
CRYOGENICALLY COOLED BROAD-BAND GaAs FIELD-EFFECT TRANSISTOR PREAMPLIFIER

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ABSTRACT

A cryogenically cooled 1-2 GHz low-noise broad-band prototype preamplifier utilizing GaAs field-effect transistors was constructed. The optimum noise figure at temperatures of 293 K and 18 K, respectively. The noise figure has a minimum value of 0.75 at 300 K and 0.24 at 18 K. The optimum preamplifier operating conditions for a minimum noise figure at temperatures of 293 K, 80 K and 18 K are given and are discussed. Also, the phase-shifter with only minor adjustments in gate bias voltages to obtain the best performance from each stage. In spite of discrete components construction, both preamplifiers performed reasonably well upon initial turn-on with only minor adjustments in gate bias voltages to obtain the best performance. Better matching was achieved by some minor adjustments which were done at room temperature around 295 K.

INTRODUCTION

The Antiproton Source of the Fermi National Accelerator Laboratory will be capable of accumulating a total of 4.3 x 1011 antiprotons in four hours when a wide-band feedback system for stochastic beam cooling is used. The feedback system detects and corrects at every revolution, the statistical fluctuations of the beam position and momentum. One of the essential components of a system is a low-noise broad-band preamplifier. The preamplifier should satisfy various requirements for this application such as having a very low noise figure, wide bandwidth, high gain stability, moderate phase shift and moderate input and output voltage standing wave ratios as well as widest possible dynamic range. Our previous preamplifier prototype designs have shown that a properly designed cryogenically cooled preamplifier using GaAs field-effect transistors can satisfy the above requirements.

In general, the noise in a microwave FET is caused by thermal, hot-electron, and high-field diffusion effects. For frequencies below 3 GHz noise is also possibly caused by trap generation-recombination effects. The thermal noise of the FET channel and parasitic resistors is dominant. The ambient temperature and the transistor trans-conductance. Furthermore, the transconductance increases with decreasing temperature because of the increase of free carrier mobility and higher saturated velocity in GaAs. The increase in mobility is caused by fewer collisions with energetic lattice atoms and is approximately proportional to for physical temperatures greater than 80 K. Hot-electron and high-field diffusion noise may remain constant or increase at cryogenic temperature, depending upon the particular transistor and its operating conditions. Alsotrap generation-recombination noise has a peak at some temperature. Because of the complex dependence of the noise figure upon ambient temperature, the noise figure of several commercially available GaAs FET's was measured from 300 K to 12 K in an amplifier with a frequency pass band centered at 500 MHz and having a width of 30 MHz. On the basis of the results of these measurements, and data presented in Ref. 4, the Mitsubishi devices 1402 and 1412 were selected for preamplifier. By cooling such a preamplifier to 80 K the noise figure can be reduced by a factor of 3 or 4. A narrow band preamplifier will have a better noise figure, mainly because a better input impedance match can be achieved. In the case of a broadband preamplifier, compromises in various above requirements, must be made.

Based on our previous prototype preamplifier designs, two production models of the 1-2 GHz cryogenically cooled preamplifier had been built for stochastic beam cooling systems. The noise of the preamplifier utilized three GaAs field-effect transistors. Except for a series quarter wave-lengths line at the input for matching purposes, discrete components were used in the construction of the preamplifiers. Chip resistors and capacitors were used extensively for bypassing, decoupling and tuning. For D.C. biasing metal film resistors were used. The transistors were mounted on copper studs which were soldered directly to the copper enclosure to minimize the thermal conductivity between the copper enclosure and the transistors. The rest of the components were soldered on a microwave substrate (Rogers Duroid 2.2, 0.020 thick) having a dielectric constant of 2.2. The matching series 1/4 line length at the input was constructed on a microwave substrate (3M Epsilon 10,) with a dielectric constant of 10. All three stages of the preamplifier operate with a drain current of 10 mA and the gate bias voltages could be adjusted independently to obtain the best performance from each stage. In general, the discrete components construction, both preamplifiers performed reasonably well upon initial turn-on with only minor adjustments in gate bias voltages to obtain the best performance. Better matching was achieved by some minor adjustments which were done at room temperature around 295 K.

The uniform performance of the two amplifiers indicate that the preamplifier characteristics are highly reproducible. The performance of these two production models was identical to that of the prototype. At the time of this writing, both amplifiers had been cycled from 296 K to 18 K and back up to 296 K for twenty times with no indication of degrading performance. The temperature cycling was done in a cryostat with a cooldown time from 300 K down to 18 K and a warm-up time back up to 300 K in about 3 hours. Cooling and heating must be avoided to minimize damage to the components. Data presented in this paper were typical of these two amplifiers.

