L- and S-Band Low-Noise Cryogenic GaAs FET Amplifiers

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Abstract —**We present the results of the construction and testing of three cryogenic low-noise GaAs FET amplifiers, based on a National Radio Astronomy Observatory design, to be used in a detector for the axion, a hypothetical particle. The amplifiers are centered on 1.1 GHz, 1.1 GHz, and 2.4 GHz, have a gain of approximately 30 dB in bandwidths of 300 MHz, 225 MHz, and 310 MHz, and have minimum noise temperatures of 7.8 K, 8 K, and 15 K, respectively.**

I. Introduction

It has been proposed [1], [2] that galactic axions, if they exist, may be detected through their conversion to microwave photons in a strong magnetic field. The frequency of such a photon is proportional to the axion mass, constrained to lie between 10^{-3} eV and 10^{-6} eV [3]–[5].

A Rochester–Brookhaven–Fermilab [6] experiment attempts to convert axions to photons in a microwave cavity. This produces a signal whose expected power is of the order of 10^{-23} W in a 100 Hz bandwidth. To detect such a small signal, it is necessary to have a detector based on a very low noise cryogenic amplifier. The amplifier is critically coupled to the cavity through an inductive loop; to obtain the optimum signal-to-noise ratio it is important that cavity and amplifier be well matched [7].

Since the axion mass is not well constrained, our goal is to cover a 1–6 GHz frequency range using different tunable cavities, each of which is coupled to an amplifier whose bandpass matches the cavity tuning range.

In this paper we report the experimental results of gain and noise temperature for the first three amplifiers we built and describe the techniques used to test them.

II. Amplifier Description

The amplifiers we constructed are modified versions of the L-band amplifier designed by the National Radio Astronomy Observatory (NRAO) [8], which has very low noise, a wide bandwidth, and a 50 Ω input impedance, three features important to our application. The amplifiers use three GaAs FET stages in a lumped circuit element design with a stripline input network.

To date we have built two 1.1 GHz amplifiers (amplifiers 101 and 102) and one 2.4 GHz amplifier (amplifier 103). To adjust the amplifier to a new frequency band we changed the length of the $\lambda/4$ stripline input impedance transformer and the values of the inductors. Furthermore, for amplifier 103 we changed the original 10 dB output attenuator to a 3 dB one, and the FET drain lead RC filter parameters.

Fig. 1 shows the NRAO amplifier scheme and Tables I–V list the component values. Note that because the inductors are deformed to tune the amplifier the exact value of the inductance is not known after tuning. This accounts for the differences we observed between amplifiers 101 and 102.

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III. Optimization of the Amplifiers' Characteristics

Because the amplifiers are to be used at liquid helium temperature (4.2 K) and because it is impractical to change their parameters while they are in the helium bath, it is necessary to iteratively tune the amplifiers at room and liquid nitrogen temperature (77 K). We find that the input impedance and gain curve shape do not change substantially from 77 K to 4.2 K.

We first optimized the reflection coefficient by tuning the inductor L10 and moving the shorting plate on the input transformer T2. After a preliminary adjustment at room temperature, the amplifiers were tested and further adjusted in the nitrogen bath; many thermal cycles are usually required to obtain a small reflection coefficient.

To minimize the noise figure the principal adjustment is to tune the input inductor L1, while most of the other inductors determine the bandwidth and the gain of the amplifier. The same iterative technique has been used to adjust these, also.

In our application, low noise over a wide frequency band is important. As a consequence we tuned the components to maximize the width of the noise band without increasing the lowest noise of the amplifier.

IV. Cryogenic Amplifier Test Procedure

We used two different arrangements to determine the gain and the noise temperature of the amplifiers in liquid helium: a diode noise source with a spectrum analyzer for amplifier 101 and a noise figure meter for amplifiers 102 and 103.

