Title
LOW-NOISE CRYOGENICALLY COOLED BROAD-BAND MICROWAVE PREAMPLIFIERS

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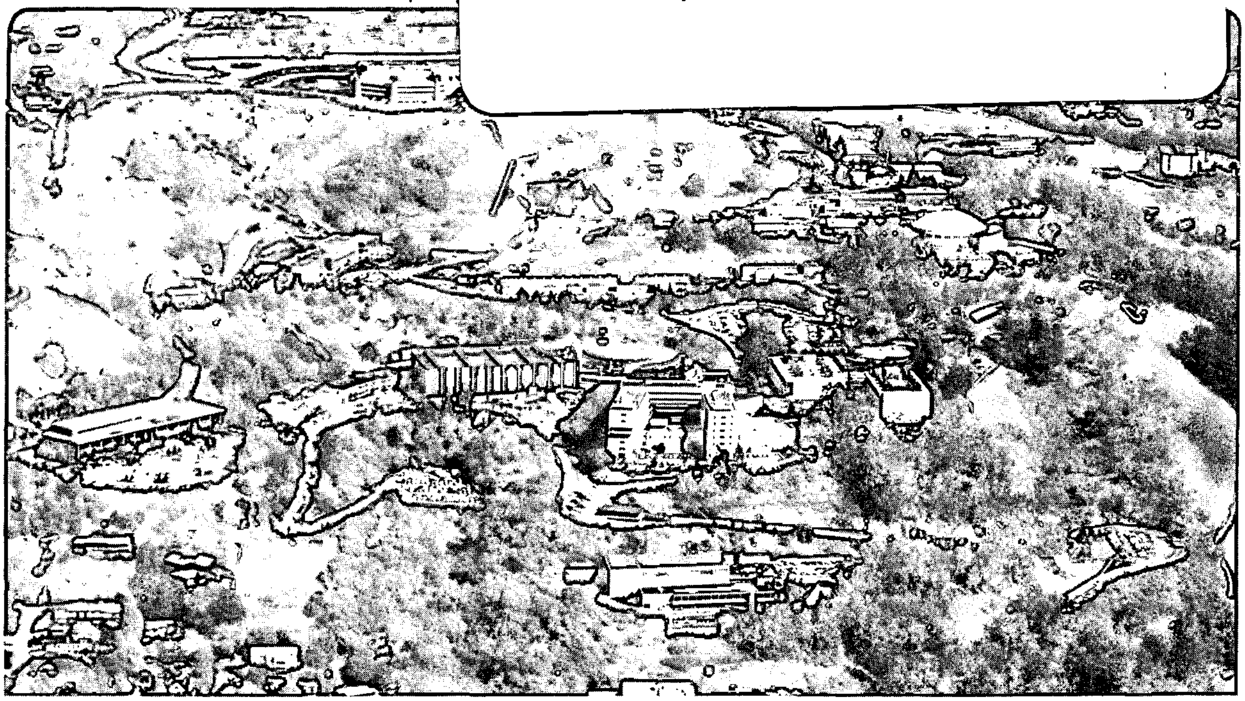
Low-Noise Cryogenically Cooled Broad-Band Microwave Preamplifiers

B. Leskovar

April 1987



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DISCLAIMER

LOW-NOISE CRYOGENICALLY COOLED BROAD-BAND MICROWAVE PREAMPLIFIERS

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Abstract

The present noise performance, bandwidth capability and gain stability of low-noise cryogenically cooled broad-band preamplifiers are summarized and reviewed in the 150 MHz - 4 GHz frequency range. Stability factor of Galium Arsenide Field-Effect transistors as a function of frequency and ambient temperature is presented and discussed. Also other performance data, such as gain nonuniformity, phase shift as a function of frequency, and voltage standing-wave ratio, of several low-noise wide-band preamplifiers of interest for research instrumentation systems are presented.

Introduction

In many instrumentation systems for experimental research, such as those for stochastic cooling of antiprotons in storage rings, radio astronomy and space communication, there are at present no devices operating at room temperature which have sufficiently low noise. Consequently, cryogenic cooling is required for the low-noise preamplifiers, mixers, upconverters and detector devices used in these applications to achieve the lowest possible noise (1). A number of cryogenically cooled narrow-band preamplifiers have been successfully designed for the microwave frequency region offering a noise temperature as low as 20 K (2). Also for the above mentioned instrumentation systems a broad-band frequency capability of amplifier is often necessary (3-8). This paper summarizes and compares the present performance of cryogenically cooled amplifiers for the 150 MHz - 4 GHz frequency range using Gallium Arsenide Field-Effect transistors.

