# Noise Performance of a Cryogenically Cooled 94 GHz InP MMIC Amplifier and Radiometer

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## ABSTRACT

We have developed an ultra-low noise 94 GHz MMIC amplifier using InGaAs/InAlAs/InP transistor technology. The MMIC designs incorporate a single transistor stage with input and output matching networks as well as gate and drain bias networks. Two MMICs have been incorporated into a single housing providing 10 dB of gain. At room temperature, the integrated amplifier has a measured noise of 365 K (3.5 dB) at 94 GHz. Cryogenic measurements have been performed using a direct detection total power radiometer with all amplification provided by MMIC amplifiers. The noise figure for the entire radiometer has been measured to be 78 K (1.01 dB). The noise figure for the cryogenic InP MMIC 2-stage amplifier unit has been measured to be 51 K (0.69 dB) with a low power consumption of 0.84 mW per stage. The stability of the radiometer with a 4 GHz bandwidth, is characterized by a power spectrum with a "1/f knee" frequency of 45 Hz.

*Keywords*: low-noise amplifiers, millimeter wave technology, monolithic circuits

## 1. INTRODUCTION

Recent advances in device technology have led to a new generation of millimeter-wave amplifiers operating with low noise at high frequencies. The availability of amplifiers at frequencies as high as 140 GHz has broad implications in the areas of communications, remote sensing and high speed data transmission, while cryogenic operation of low noise amplifiers has yielded noise performance which is unmatched at frequencies as high as 50 GHz[1]. This technological advance has already transformed the field of radio astronomy by providing ultra-low noise broadband receivers which are straightforward to design and build and have modest cryogenic requirements, reducing cost and enhancing reliability.

Advances in high electron mobility transistors (HEMTs , a.k.a. MODFETs, HFETs) have now enabled low noise amplifiers to become competitive with other detection technologies at frequencies higher than 100 GHz. InGaAs/InAlAs/InP HEMT technology has demonstrated the best low-noise performance at millimeter-wavelengths for any three terminal device. Room temperature amplifiers using InP HEMTs have demonstrated record performance of 121 K (1.5 dB) noise at 45 GHz and 335 K (3.3 dB) noise at 94 GHz [2]. Cryogenic operation of InP based amplifiers has resulted in measured noise performance of 10K (0.15 dB noise ) at 32 and 40 GHz [3], and 50 K at 75 GHz [4].

InP HEMT monolithic microwave/millimeter-wave integrated circuits (MMICs) offer several advantages over hybrid circuit designs. Amplifier fabrication is simplified by the elimination of tunable elements, and the reduction of the number of micro-assembled parts. They are mechanically robust and well suited for space applications. At higher frequencies MMIC designs offer the advantages of the reduction of parasitic inductance associated with wire bonding, and the dimensional control afforded by the use of semiconductor manufacturing processes. InP MMIC amplifiers have also demonstrated record performance, with measured 172 K (2.0 dB) noise at 44 GHz [5], 335 K (3.3 dB) noise at 94 GHz, and an unprecedented 9 dB gain at 140 GHz [6], all at room temperature. Results have previously been reported, in

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which cryogenic operation of MMIC amplifiers has yielded 25 K (0.35 dB) noise at 44 GHz [7] and 100 K (1.27 dB) noise at 100 GHz [8].

The following sections describe the design, fabrication and measured performance of a 94 GHz InP MMIC low noise amplifier (LNA). This work was carried out to demonstrate the technology for the Primordial Structures Investigation (PSI), a proposed NASA mission to map the cosmic microwave background. Included are room temperature and cryogenic measurements of the amplifier and the entire test radiometer noise and stability, the latter of which is critical for radiometric measurements. This result represents a new record low noise performance at 94 GHz . The radiometer exhibits excellent gain stability, even under very low power bias conditions.

## 2. InP HEMT DEVICE STRUCTURE AND PROCESSING

The baseline epitaxial InGaAs/InAlAs/InP HEMT structures are shown in Figure 1. The InP HEMT structure is grown on two inch semi-insulating InP substrate. The channel layer for the data presented in this paper is a pseudomorphic InGaAs layer with an indium composition of 0.65, employed to achieve very high mobility and velocity of electron carriers in the channel. A planar doped silicon donor layer in the InAlAs is employed to improve device aspect ratio, transconductance ($g_m$) , carrier confinement and breakdown compared to the uniformly doped design. Typical room temperature mobilities greater than 10,500 $cm^2/V$-sec and sheet carrier concentrations of $3.0x10^{12}$ $cm^{-2}$ are measured on these InP HEMT structures. A key element in the layer structure design is a thick, highly doped InGaAs cap layer which minimizes the source resistance (typically less than 0.3 ohm-mm at room temperature) and minimizes the effective gate length of the device, resulting in high device gain and cutoff frequency.

