MMA RECEIVERS: HFET AMPLIFIERS

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Summary

This section describes HFET low-noise amplifiers [1] which may be used for MMA front ends between 26.5 and 116 GHz, depending on final decisions regarding the lowest frequency at which the MMA must operate and the highest frequency at which amplifiers are preferable to SIS mixers. The goals of the development effort are: (1) determine the performance of HFET receivers up to 116 GHz, (2) evaluate presently available devices, (3) evaluate the suitability of present designs below 116 GHz for MMA use, (4) produce prototypes of any required new designs, and (5) produce amplifiers for use in test receivers.

Table 5.4.1 HFET amplifier specifications

Item	Specification
Receiver noise temperature	As low as possible, limited by device performance
Frequency bands covered	Tentatively 33-50, 68-90, 90-116 GHz

Table 5.4.2 HFET amplifier milestones

Deliver test receiver 30 GHz amplifier	6/30/99
Deliver prototype 30 GHz amplifier	1/3/00

5.4.1 Amplifier frequency bands

The HFET amplifiers will be designed to produce the lowest noise compatible with the receiver band (up to a whole waveguide band), with sufficient gain to overcome second stage noise. It should be noted that HFET amplifiers have greater immunity to in-band interference than SIS mixers, a feature which may be important in deciding between the two below 116 GHz due to the possibility of interference from satellite-borne transmitters in this region of the spectrum. In addition, HFET amplifiers require cooling only to 15 K instead of 4 K; this may be relevant or not, depending on the dewar configuration (see section 6).

Possible bands to be covered, along with characteristic performance data for InP amplifiers, are listed in Table 5.4.3. Note that the first two bands are required if the MMA must operate below 33 GHz, thus requiring 2 receivers to cover 26.5-50 GHz; but if the lowest frequency is chosen to be 33 GHz, then the entire band 33-50 GHz can be covered with just one receiver. If standard waveguide is used, then in order to provide complete coverage above 68 GHz (the frequency at which the atmospheric oxygen line begins to permit observations) we must stop at 90 GHz for this receiver. If non-standard waveguide is used, then the region 68-102 GHz could be covered. Thus, it is possible to cover all atmospheric frequencies from 33 to 102 GHz with just two HFET receivers; an examination of Table 5.4.3 will also reveal that the receiver temperatures at some frequencies would be slightly higher in this case than if narrower-band amplifiers are used.

Table 5.4.3 Possible HFET amplifier bands

Band (GHz)	Waveguide Designation	Trcvr (K) at Center of Band
26.5-40	WR-28	16
40-50	WR-22 or 19	25
33-50	WR-22	25
68-102	WR-10 or non-standard	50
68-90	WR-12	40
90-116	WR-08	60

Low-noise HFET amplifiers have a higher threshold for problems caused by interference than do SIS mixers, which will be important if a proposed 94 GHz satellite-borne cloud radar is implemented.

5.4.2 Development work

The InP HFETs used in current NRAO amplifiers consist of a 250-nm undoped AlInAs buffer, a 40-nm GaInAs channel, a 1.5-nm undoped spacer, an 8-nm AlInAs donor layer doped to approximately 7e18 cm-3 and, finally, a 7-nm GaInAs doped cap, all grown lattice-matched to an InP semi-insulating substrate. These devices typically exhibit an electron sheet density of 2.5 to 2.8 $.10^{12}$ cm^{-2} and a room-temperature mobility of 10,000 to 11,000 cm^2/Volt-sec.