A. Spectrum Analyzer Procedure

The basis of the gain and noise measurement is the detection of a difference in power spectral density at the amplifier output when the input power is varied. Indeed:

$$P_{\text{out}}(\omega)|_{\text{on}} = G(\omega)[P_N(\text{on}) + P_A]$$
$$P_{\text{out}}(\omega)|_{\text{off}} = G(\omega)[P_N(\text{off}) + P_A]$$

where $G(\omega)$ is the amplifier gain, P_N is the power supplied by the noise source biased (on) and unbiased (off), and P_A is the intrinsic amplifier noise. From these relations we obtain for the amplifier gain:

$$G(\omega) = \frac{P_{\text{out}}(\omega)|_{\text{on}} - P_{\text{out}}(\omega)|_{\text{off}}}{P_N(\text{on}) - P_N(\text{off})}$$

and the noise temperature T_N:

$$T_N(\omega) = \frac{P_A}{kGB} = \frac{P_{\text{out}}(\omega)|_{\text{off}} - P_N(\omega)|_{\text{off}}}{kGB}$$

where k is Boltzmann's constant and B is the measurement bandwidth.

A calibrated microwave diode noise source (Micronetics Inc. NSI-118) provided broad-band noise power to the amplifier input. The spectrum analyzer (Hewlett-Packard 3582A) measured the output power spectral density.

Fig. 2 shows the test arrangement. The postamplifier (Miteq AM-3A-1020) was needed to overcome the high intrinsic noise of the spectrum analyzer, and the 20 dB attenuator in the cold bath was necessary to bring the reference signal of the noise source to a low temperature when the noise source was unbiased. The connections between noise source and the attenuator, and the

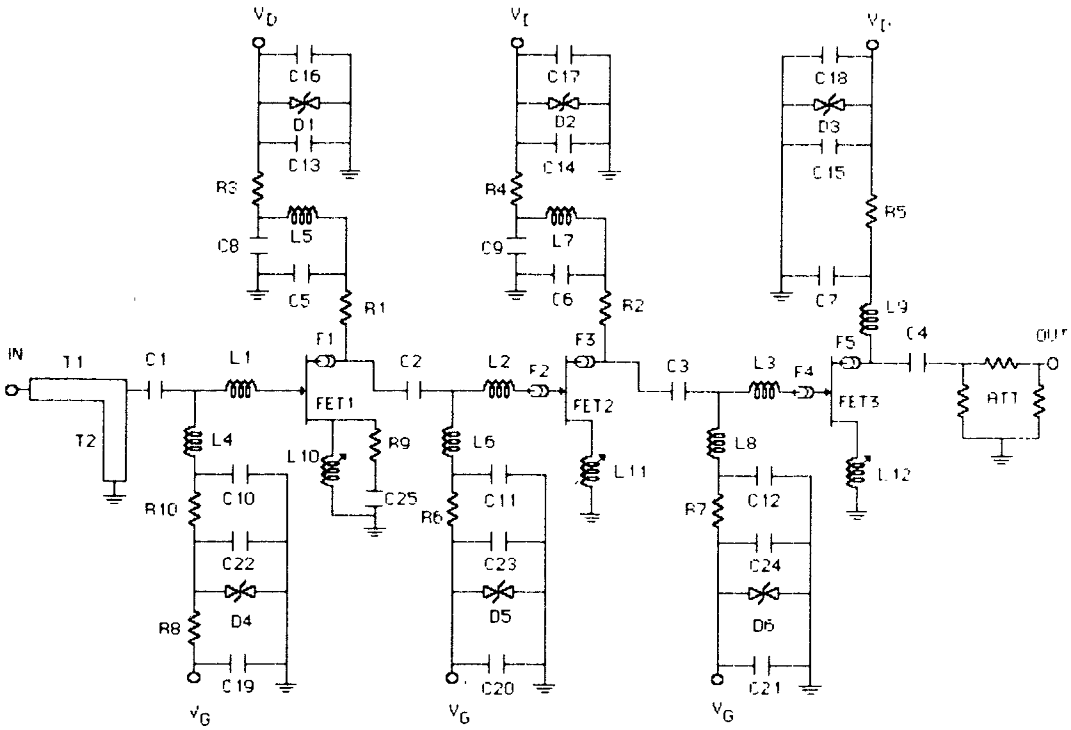

Fig. 1. Schematic diagram of the amplifier. F 1–5 are ferrite toroids; F4 was present only in amplifier 103