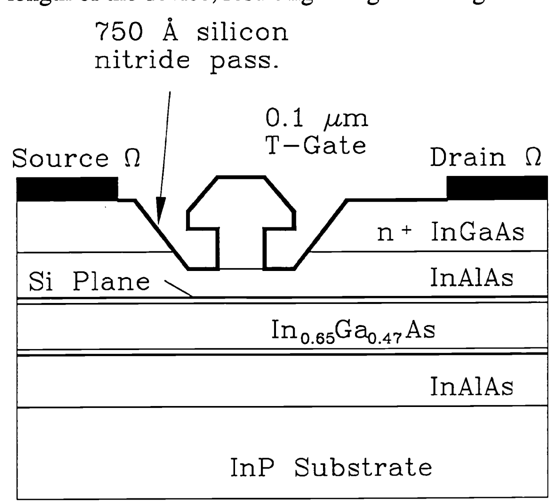


Figure 1. The 0.1 micron InGaAs/InAlAs/InP HEMT device profile.

The InP HEMT MMIC fabrication process has been described previously in detail[2]. The key features are 0.1 μm length Ti/Pt/Au gates defined by electron-beam lithography, 750Å total silicon nitride passivation over the InP HEMT devices and metal-insulator-metal (MIM) capacitors. The wafers are subjected to a stabilization bake of 200°C for 72 hrs. The wafers are subsequently backside lapped to 75 μm thickness and wet-etched via holes are defined with a bottom diameter less than 100 μm. 4 μm Ti/Au metal is then sputtered and plated onto the backside of the wafer.

The devices fabricated for this work exhibited greater than 800 mS/mm device transconductance, 160 GHz cutoff frequency and 300 GHz maximum oscillation frequency at 1.0V drain bias (Vd). One of the key device features for optimum cryogenic operation and for ultimate low noise performance is high gain at low drain bias and low drain current levels. Cryogenic DC device parameters were measured for the 4-finger 40 μm gate devices in this MMIC and are shown in Figure 2. The I-V curves are well behaved and exhibit sharp pinch-off. $g_m$ is greater than 25 mS for $V_d$ as low as 0.3 V and $I_d$ as low as 2 mA, indicating excellent performance at low power.

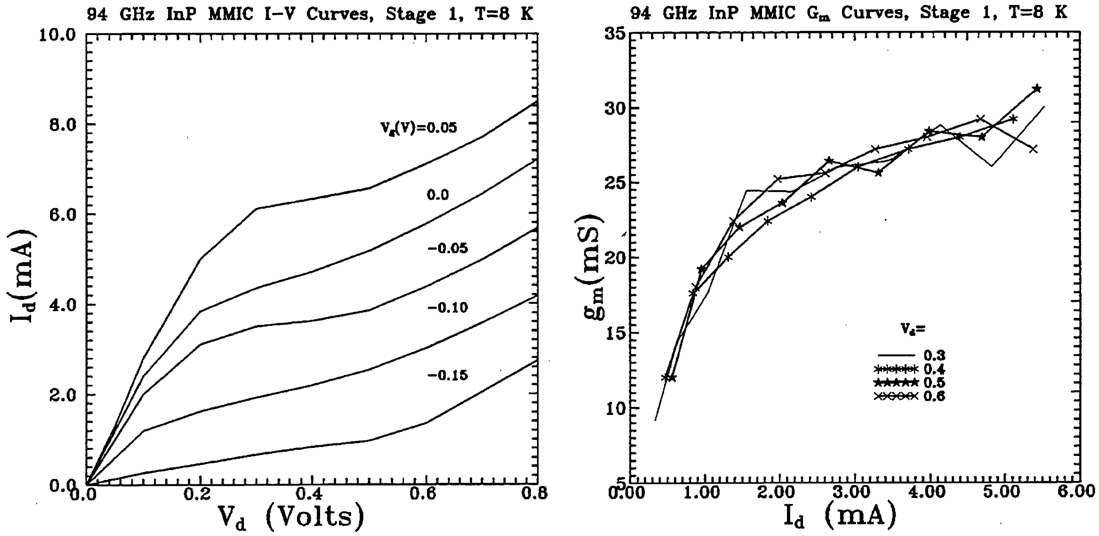


Figure 2 a) Measured cryogenic I-V characteristics for the InP first stage device; b) $g_m$ measurements for the same device.