PREAMPLIFIER DESIGN

Figure 1 shows a schematic diagram of the preamplifier, which uses a Mitsubishi GaAs FET transistor in each of three cascaded stages to obtain a total gain of 30 dB across the 1-2 GHz band. The input matching was achieved by a 1.5 GHz series quarter wavelengths line, and inductors L1, L3, and L11. Inductors L4 and L5 also affect the input matching but were less critical than the components. The main input matching criterion was a good impedance match across the 1-2 GHz bandwidth. This was done because maximum usable power bandwidth was important. Since the optimum noise matching was not too far off from good impedance match, the best possible VSWR would likely yield a very low value of the noise temperature across the octave bandwidth. The interstage matching was mainly done by inductors L6, L12, L18, L19, and L20. The 3-stage amplifier had high enough gain, a 6 dB pad used at the output point was a convenient and practical solution both for the output matching and stability.

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The gain and phase characteristics of the preamplifier were measured using the system shown in Fig. 3. A 5-parameter test set combined with a network analyzer, phase/gain display unit, and a sweep generator, provided a versatile system for measuring the preamplifier characteristics. An important point in this measurement was that the input signal level should be properly adjusted so the network analyzer could lock onto the signal in order to work properly. But at the same time it should not saturate the preamplifier. Data taken when operating at or near saturation would not be representative. A 20 dB attenuator was found to be essential at the input of the preamplifier to meet both of these requirements for this particular measurement. The gain measurement was a straightforward procedure using the S21 mode on the S-parameter test set. The results are shown in Fig. 4. The 3-stage preamplifier had a gain of 29.5 dB ± 1 dB over the 1-2 GHz bandwidth at 296°K. The gain increased to 33 dB at 80°K and remained constant down to 18°K. The gate bias voltages were adjusted at room temperature for maximum gain and were not readjusted at lower temperatures.

The phase measurement was made with the same system shown in Fig. 3. Since the phase variation across the 1-2 GHz band was to be measured, the delay of the interconnecting cables to the antenna from the preamplifier must be compensated for before the phase variation can be measured. In Fig. 3, the external compensating cable of the S-parameter test set must be adjusted to provide the proper delay for this measurement. Figure 5 shows the phase variation as a function of frequency for the preamplifier. At room temperature the phase variation was +17° decreasing to -15° at 80°K and +4° at 18°K. The group delay of the preamplifier was 2.5 ns ± 0.2 ns.

VOLTAGE STANDING-WAVE RATIO MEASUREMENTS

The input and output impedance measurements were also made with the system shown in Fig. 3. The polar display unit with a Smith Chart overlay was used with the network analyzer. Calibrations were made with all interconnecting cables intact but without the preamplifier in the system, so the input and output reference points could be established. The 20 dB attenuator was removed from the system for these measurements. The input Voltage Standing-Wave Ratio (VSWR) and impedance data were derived from the network analyzer display obtained in the S11 mode. Figure 6 shows the input and output VSWR's of the preamplifiers at 296°K. At temperatures 80°K to 18°K the input VSWR became somewhat better across the 1-2 GHz bands, but not by a significant amount. The output VSWR stayed very much the same, around 1.5, throughout the 1-2 GHz bands at all temperatures. The input impedance is shown in Fig. 7. Again the data were derived from the Smith Chart display obtained in the S11 mode.

OUTPUT POWER AND INTER MODULATION PRODUCTS MEASUREMENTS

The system shown in Fig. 8 was used for the output power and intermodulation measurements. The system shown was set up for two input signals intermodulation products measurement. For single input signal measurements, one signal generator and the power combiner were disconnected from the system. The outputs of the two signal generators were first calibrated using the spectrum analyzer. The variable attenuator was then used to provide different input signal levels for the measurement. Figure 9 shows the typical carrier output power and some of their harmonics as a function of input power level at room temperature. Figure 10 shows the carrier output power and intermodulation products as a function of the input power level. At lower temperature the behavior was similar, although the output was somewhat reduced. For the same reason, the intermodulation products were reduced in the slight increase in gain. The 1 dB compression point occurred at -5 dBm for single input signal operation, whereas the third order intercept point occurred at 3 dBm for two input signal operation.

NOISE FIGURE MEASUREMENT

The system used to measure the noise figure is shown in Fig. 11. A hot-cold noise source was used as
the noise generator with the hot and cold source operating 373.2°K and 77.3°K, respectively. A dc-micro-wave single pole double-throw switch was used to connect the amplifier to the hot and cold sources alternately. The loss through this switch across the 1-2 GHz band was approximately the same as the noise figure.

