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Low-Noise Gallium-Arsenide Field-Effect Transistor Preamplifiers for Stochastic Beam Cooling Systems

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Summary

The present noise performance, bandwidth capability and gain stability of bipolar and field-effect transistors, parametric amplifier, Schottky diode mixer and maser are summarized and compared in the 100 MHz to 40 GHz frequency range for stochastic beam cooling systems. Stability factor of GaAs FET's as a function of ambient temperature is presented and discussed. Performance data of several low-noise wide-band cryogenically cooled preamplifiers are presented including one with a noise figure of 0.35 dB over a bandwidth range of 150-500 MHz operating at ambient temperature of 20°K. Also, data are given on a broadband 1-2 GHz preamplifier having a noise figure of approximately 0.2 dB. The gain, operating noise temperature, stability, gain nonuniformity and phase-shift as function of frequency of interest for beam cooling systems are discussed.

Introduction

An effort is underway at the Fermi National Accelerator Laboratory and Lawrence Berkeley Laboratory to design an Antiproton Source.[1] This source, incorporating a wide-band feedback system for stochastic beam cooling, will be capable of accumulating a total of 4.3×10^{11} antiprotons in four hours. The method has been effectively used to reduce the betatron oscillations and longitudinal momentum spread in a coasting particle beams.[2]

The Antiproton Source program requires the development of two types of wide-band amplifier systems, one capable of operating at power levels of several hundred watts and the other at power levels of several thousand watts in frequency bands covering 1-2 GHz and 2-4 GHz. Since the antiproton beam pickup electrode arrays generate signals at very small power levels, the amplifier system should have gains in excess of 90 dB and 150 dB and noise figures as low as possible.

Our earlier studies[3-7] indicate that new amplifier systems should be designed. This paper specifically deals with the noise characterization of the continuous wave wide-band amplifier systems required for stochastic cooling experiments and the necessary design considerations for a low-noise wide-band preamplifier.

Noise Characterization of the Amplifier System

The particle beam cooling process is governed by the following: (1) the coherent effect where each beam sample cools itself via the feedback system by the signal it generates and (2) the incoherent effect, where the beam heats itself because of the noise generated by the other beam particles (beam Schottky noise) and the presence of the noise in the amplifier system. For particle beam intensities such as those in the FNAL Antiproton Source facility, the heating effect will be predominately the result of amplifier noise rather than beam noise.

The usual noise that exists in a low-noise power amplifier is partly of thermal origin and partly due to other noise generating processes. Generally, the noise of a low-noise power amplifier can be characterized either by the effective input noise temperature T_e, defined as $T_e = P_n/k\Delta f$, where P_n is the available noise power, k is Boltzman's constant and Δf the bandwidth, or by the noise figure F. The relationship between the noise figure in dB and effective noise temperature is given by: $T_e = 230\ (10^{F db/10} - 1)$. A block diagram of the low-noise power amplifier system used in the system noise temperature calculations is shown in Fig. 1. The first component is the pickup electrode array followed by a transmission line that connects the pickup electrode array to the in-phase power combiner input terminal. The combiner, having a temperature T_{sc} and an insertion loss factor L_c, is followed by a transmission line which connects the combiner to the low-noise preamplifier input terminals. For this system, the operating noise temperature T_{op} will be given by the expression:[7]

$$T_{op} = T_a + T_{ra} + L_{ra}\, T_{sc} + L_{ra} L_c T_{rb} + L_{ra} L_c L_{rb} T_e$$

where T_{ra} is the first transmission line noise temperature, L_{ra} its loss factor; T_{sc} is the combiner noise temperature, L_c its loss factor; T_{rb} is the second transmission line noise temperature, L_{rb} its loss factor; T_e is the amplifier system effective input noise temperature at preamplifier input terminals, and T_a is the noise temperature of the pickup electrode array, representing the available noise power at the pickup electrode array terminals. The transmission line loss factor L_{ra}, is defined as a ratio of the signal power available at its input to that available at its output. The transmission lines noise temperature can be expressed by the equation: $T_{ra} = T_{tra}\ (L_{ra} - 1)$ and $T_{rb} = T_{trb}\ (L_{rb} - 1)$, where T_{ra} and T_{trb} are the transmission lines thermal temperatures.

