indicate the noise floor of the test set. The data is taken in three interleaved frequency spans (f_{max}:f_{min}=250:1) and equal record length.

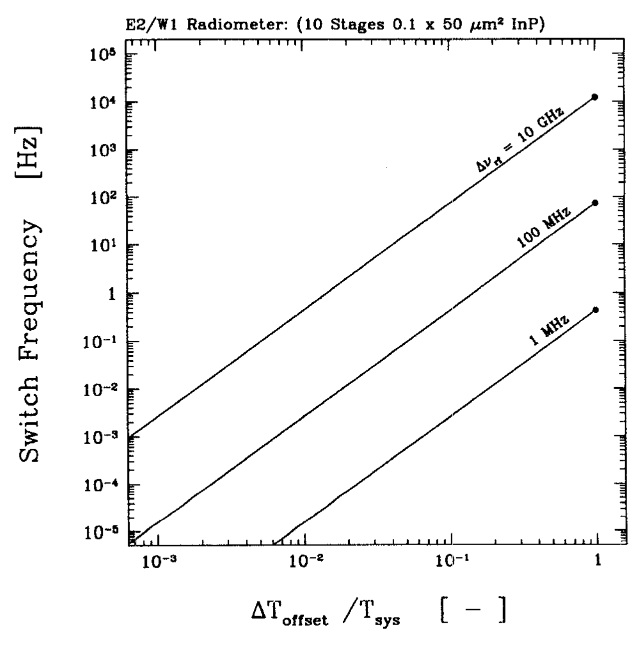

Fig. 4. Required switch frequency as a function of radiometer offset. The measured spectral index and density of gain fluctuations are used to estimate the switching frequency required to limit the noise contribution due to variations in the radiometer gain to 10% of the system noise. The filled dots indicate the switch frequency for a differencing or subtraction-type radiometer. The solid lines indicate the calibration rate required in a correlation or multiplication-type receiver as a function of the deviation from a balanced output.