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TRANSISTOR PREAMPLIFIER

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ABSTRACT

A cryogenically cooled 1-2 GHz low-noise broad-band prototype preamplifier utilizing GaAs field-effect transistors is described. The preamplifier has an average gain of 30 dB and 35 dB at ambient temperatures of 293°K and 18°K, respectively. The noise figure has a minimum value of 0.75dB at 300°K and 0.24dB 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-shift characteristics, the input and output voltage standing-wave ratio as a function of frequency and intermodulation products content as a function of the input power level were measured.

INTRODUCTION

The Antiproton Source of the Fermi National Accelerator Laboratory will be capable of accumulating a total of 4.3×10^{11} antiprotons in four hours when a wide-band feedback system for stochastic beam cooling is used.¹ The feedback system detects and corrects at every revolution, the statistical fluctuations of the beam position and momentum. One of the essential components of such a system is a low-noise broad-band preamplifier.² 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 designs³ 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 resistances is proportional to the ratio T/g_m , where T is the ambient temperature and g_m is the transistor transconductance. Furthermore, the transconductance increases with decreasing of 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 $T^{-3/2}$ for physical temperatures greater than 60°K. Hot-electron and high-field diffusion noise may remain constant or increase at cryogenic temperatures, depending upon the particular transistor and its operating conditions. Also trap 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.³ On the basis of these measurements, and data presented in Ref. 4, the Mitsubishi devices MFG 1402 and MGF 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,⁵ two production models of the 1-2 GHz cryogenically cooled preamplifier had been built for stochastic beam cooling systems. The noise of the preamplifier was made as low as possible so that its noise in the output power would not reduce the cooling of the particle beam. The preamplifier utilized three GaAs field-effect transistors. Except for a series quarter wavelengths 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 maximize the thermal conductivity between the copper enclosure and the transistors. The rest of the components were assembled on a microwave substrate (Rogers Duroid 2.2, 0.020" thick) having a dielectric constant of 2.2. The matching series $\lambda/4$ 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 10mA and the gate bias voltages could be adjusted independently 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 296°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 cool-down and warm-up time span of a few hours. Sudden 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 T_1 , and inductors L_1 , L_3 and L_{11} . Inductors L_4 and L_5 also affect the input matching but were less critical than the components referred to previously. 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 a good impedance match, the best possible VSWR would likely yield a very low value of the noise temperature across the octave bandwidth. Interstage matching was mainly done by inductors L_6 , L_{12} , L_9 and L_{13} . Since 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

problems. The first two stages of the amplifier used Mitsubishi MGF 1412 transistors and the third stage used a MGF 1402 transistor. Each operated with a drain current provided by three separate current regulators. The gate biases were provided by three separate bias supplies, each of which could be individually adjusted to yield the best overall performance of the amplifier.

Although these transistors have excellent low-noise characteristics, they do not satisfy the necessary and sufficient conditions for unconditional stability: $K_S > 1$ and $\Delta < 1$; in the frequency region from 0.5 to 21 GHz, as was shown in Refs. 3 and 5. Generally, most GaAs FET's are potentially unstable in certain frequency regions which lie below 3 GHz because of the presence of internal feedback such as that due to the gate-to-drain capacitance. The stability factor was increased by a low loss FET source inductive series feedback to off-set the internal feedback. Also, such inductive feedback increases the real part of the input impedance resulting in better matching conditions between the signal source and the amplifier input.

The series feedback was accomplished by the source inductor L_{S1} . This inductor can be represented by an impedance Z_{L1} added in series with the gate. The impedance is to some extent dependent also on the first stage load impedance. However, in the first approximation it is resistive and given by $g_m L_{S1}/C$, where g_m and C are the transistor transconductance and gate capacitance, respectively.⁶ The noise figure of the preamplifier is essentially unaffected by the series feedback, because the addition of a lossless element to a network does not change the noise performance of the network.

With broad-band operation in mind all three stages operated with low Q components. Since the first stage determined the noise figure of the preamplifier to the greatest extent it had been made to provide good input matching across the widest bandwidth possible and at the same time to provide the highest gain across the 1-2 GHz band.

Since the source leads of the transistors had been used as part of the source inductors, each source lead was soldered to a 0.1" copper stud which was soldered directly to the enclosure for both good RF grounding as well as good thermal conductivity. While this is not the best way to obtain an extremely low thermal gradient, the relative ease of assembly off-sets a relatively small improvement in performance.

The other inductor used to obtain a better input matching was L_1 , which was connected about midway of T_1 . By moving L back and forth about this point, a better match could be realized for the 1-2 GHz octave bandwidth. Figure 2 is a photograph of one of the amplifiers. A piece of microwave absorbing material, Emerson-Cumming MF-124, was attached to the cover of the gold plated copper enclosure producing a lossy enclosure wall area to reduce the possibility of parasitic oscillation. For the same reason ferrite beads, Amindon Associates T10-6, were used on some of the source leads.

GAIN AND PHASE CHARACTERISTICS MEASUREMENT

The gain and phase characteristics of the preamplifier were measured using the system shown in Fig. 3. A S-parameter test set combined with a network analyzer, phase/gain display unit or meter, 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 $29.5 \text{ dB} \pm 1 \text{ dB}$ over the 1-2 GHz bandwidth at 296°K. The gain increased to $33 \text{ dB} \pm 1.5 \text{ dB}$ at 80°K and gained another 0.5 dB at 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 inter-connecting cables and the amplifier itself 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 $\pm 17^\circ$ decreasing to $\pm 15^\circ$ at 80°K and $\pm 13^\circ$ at 18°K. The group delay of the preamplifier was $2.5 \text{ ns} \pm 0.2 \text{ ns}$.

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 inter-connecting 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 was derived from the S11 measurement. The output VSWR and impedance data were obtained from the S22 measurement. Figure 6 shows the input and output VSWR's of the preamplifiers at 196°K. At temperatures 80°K and 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 band 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 INTERMODULATION 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 obtain 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 very much the same except for the evidence of 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 signals 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 0.03 dB.

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° 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 adjustments 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 development 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 .01-18 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 for 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 - .45 dB $\pm$ .03 dB. At 18°K the noise figure decreased to 0.25 - .35 dB $\pm$ .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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NOTES: UNLESS OTHERWISE INDICATED

1. CHIP CAPACITORS IN pF AS SHOWN.
2. RESISTORS 1/8W 1% METAL FILM.
- *3. COILS: MADE OUT OF 0.010 INCH DIA. GOLD PLATED PHOSPHOR BRONZE WIRE USING 1mm DIA. WIRE AS A COIL FORM $\approx 4T$ 0.1 INCH.

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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.

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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°K, 80°K and 18°K.

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

Fig. 9 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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