TABLE I*
INDUCTORS[(a)]

L	ID (mm)		Coil Length (mm)		Turns		Total Length (mm)		Total L (nH) (calculated)	
L1	2.1	**1**	2.0	**3**	4.25	**2**	3	**7**	32	**3.5**
L2[(b)]	1.8	—	2.5	—	4	**0**	3	**3**	21	**1.5**
L3	2.1	—	0.8	—	2	**0**	3	**(c)**	11	**1.4**
L4	2.1	**2.1**	3.8	**2**	5	**3**	9	**2**	30	**9.0**
L5	—	—	5.8	—	0	**0**	5.8	**2.5**	4.4	**1.4**
L6[(b)]	2.1	**2.1**	3.8	**2**	3	**3**	5.6	**5.6**	11.7	**9.0**
L7	—	—	4.6	—	0	**0**	4.6	**2**	3.3	**1.2**
L8	—	—	3.8	—	0	**0**	3.8	**3.5**	2.6	**2.0**
L9	2.1	**1**	3.8	**3**	5	**2**	9	**7**	30	**3.5**

***Bold face type indicates amplifier 103.**
[(a)]All wound with 0.25 mm diameter wire.
[(b)]Wind in reverse direction from other coils.
[(c)]For this inductor we used the lead of the FET drain.

TABLE II*
CAPACITORS

Capacitors	C (pF)
C1 = C7 = C10 = C11 = C12	22
C2 = C3 = C4	16
C5 = C6	1–**0.5**
C13 = $\cdots$ = C24	680

***Boldface indicates amplifier 103.**

TABLE III
RESISTORS

Resistors	R (Ω)
R1 = R2	50
R3 = R4	49.9
R5 = R10	100
R6 = R7 = R8	1000

TABLE IV*
IMPEDANCE TRANSFORMER

Line	Length (mm)	
T1	19.63	**11.3**
T2	27.31	

***Boldface indicates amplifier 103.**

TABLE V*
DIODES AND FET'S

Diodes	Type	FET	Type
D1 = D2 = D3	IN4099	FET1	MITSUBISHI MGF 1412
D4 = D4 = D6	IN821	FET2	MGF 1412
		FET3	MGF 1402 **MGF 1412**