Successful design of cryogenically coolable amplifiers requires knowledge of both signal and noise models of HFETs at cryogenic temperatures. These models have been developed with sufficient accuracy to allow for computer-aided designs of cryogenic amplifiers with optimal noise bandwidth performance. An example of a cryogenic amplifier covering WR10 waveguide bandwidth (75-110 GHz) is shown in Figure 5.4.1, with calculated and measured performance data shown in Figure 5.4.2. This amplifier, built for the Microwave Anisotropy Probe (MAP) project, was realized in hybrid technology using pure polytetrafluoroethylene (PTFE), 0.003" thick substrates. The choice of "chip and wire" technology was dictated not only by the objective of achieving the lowest possible noise performance, but also by much lower cost than full-blown development of MMICs, in relatively low volume radio astronomy applications. The amplifier uses full waveguide bandwidth, E-plane probe, waveguide-to-microstrip transitions. It employs six InP HFET chips, each having gate dimensions 0.1 x 50 microns. The input and first two interstage coupling networks were designed to achieve the lowest average noise temperature across the band while the last three interstage coupling networks were designed to achieve a flat gain across the band. The bias networks also use "chip and wire" technology with bond wires being treated as transmission lines in the design process. All the bias network elements having influence on millimeter-wave characteristics and coupling capacitors are manufactured using 0.003" thick quartz substrates.
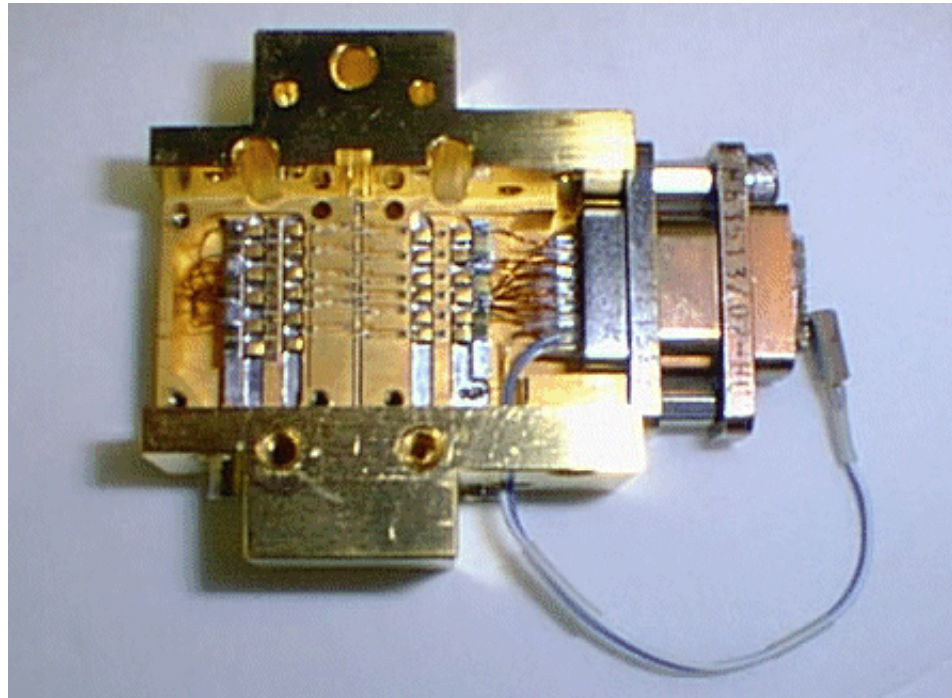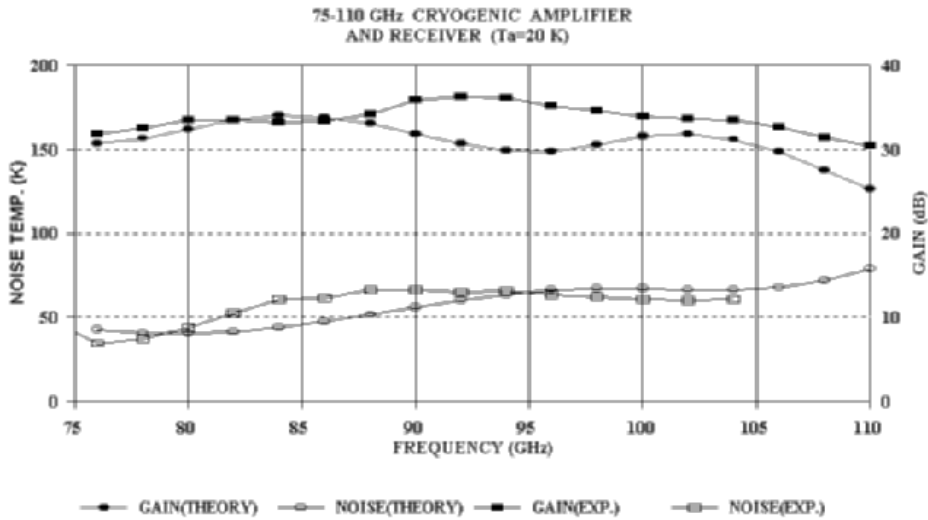
**Figure 5.4.1 Six-stage 75-110 GHz amplifier**