Noise of Cryogenically-Cooled GaAs FET's

Generally, microwave FETs 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 to silicon. Furthermore, at temperatures below 125 K electrons are frozen out of the conduction band and holes out of the valence band for silicon leaving the semiconductor with very few carriers to support device operation. In the case of GaAs no freeze out occurs at cryogenic temperatures because of the extremely small energy gap between donor levels and the conduction band for most n-type dopants used in FET's (6 meV for sulfur, selenium and tin and 3 meV for tellurium). A comprehensive treatment of noise theory of FETs is given in Ref. 9. In summary, the noise in a microwave FET is caused by thermal, hot-electron, and high-field diffusion effects. For frequencies below 3 GHz the noise is possibly also caused by trap generation-recombination effects. The thermal noise of 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, for GaAs the transconductance increases with a decrease of temperature because of the increase in free carrier mobility and saturated velocity. The increase of mobility is caused by fewer collisions with energetic lattice and is approximately proportional to $T^{-3/2}$ for physical temperatures above 60 K. Hot-electron and high-field diffusion noise may remain constant or increase at cryogenic temperatures, depending upon 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 a 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 (5). On the basis of these measurements the Mitsubishi devices MFG 1402 and MGF 1412 were selected as most suitable for detailed study. The device MGF 1402 was used in the design of a broadband 150-500 MHz preamplifier. Schematic diagram of the preamplifier is given in Fig. 1. The preamplifier 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. 2. The noise figure has a value of 1.4 dB and 0.35 dB at ambient temperature of 300 K and 20 K, respectively.

There was a significant increase of the noise figure values at frequencies below 100 MHz because of the presence of 1/f noise. A reduction of the ambient transistor temperature from 300 K to 20 K was found to have a very small effect on the noise figure value at these frequencies.

Design Considerations for Low-Noise Wide-Band Preamplifiers

Design criteria for low-noise wide-band preamplifiers for instrumentation systems for experimental research 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 can not be operated over a wide frequency band 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 preamplifier's characteristics such as noise figure and gain stability.

It has been shown previously that MGF 1402 and MGF 1412 transistors offer excellent noise performance when used in the narrow-band amplifiers. In Fig. 3 noise figure is shown as a function of frequency for the two transistors for a frequency range from 0.5 GHz to 12 GHz. Noise figure values are given for the narrow-band application of devices under noise matched conditions and corrected for the circuit losses. To calculate the device stability factor K_S and factor Δ as a function frequency (4), the scattering parameters were measured for five devices in the frequency range from 0.5 to 2.0 GHz at an ambient temperature of 300 K. These transistors showed a relatively small spread of S-parameters between various device numbers. The transistor stability factor K_S and factor Δ were calculated from the S-parameter data using the following equations:

$$K_S = \frac{1 + \left| S_{11}S_{22} - S_{12}S_{21} \right|^2 - \left| S_{11} \right|^2 - \left| S_{22} \right|^2}{2 \left| S_{21} \, S_{12} \right|} \qquad (1)$$

$$\text{and } \Delta = \left| S_{11}S_{22} - S_{12}S_{21} \right| \qquad (2)$$

The results of the calculations are shown in Fig. 4.

It can be seen from the results given above that this transistor does not satisfy the necessary and sufficient conditions for unconditional stability

$$K_S > 1 \text{ and } \Delta < 1 \qquad (3)$$

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 using a low loss FET source inductive series feedback to offset 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. However, our calculations and measurements have shown that this type of feedback can be only partially applied because it seriously decreases the device gain when the value of $K_S = 1$ is approached. Alternatively, it is also possible to use parallel feedback, consisting of a capacitance and resistance applied from the gate to the drain of GaAs FET to increase the stability factor. Our analyses have shown that a wide frequency band, 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 an ambient temperatures around 300 K. This increase is mostly due to various losses presented 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. At cryogenic temperatures these losses will be reduced resulting in a decrease of the noise figure. Results of these analyses on parallel feedback properties are in a good agreement with data recently obtained with FET broadband amplifiers operating at 300 K (10).

Low-Noise 1-2 GHz Preamplifier Design

Figure 5 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 T1, inductors L1, L3 and L11. Inductors L4 and L6 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 voltage standing-wave ratio, (VSWR), would likely yield a very low value of the noise temperature across the octave bandwidth. Interstage matching was mainly done by inductors L6, L12, L9 and L13. 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 its own separate current regulator. 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 20 GHz, as was shown above. 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 L11. This incuctor can be represented by an impedence Z_{FL} 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 L11/C, where g_m and C are the transistor transconductance and gate capacitance, respectively (3). 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 a good thermal conductivity. While this is not the best way to obtain an extremely low thermal gradient, the relative ease of assembly offsets a relatively small loss in performance.

The other inductor used to obtain a better input matching was L1, which was connected about midway of T1. By moving L1 back and forth about this point, the best match could be realized for the 1-2 GHz octave bandwidth. Furthermore, 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 transistor leads.