***Boldface indicates amplifier 103.**

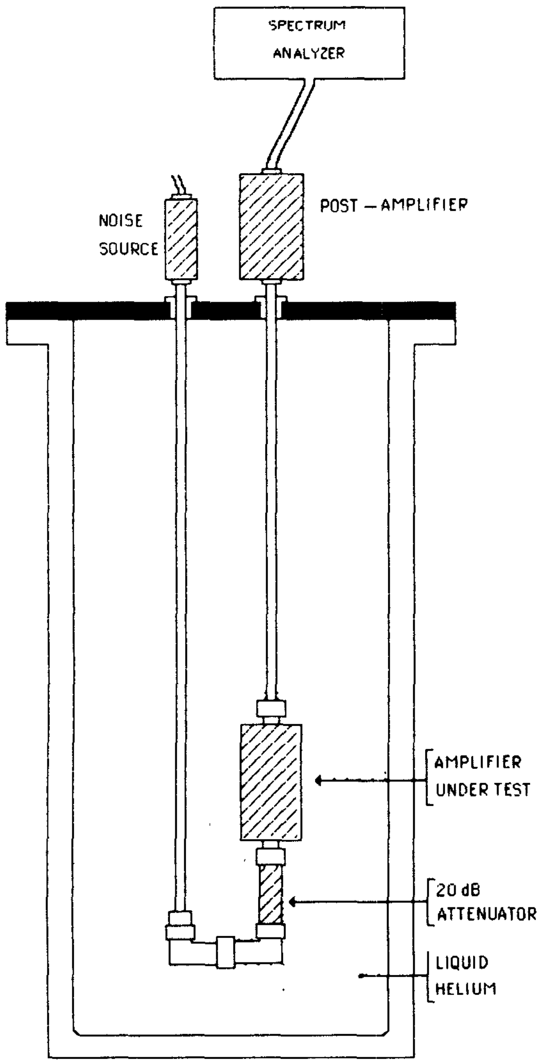

Fig. 2. Spectrum analyzer test arrangement.

preamplifier output and postamplifier were made with 50 Ω, 0.141 in. copper conductor/Teflon dielectric coaxial lines. For the warm connections we used flexible coaxial lines.

It is necessary to determine the attenuation of the input components and the characteristics of the postamplifier to obtain the correct values for the amplifier gain and noise temperature. These are given by

$$G = \frac{\Delta P}{\Delta p(1-A)}$$

$$T_N = \left(\frac{P}{kG_p B} - T_p\right)\frac{1}{G} - AT_B - (1-A)T_s$$

where ΔP is the power difference at the spectrum analyzer (with the amplifier) with the noise source on and off, Δp is the power difference at the spectrum analyzer (postamplifier only) with the noise source on and off, P is the total power seen at the spectrum analyzer, $(1-A)$ is the power transmission of the input line and the attenuator, T_B is the physical temperature of the attenuator, T_p is the noise temperature of the postamplifier, T_s is the noise temperature of the noise source and G_p is the post-amplifier gain.

When the noise temperature expression is written in terms of directly measured quantities, the largest contribution to the error