## 3. DEVICE MODELING, CIRCUIT DESIGN AND PERFORMANCE

The MMIC amplifiers use four fingered, 40 µm gate periphery HEMTs. S-parameter measurements of discrete devices are performed up to 50 GHz and, by curve fitting, the linear small signal equivalent circuit parameters are obtained. By fitting the measured noise parameters through 40 GHz , the noise model [9] parameters that are used for the simulations are obtained. The resulting model parameters are consistent with the estimated values based on the device parameters and physical dimensions.

Figure 3 shows a photograph of the single-stage MMIC amplifier chip with a size 1.25×1.8 $mm^2$. The circuit topology and design methodology of these chips are similar to previously published W-band MMIC LNAs [10,11]. Matching networks are constructed by cascading high-low impedance microstrip lines on the 75 µm thick substrate. MIM capacitors are used for DC blocking and radial stubs are employed for RF bypass. Shunt RC networks are included in the bias networks for amplifier stability. The design/analysis procedures for this monolithic chip design, which utilize full-wave electromagnetic analysis have been previously documented [12].

The amplifier module constructed utilizes two cascaded single stage MMIC amplifier chips, with WR-10 waveguide input and output. Figure 4 shows a photograph of the assembled amplifier module. To couple the RF signal from the waveguide to the microstrip, E-plane waveguide-to-microstrip probe transitions were developed and fabricated on 0.005 inch thick fused silica substrate. The transitions demonstrate 0.4 dB insertion loss with 16 dB return loss. The transitions are part of the assembled amplifier, and no corrections are made for the losses. At room temperature the assembly has a noise figure of 365 K (3.5 dB) and a gain of 10 dB from 92 to 96 GHz.

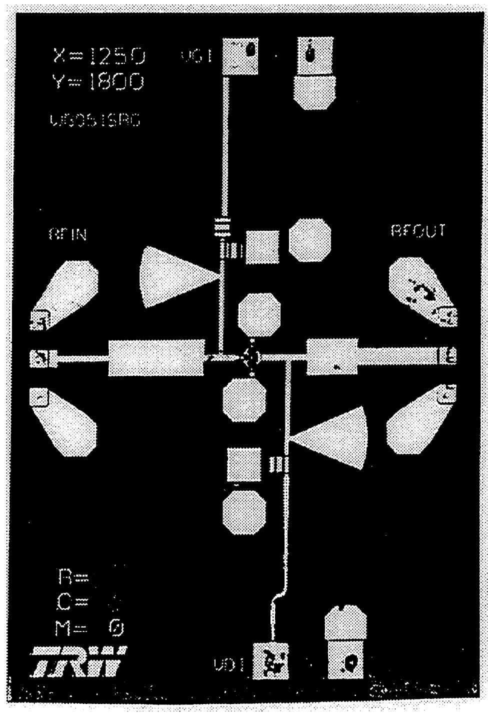


Figure 3. Photograph of single stage InP MMIC amplifier.