Before the noise figure was measured the loss as a function of frequency of the inter-connecting cables between the amplifier in the cryogenic cooler and the signal source was measured at 296°K, 80°K and 18°K. A cable loss calibration curve for 1-2 GHz was then prepared for the purpose of subtracting this loss from the measured noise figure to obtain the preamplifier noise figure.

Measurements were made under two conditions. First, the two preamplifiers were adjusted for best gain and response at 296°K and noise figures were measured at 296°K, 80°K and 18°K without further adjustment. The results are given in Fig. 12. Second, the preamplifiers were cooled to 80°K and 18°K and adjustment were made at these temperatures to obtain the best noise figure.

In the two production models, the noise figure did not improve by changing the gate bias at lower temperatures. However this was not the case with the developmental prototype preamplifier; and the noise figure could be improved by adjusting the gate bias. Nevertheless the optimized noise figure in that case was almost the same as the noise figure shown in Fig. 12. This leads to the conclusion that in some cases the adjustment improved the noise performance and in others the adjustment was not necessary. When adjustments were required, normally only a slight change was needed on the gate bias of the first stage. Other performance characteristics were only slightly altered by this adjustment.

STABILITY MEASUREMENT

Two stability measurements were made on the preamplifier. On the input port stability measurement a wide band 0.1-18 GHz power meter was connected to the output of the preamplifier for monitoring any oscillation which might occur. Sliding shorted and open lines were connected to the input port alternately. The preamplifier was found to be stable at any phase of the shorted and open lines.

In the output port stability measurement, a 20 dB 1-4 GHz directional coupler was used as a signal pick-off at the power meter at the output of the preamplifier. The shorted and open sliding lines were connected at the output end of the directional coupler alternately. The preamplifier was found to be stable at any phase of the shorted and open line.

The same test was performed at 80°K and 18°K. The preamplifier was stable at room temperature and at both the lower temperatures. A spectrum analyzer was used further to look for spurious oscillation but none could be found up to 18 GHz.

CONCLUSIONS

The performance of a 1-2 GHz cryogenically cooled low noise preamplifier has been presented. Measurements made on two production models showed similar performance. Their performance was almost identical to that of the developmental prototype. In spite of the discrete component design, they were reproducible. The reproducibility could be credited to the tight control of physical layout and construction. The noise figure across the 1-2 GHz band at 80°K varied from .35 - .15 dB ± .03 dB. At 18°K the noise figure decreased to .025 - .35 dB ± .03 dB across the 1-2 GHz band. Further improvement in noise figure performance may not be possible without a better input matching and a more elaborate way to heat sink the transistors. For any low noise amplifier, input matching must be done with lossless elements because any loss between the signal source and the amplifier will add to the noise figure. Better matching can be achieved in a narrow band amplifier, however for an octave band-width amplifier a compromise is almost certain to be necessary. Since in some cases best performances can be achieved with slight gate bias adjustment at different ambient temperatures, it is necessary to optimize the performance at the temperature the amplifier is intended to operate.

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REFERENCES

NOTES: UNLESS OTHERWISE INDICATED
1. CHIP CAPACITORS IN pF AS SHOWN.
2. RESISTORS 1 8W 1Ω METAL FILM.
*3. COILS: MADE OUT OF 0.010 INCH DIA. GOLD PLATED PHOSPHOR BRONZE WIRE USING 1mm DIA. WIRE AS A COIL FORM ±AT 0.1 INCH.

Fig. 1 Schematic diagram of the 1-2 GHz preamplifier.

Fig. 3 System block diagram for measuring gain, phase, voltage standing-wave ratio, input and output impedance.

Fig. 4 Preamplifier gain as a function of frequency at ambient temperatures of 296°K, 80°K and 18°K.
Fig. 2 A photograph of the preamplifier with the amplifier enclosure cover.

Fig. 5 Preamplifier phase-shift as a function of frequency at ambient temperatures of 296°C, 80°C and 18°C.

Fig. 6 Input and output voltage standing-wave ratio of the preamplifier.
Fig. 7 Input impedance of the preamplifier.

Fig. 8 System block diagram for measurements input and output power and intermodulation products.

Fig. 9 Typical performance characteristics of the 1-2 GHz preamplifier.

Fig. 10 Typical performance characteristics of the 1-2 GHz preamplifier.

Fig. 11 System block diagram for measuring noise figure.

Fig. 12 Noise figure of the preamplifier as a function of frequency at ambient temperatures of 296°K, 80°K and 18°K.
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