A comparison of the pickup electrode array noise with the effective input noise temperature of the amplifier front end shows that the pickup electrode array noise can contribute significantly to the total system operating noise.

Noise Performance for 1982 State-of-the-Art Low-Noise Devices

The present noise performance of state-of-the-art microwave devices is summarized in Fig. 2 over the 100 MHz to 40 GHz frequency range. The values are taken from manufacturers data sheets,[9-11] the references cited below[12-13] (with the most recent corrections), and also from measurements on low-noise amplifiers designed at the Lawrence Berkeley Laboratory.[7] In all cases the narrow-band amplifier noise performance data are plotted. The mixer values are single sideband noise temperatures. At ambient temperatures of 300°K the Gallium-Arsenide Field-Effect Transistor Amplifier has a higher noise temperature value than the best parametric amplifiers in the 1 to 4 GHz frequency range. However, the GaAs FET amplifier offers a considerably larger bandwidth and higher gain stability. Furthermore, the noise temperature of the cryogenically cooled GaAs FET amplifier is lower than that of the cooled parametric amplifier. Only a 4°K maser amplifier with a state-of-the-art converter has a lower noise temperature. Its noise performance data are given for comparison purposes only. The maser amplifier is essentially a narrow band device.

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Noise of Cryogenically-Cooled GaAs FET's

Generally, microwave FET's use as semiconductor material GaAs rather than silicon. GaAs has approximately six times higher low field electron mobility and two times higher maximum drift velocity as compared with silicon. Furthermore, for silicon at temperatures below 125°K electrons are frozen out of the conduction band and holes out of the valence band which leaves the semiconductor with very few carriers to support the device operation. On the other hand for GaAs no freeze out occurs at cryogenic temperatures because of the extremely small energy gap between the donor levels and the conduction band for most n-type dopants used in FET's. 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 transductance. 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 due to the temperature dependence of the time constant. Because of the complex dependance 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.[7] On the basis of these measurements, the Mitsubishi devices MFG 1402 and MGF 1412 were selected for more detailed study. The device MGF 1402 was used in the design of a broadband 150-500 MHz amplifier planned for an earlier version of the Stochastic beam cooling system.[7] This amplifier had a gain of 24 dB. Noise figures versus frequency for ambient temperatures of 300°K, 100°K and 20°K are given in Fig. 3. The preamplifier noise figure had values of 1.4 dB and 0.35 dB at ambient temperatures of 300°K and 20°K, respectively.

There was a significant increase in the noise figure values at frequencies below 100 MHz because of the existance of 1/f noise. The reduction of the ambient transistor temperature from 300°K to 20°K had a very small effect on the noise figure value at these frequencies.

Design Considerations for Low-Noise Wide-Band Preamplifiers

The design criteria for low-noise wide-band preamplifiers for the stochastic cooling system are primarily determined by the various requirements of preamplifier gain, bandwidth, noise figure, gain stability and uniformity, phase-shift, input and output voltage standing wave ratios and dynamic range. Although, some devices offer an excellent narrow-band noise figure at room and cryogenic temperatures they cannot be operated over a wide bandwidth without lossy gain-compensating and gain stabilizing networks which in turn increase the noise figure. Generally, the preamplifier noise figure cannot be optimized without sacrificing other performance characteristics. This chapter briefly addresses possible tradeoff in the preamplifier's characteristics such as noise figure and gain stability. It had been shown previously that devices MGF 1402 and MGF 1412 offer excellent noise performance when used in narrow-band amplifiers.[7,12] To calculate the device stability factor K_S[14] and factor Δ as a function frequency, the scattering parameters were measured for five devices in the frequency range from 0.5 to 2.0 GHz at ambient temperatures of 300°K, 80°K and 13°K. The transistor stability factor K_S and factor Δ were calculated from the S-parameter averaged data. The results of the calculations are shown in Fig. 4.