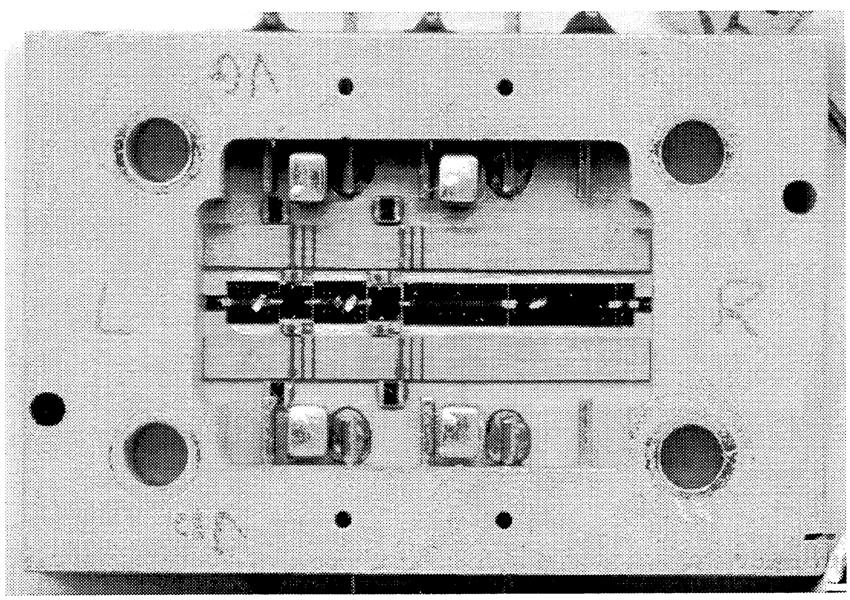

Figure 4. Photograph of the InP amplifier assembly. The amplifier uses two single stage MMIC chips (pictured in Fig. 3).

## 4. THE CRYOGENIC TEST SET

Figure 5 is a schematic of the cryogenic test set. This direct detection system enables simultaneous measurements of radiometer noise and stability. The cryostat uses $He^4$ to provide a thermally stable cryogenic environment. The waveguide termination assembly consists of a WR-10 waveguide termination in a copper block with a heater resistor and silicon diode temperature sensor attached directly to the waveguide. The block is thermally sunk to the 4.2 K cold plate with a copper strap. The termination assembly is thermally isolated from the amplifiers by a 1 inch section of gold plated stainless steel (SS) waveguide. This design allows the termination to be heated to 20 K without significant heating of the amplifiers (less than 1 K) with minimal signal loss.

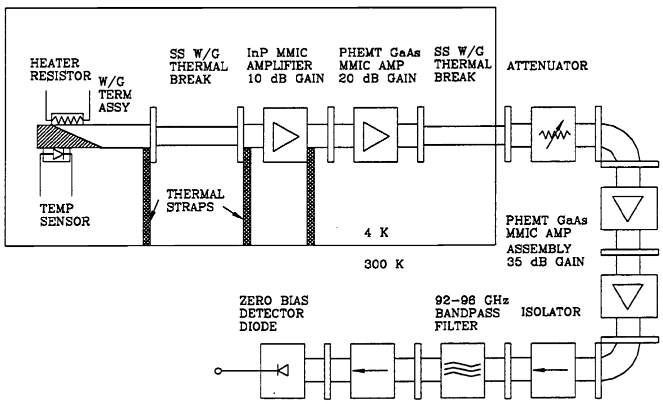


Figure 5. Cryogenic Noise and Stability Test Set.

The amplifier assembly consists of two separate amplifier housings, both maintained at 6 K. The first housing contains the 2 single stage InP MMIC amplifier chips (discussed in the previous sections) and provides in excess of 10 dB total gain from 92-96 GHz. The output of this amplifier is fed directly into a second amplifier body, containing a pseudomorphic GaAs HEMT LNA, 3-stage MMIC amplifier with 20 dB of gain and balanced output[13]. The signals are then passed out of the cryostat via a section of gold plated SS waveguide. Vacuum is maintained by a window made of 0.0005 inch PVC.

The room temperature portion of the test radiometer consists of a variable attenuator provided for isolation and impedance matching, a 35 dB gain GaAs PHEMT MMIC amplifier assembly, waveguide isolator, 92-96 GHz band definition filter, a second isolator and a zero bias Schottky diode detector. For the purposes of stability measurement, the total number of gain stages is relevant. Warm gain is provided by seven total stages, two of them balanced, and cryogenic gain stages were specified above.

## 5. CRYOGENIC NOISE TEMPERATURE MEASUREMENTS

The band averaged radiometer noise is measured by the standard hot-cold load technique, using a cryogenic termination. The radiometer output and termination temperature are monitored when the termination is at equilibrium (about 6 K). The termination is then heated to approximately 15 K Because of the low ambient temperature, the heat capacity of the termination is small, and the physical temperature of the termination is very close to the temperature measured by the sensor. The low heat capacity also allows the temperature to be changed in a relatively short time, minimizing the effect of system drifts. The radiometer output is monitored so that a noise temperature can be calculated. Several offsets are measured. The InP amplifier assembly is powered off to provide a measure of the offset due to the GaAs cold amplifier. This offset is measured before and after termination heating, in order to monitor any changes in the cryogenic portion of the system. No significant variations were observed. The attenuator was fully inserted to provide a measure of the warm amplifier noise component. Finally all RF components were powered off to provide a measure of the DC electrical offset. The radiometer noise ($T_{sys}$) is calculated using the last offset only (this offset was typically small at 0.3% of the typical signal level).