Click to zoom

Figure 5.4.2 Theoretical and experimental gain and noise of a laboratory receiver employing the amplifier shown in figure 5.4.1

An amplifier can be designed to provide good performance in any of the bands listed in Table 5.4.3. The only region of the spectrum in which an NRAO amplifier has not already been designed and tested is 110-116 GHz. In this highest frequency range appropriate for use of an HFET amplifier, performance becomes critically dependent on device geometry. The dimensions of the presently available devices from the NRAO wafer designated "518" are 10 by 12 mils, which is marginally too large for a robust design reaching 116 GHz. A wafer procured for the MAP project has somewhat smaller devices, 6 by 8 mils, but the surface passivating layer on this wafer increases capacitance and precludes its use above about 100 GHz. In order to make a design reaching 116 GHz, and to have enough devices to build all the HFET amplifiers for the MMA with the best possible noise temperature, the plan calls for fabrication of a new wafer with devices similar to the MAP wafer, but without the surface passivating layer.

5.4.3 Gain Fluctuations

A feature of the transistors is the gain fluctuation commonly called "1/f noise" which can be significant in single-dish astronomical observations with very large detection bandwidth X integration time products. Since the MMA will be used in this mode to make large-scale maps, probably on-the-fly, the effect of gain fluctuations must be considered. Theoretical calculations and laboratory experiments have been reported by Wollack [2] and by Wollack and Pospieszalski [3]. Using direct total power detection in a receiver at 80 GHz using 10 stages of InP amplification at ambient temperatures of 54 K and 300 K yielded the results shown in Figure 5.4.3.
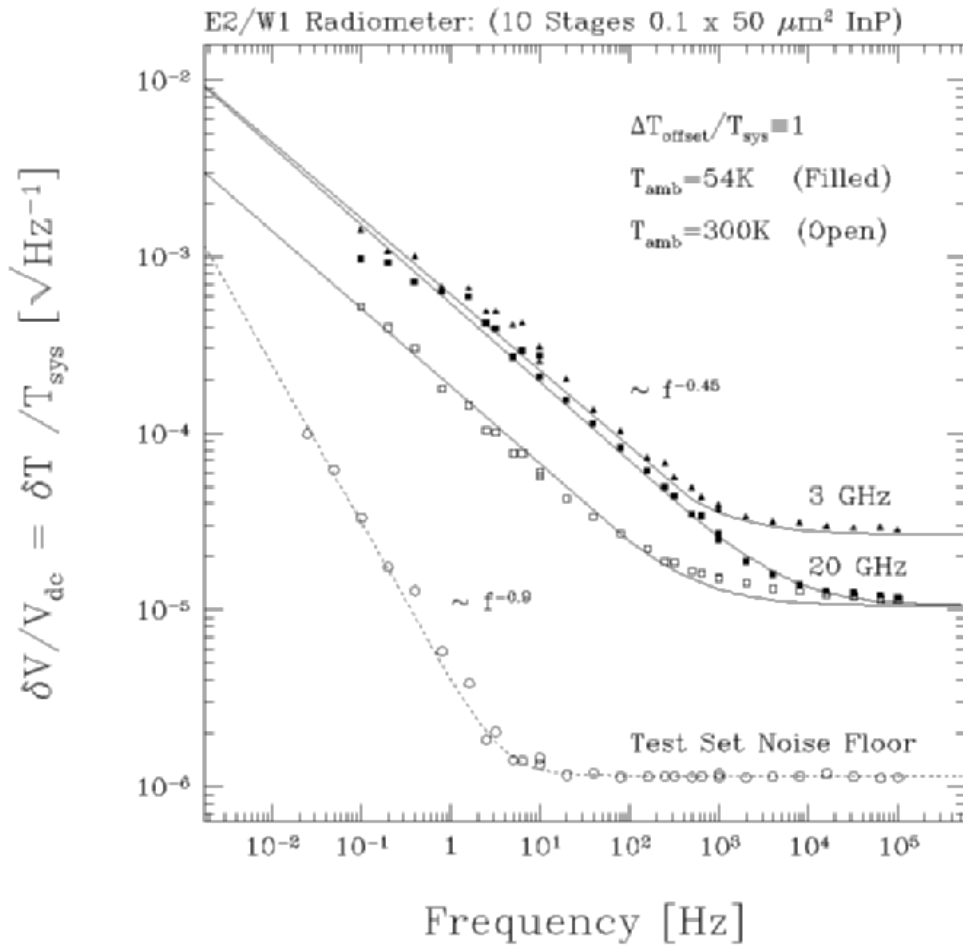
Click to zoom