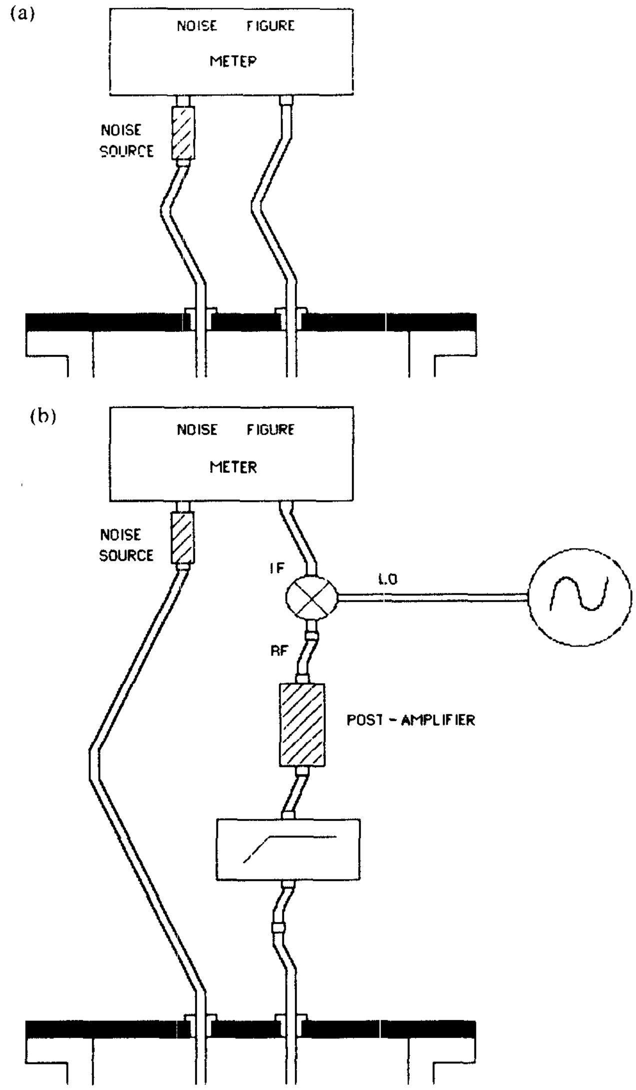

Fig. 3. Noise figure meter test arrangement for (a) amplifier 102 and (b) amplifier 103. Because the noise figure meter has a 0.5–1.5 GHz frequency range, for amplifier 103 we down-converted the frequency with a mixer (Hewlett-Packard HMXR-5001; local oscillator frequency 3.6 GHz). A 2 GHz high-pass filter eliminated out-of-band signals from the amplifier. The postamplifier used was a Miteq AFD4-020040-30.

is seen to come from the nonlinearity of the spectrum analyzer, which we have taken to be the manufacturer's claim of 0.5 dB. The error is typically 2 K.

B. Noise Figure Meter Procedure

In this scheme we again used a calibrated microwave diode noise source (Hewlett-Packard 346B), controlled by the noise figure meter (Hewlett-Packard 8970A), that automatically makes measurements with the noise source biased and unbiased after a self-calibration of the system. With this procedure the noise figure meter displays the amplifier noise figure and gain curve.

The arrangements used are shown in Fig. 3(a) (amplifier 102) and 3(b) (amplifier 103). Again, the error depends only on the nonlinearity of the instrument and of the noise source, claimed by the manufacturer to be 0.1 dB.

V. Results

Fig. 4 shows the gain G and the noise temperature T_N at liquid helium temperature for the three amplifiers. All of them possess a 3 dB bandwidth larger than 200 MHz, approximately the tuning