The noise is measured with InP stages biased at $V_d$=0.4 V and $I_d$=2.1 mA, for an extremely low total power consumption of 0.84 mW per stage. The band averaged noise temperature for the entire 92-96

GHz radiometer (end to end) is measured to be 78 ± 5 K (1.02 dB). The cryogenic portion of the radiometer (including the cryogenic GaAs assembly) is measured to be 71±8 K (0.94 dB). By measuring the offset due to the second cold amplifier, the noise of the InP assembly is estimated to be 51 ± 10 K (0.69 dB), the lowest noise measured for a 94 GHz amplifier. The large error is due to the uncertainty introduced by the impedance change incurred when the InP amplifier is off. The measurement was later repeated with a cryogenic isolator between the two cold amplifier assemblies to provide a constant impedance. This results in a radiometer noise of 85 K (1.1 dB) and an inferred InP noise of 60 K (0.8 dB), consistent with the previous measurement (the isolator loss is not accounted for, and could be adding as much as 8 K). The noise of the cryogenic GaAs assembly is estimated to be 180 K (2.06 dB) based upon measurements at 77 K, which is consistent with these measurements.

The broadband noise (Figure 6) is measured by placing a balanced mixer in the circuit following the first warm isolator (See Figure 5). The mixer employed only operates from 83 to 96 GHz . The IF amplifier has a 500 MHz bandwidth resulting in a 1 GHz resolution band. The measurement is carried out by the same technique described above with a different LO frequency for each measurement.

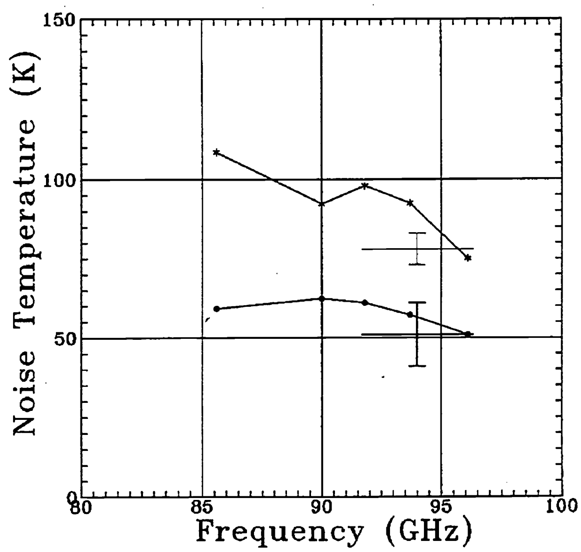


Figure 6. Cryogenic noise measurements for the cryogenic radiometer. The horizontal lines with error bars are the radiometer (thin line) and InP amplifier (thick line) band averaged noise. The broadband noise is shown for the radiometer (*) and InP amplifier (•) .

## 6. CRYOGENIC RADIOMETER STABILITY MEASUREMENTS

Radiometer stability is critical to noise performance. The advantages of having a low noise temperature in a radiometer can be easily lost to receiver gain instability for certain radiometer designs. The stability of the radiometer described above is measured in the following manner. The unheated termination is allowed sufficient time to thermalize. The detector diode output is amplified by a low noise amplifier with 10 kHz bandwidth and the DC level out of the amplifier is monitored. The output is also measured using a low frequency spectrum analyzer and the output power spectrum recorded. The DC portion level of the amplifier is approximately given by:

$$V_{dc}= \{(T_{term}+T_{sys})\, G\beta K + V_{off}\}\, G_{dc}$$

where $T_{term}$ is the termination temperature, $T_{sys}$ is the system noise temperature, G is the system RF gain, $\beta$ is the RF bandwidth, and K is a proportionality constant for detector diode conversion. $V_{off}$ is any DC offset present in the measurement, and $G_{dc}$ is the gain of the DC amplifier. If the radiometer instability is due to RF gain variations then the post-detection fluctuation term is approximately given by :

$\Delta V= [(T_{term}+T_{sys})\{(1/\beta\tau)+(\Delta G/G)^2\}^{1/2}\ G\beta K]G_{dc}$

or for small $V_{off}$

$\Delta V/V_{dc}= \{(1/\beta\tau)+(\Delta G/G)^2\}^{1/2}$

where $\tau$ is the post-detection integration time (for this measurement $\tau$ is one half the bandwidth of the spectrum analyzer which is normalized $Hz^{-1}$ ). The fluctuation due to the first term in the brackets is frequency independent, while second term typically has a "1/f" spectrum. We define the knee frequency as the frequency at which the noise *power* (not the noise voltage) equals twice the high frequency noise limit (given by the first term in the brackets). Because the second term falls with increasing frequency, the high frequency end of the output spectrum is a measure of RF bandwidth of the ideal radiometer.