It can be seen from the figure that this transistor does not satisfy the necessary and sufficient conditions for unconditional stability: $K_S > 1$ and $\Delta < 1$; in the frequency region from 0.5 to 2 GHz. 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 can be increased by a low loss FET source inductive series feedback to offset the internal feedback.[13] 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. However, calculations and measurements have shown that this type of feedback can be only partially applied because it seriously decreases the device gain when value of $K_S = 1$ is approached. Alternatively it is also possible to use parallel feedback, consisting of applying capacitance and resistance from the gate to the drain of the GaAs FET to increase the stability factor. Further analyses have shown that a wide bandwidth, with low input and output reflection coefficients and excellent stability can be achieved. Unfortunately, a significant increase of the noise figure also results from the application of parallel feedback in a broadband preamplifier operating at ambient temperatures around 300°K. This increase is mostly due to various losses caused by the feedback loop components and characteristics of the transmission line which is used between the FET output port and the node where the feedback loop is connected.

The device MGF 1412 was also used in the design of a broadband 1-2 GHz preamplifier.[7,12] A schematic diagram of the preamplifier is given in Fig. 5. The series $\lambda/4$ line length and its characteristics impedance at the input provided better matching with the external 50 Ohm source impedance. A 6 dB attenuator was used at the preamplifier output to ensure stability for any termination impedance. The preamplifier was unconditionally stable with a short or open sliding line of any phase connected at its input. The second and third stage were tuned to provide a good overall amplitude response across the 1-2 GHz frequency range. This amplifier has an average gain of 29 dB and 32 dB at ambient temperatures of 300°K and 17°K, respectively. The amount of the preamplifier phase shift over a bandwidth of 1-2 GHz was approximately ± 12° and ± 9° at temperatures of 300°K and 17°K, respectively. Noise figures versus frequency for ambient temperatures of 300°K, 80°K and 17°K are given in Fig. 6. The noise figure has a minimum value of 0.9 dB and 0.2 dB at ambient temperatures of 300°K and 17°K, respectively.

Acknowledgment

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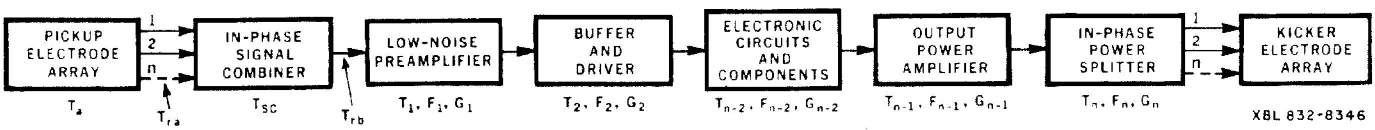

Fig. 1 Block diagram of the amplifier system used as a basis for the system noise temperature calculations.

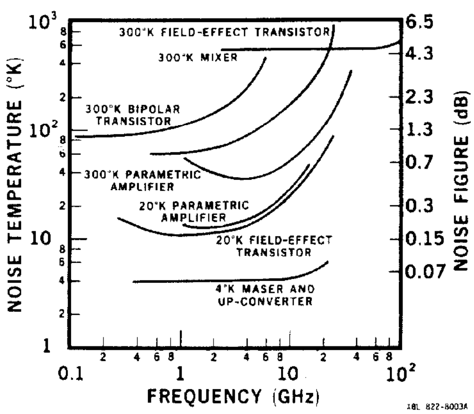

Fig. 2 Noise temperature and noise figure as a function of frequency for various 1982 state-of-the art low-noise devices.