Figure 5.4.3 Fluctuations in power spectral density under varying temperature and bandwidth conditions for a test total power radiometer

For the narrow bandwidths used in spectral line observations, these gain fluctuations are not an important factor, since the bandwidth per spectral channel will be small and the noise will be dominated by pure noise, Tsys/sqrt(time*bandwidth). For wideband continuum observations, however, gain fluctuations will be the dominant factor. As a concrete example, consider a time scale of 1 second, which might be typical of a single unidirectional scan employed for observing a continuum point source or making a continuum map. The square of the variance in gain at 20 K ambient temperature for InP devices is about $3.6 \cdot 10^{-8}$ [1/Hz] per stage; conservatively, 6 stages of gain will be needed to obtain at least 30 dB of gain before a mixer. With 6 stages and a bandwidth of 8 GHz, a total power radiometer will have sqrt($3.6 \cdot 10^{-8} * 6 * 8 \cdot 10^9 * 0.5$) = 29 times the variation in measured (delta T)/T than predicted from pure noise.

Various techniques can be used to alleviate this problem and provide continuum sensitivity closer to the situation in which pure noise, rather than gain fluctuations, dominates. The situation is analogous to the early days of radio astronomy, when bandwidths were much smaller but amplifier gain fluctuations much larger; the solution was a switching radiometer. In order to achieve full theoretical sensitivity with an 8 GHz bandwidth, a switch rate of about 10 kHz would be required; the problem is, how to switch and what to switch against. In the MAP project, a phase-switching scheme is used in effect to switch between two beams at a rate of 2.5 kHz; this results at W-band in only about a 20% loss in sensitivity for the effective 20 GHz bandwidth. A sky-switching option for the MMA would significantly increase expense, since a 2-feed receiver with all its electronics would cost at least twice as much as a single feed receiver; there might be severe difficulty going as low as 33 GHz with such a plan, due to the size of the feeds. Experiments in measuring and alleviating gain fluctuations using an out-of-band "pilot tone" have been carried out in the laboratory, with only modest success (e.g. Weinreb [4]). It is possible that a noise-adding radiometer could be employed, at least up to 50 GHz; GaAs noise diodes which can be switched on and off at least as fast as 1 kHz are available which are more stable than amplifiers in this frequency range (Wollack, private communication), but the situation at W-band is less certain. In a total power radiometer scheme, there is some advantage to performing detection at the 2 GHz stage of the IF conversion process, since both gain and noise fluctuations are somewhat decorrelated from one part of the band to another; but this advantage may be reduced by the fact that the separation into 2 GHz bands comes after fiber optic transmission and other electronic processing, which may induce gain fluctuations which dominate the noise. Some reduction in gain fluctuation may also be achieved by running all but the early stages of amplification warm, which improves gain fluctuations by a factor of ~6, and by using GaAs devices in following stages where possible, since the gain fluctuations of GaAs devices are about 1/3 that of InP devices.

Finally, we note that the SIS mixer receivers will also be affected by gain fluctuations in the wideband HFET amplifiers employed in the 4-12 GHz region. These amplifiers will use gate widths of about 400 microns, in contrast to the 50 micron gate widths used at 100 GHz, and the gain fluctuations will be correspondingly reduced by about sqrt(400/50) = 3. Following stages of warm or GaAs amplification can also help. If we can reduce gain fluctuations sufficiently, the atmospheric variations in transparency and noise will dominate the radiometer noise; but this may be difficult to achieve in practice.

REFERENCES

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