The output voltage fluctuation spectrum is shown in Figure 7. The noise at 2 KHz was measured to be 8 μV/√Hz (the noise was "white" by a few hundred Hz), for a DC level of 0.35 V, implying an RF bandwidth of 3.8 GHz, very close to the 4 GHz design bandwidth. The knee frequency is 45 Hz, much lower than knee frequencies previously reported for a 100 GHz system [14]. Calibrating this curve in temperature units, this system achieves a sensitivity of 1.9 mK/√Hz or 1.36 mK√sec at 2 KHz. The sensitivity at the knee frequency, 45 Hz, is 2.86 mK/√Hz or 2.04 mK√sec. The noise due to the InP amplifier is extrapolated to be 1.68 mK/√Hz or 1.2 mK√sec at 45 Hz. Measurements of the radiometer at room temperature reveal a knee frequency of 25 Hz, which is also the approximate knee frequency of the room temperature system configured without the InP amplifier (i.e. when the entire chain is GaAs). Utilizing the full 10 GHz bandwidth, this InP amplifier would achieve a sensitivity of 600 μK√sec at a frequency above a few hundred Hz.

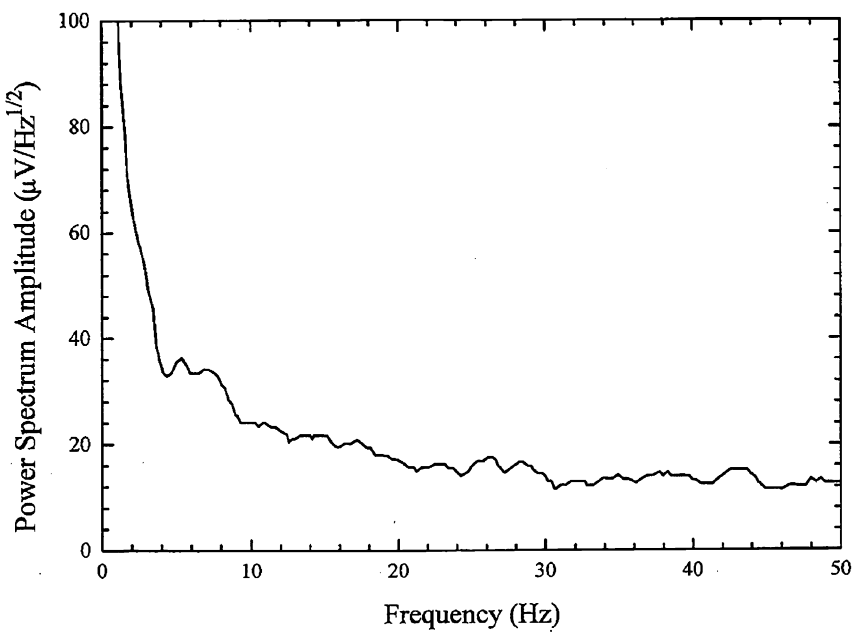


Figure 7. Measured power spectrum of cryogenic radiometer. The amplitude spectrum is shown with units μV/√Hz. The DC level is 0.35 V and the value at 2 KHz is 8 μV/√Hz. The noise at 45 Hz is 11.9 μV/√Hz corresponding to 2.86 mK/√Hz or 2.04 mK√sec.

## 7. CONCLUSION

We have designed, built and tested a 94 GHz, InP MMIC based amplifier and radiometer. The amplifier has a measured noise figure of 51 K (0.69 dB) operating at a cryogenic temperature of 6 K, the lowest noise ever measured for a 94 GHz amplifier. The power consumed per InP stage is 0.84 mW. The entire radiometer has a noise figure of 78 K (1.02 dB), and exhibits excellent stability with a measured "1/f knee" frequency of 45 Hz.

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