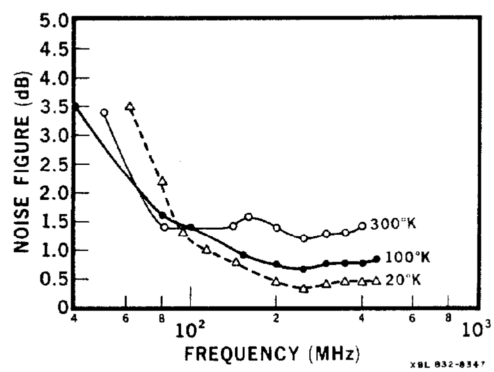

Fig. 3 Preamplifier noise figure as a function of frequency at ambient temperatures of 300°K, 100°K and 20°K.

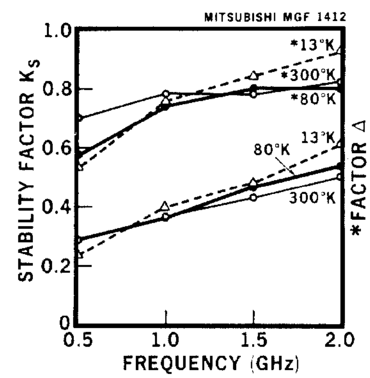

Fig. 4 Stability factor K_S and factor Δ as a function of frequency for MGF 1412 Field-Effect Transistor.

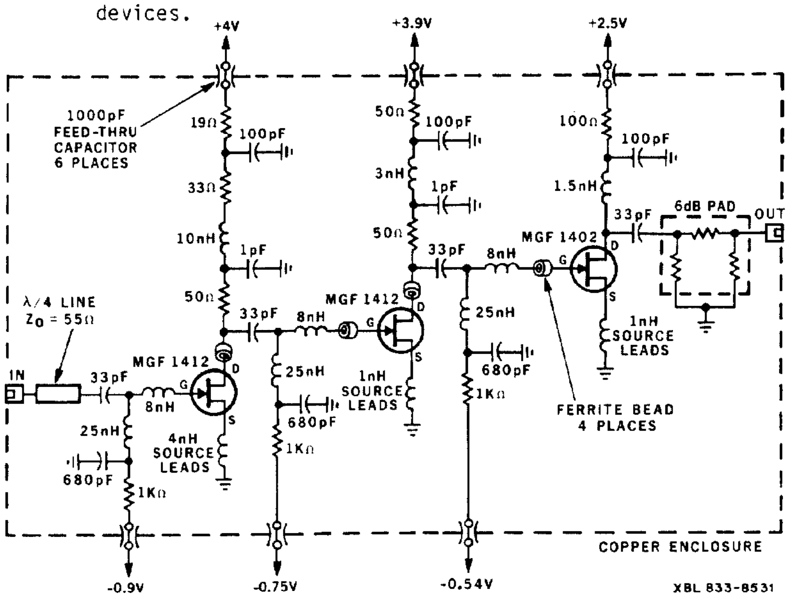

Fig. 5 Schematic diagram of 1-2 GHz preamplifier.

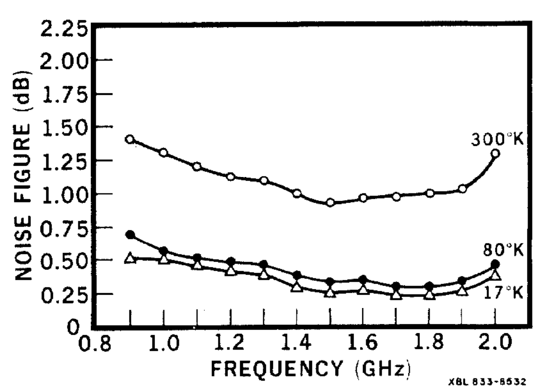

Fig. 6 Preamplifier noise figure as a function of frequency at ambient temperatures of 300°K, 80°K and 17°K.