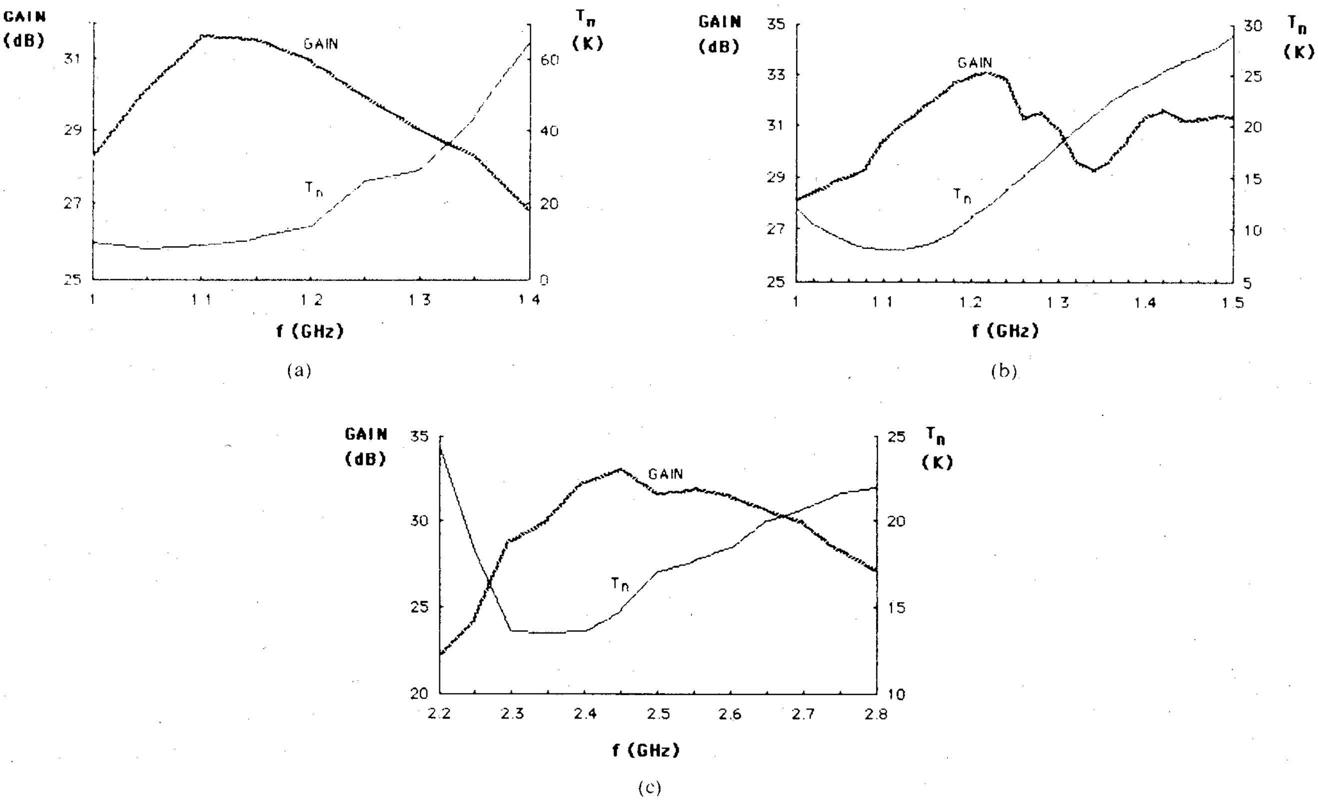

Fig. 4. Gain G and noise temperature T_N for the three amplifiers at 4.2 K.

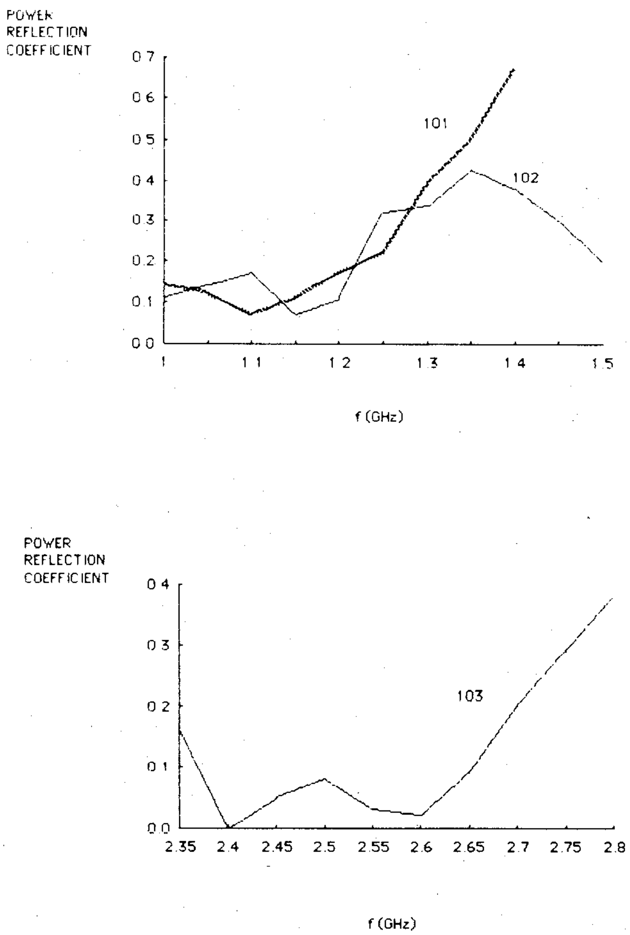

Fig. 5. Reflection coefficient for the three amplifiers.

range of our cavities. The minimum noise temperatures we obtained for these amplifiers were (7.8±1.7) K for amplifier 101, (8±0.5) K for 102, and (13.5±0.8) K for amplifier 103. For comparison, room temperature gains and noise temperatures were 21.8 dB, 28.3 dB, and 29.5 dB and 67 K, 122 K, and 102 K for amplifiers 101, 102, and 103, respectively. Fig. 5 shows the input power reflection coefficient for the three amplifiers.

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