The gain characteristics are obtained from the measurements of S_{21} scattering parameter and are shown in Fig. 6. 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 ± 1.5 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 noise figure measurements, made using a hot-cold source are presented in Fig. 7. The noise figure across the 1-2 GHz band at 80 K varied from 0.35 - 0.45 db ± 0.03 dB. At 18 K the noise figure decreased to 0.25 - 0.35 dB± 0.03 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.

The phase characteristics of the preamplifier are shown in Fig. 8. At room temperature the phase variation was ±17° decreasing to ±15° at 80 K and ±13° at 18 K. The group delay of the preamplifier was 2.5 ns ±0.2 ns.

The input voltage standing-wave ratio and impedance data were derived from the S_{11} measurement. The output VSWR and impedance data were obtained from the S_{22} measurement. Figure 9 shows the input and output VSWR's of the preamplifiers at 296 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.

Low-Noise 2-4 GHz Preamplifier

The circuit schematic of the preamplifier is shown in Fig. 10. To optimize the gain and low noise performance of the preamplifier separate gate and drain bias supplies were provided for each transistor. However, as designed, the amplifier exhibits a broad optimum bias point arount I_D = 10 mA and V_{DS} = 4.0 V. Unfortunately, with the grounded source connection used and because of production tolerances of these devices, common gate and drain supplies for all four transistors were not possible.

The gain characteristics are obtained directly from measurements of the S_{21} parameter and are shown in Fig. 11. Over the passband of 2-4 GHz and at an ambient temperature of 300 K the gain was 34.4 ±0.6 dB. At 80 K the gain has increased to 38.8 ±0.7 dB, and at 20 K the gain has decreased to 38.0 ±0.7 dB.

The noise figure measurements, made using a hot-cold source, are presented in Fig. 12. At 300 K, the noise figure over the passband averages 1.3 dB, but rises to 1.8 dB at 2 GHz and 1.5dB at 4 GHz. At 80 K, the average noise figure has been reduced to 0.65 dB, and at 20 K this figure is further reduced to 0.55 dB.

Although made with lumped components and packaged devices the two prototype models exhibited very similar characteristics. However, this required very careful control of the physical layout and construction.

The phase characteristics of the preamplifier are shown in Fig. 13. At room temperature the phase variation was from +10° to -14° increasing to 22° at 80 K.

The input and output VSWR were obtained from measurements of S_{11}, and S_{22} respectively. The input VSWR is <2.0 over the passband of 2-4 GHz at 300 K and 80 K, but does rise above 2.0 at 20 K. The output VSWR is <2.0 over the passband at all three ambient temperatures.

Acknowledgements

This work was performed as part of the program of the Electronics Research and Development Group of the Lawrence Berkeley Laboratory, University of California, Berkeley, and was supported by the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

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Subject Index

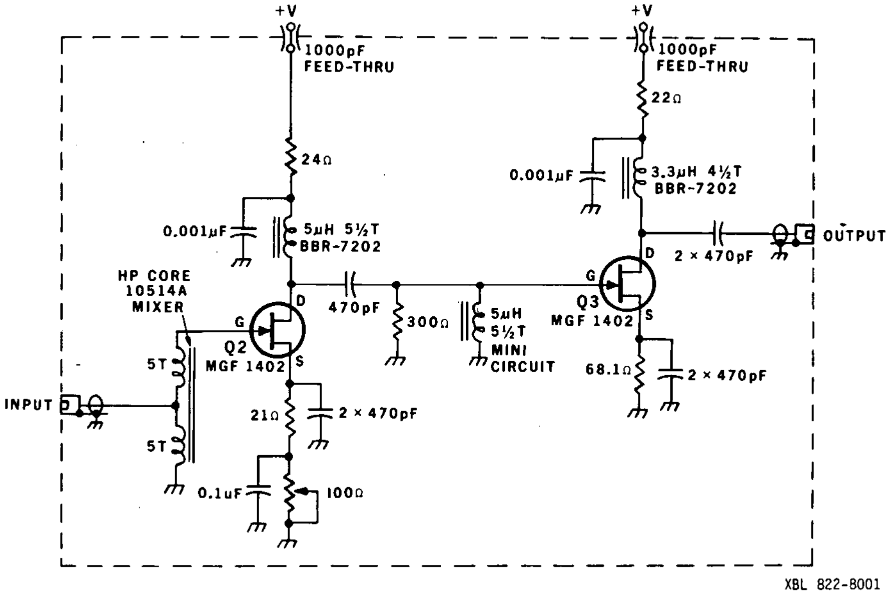


Fig. 1. Schematic diagram of the 150-500 MHz preamplifier.

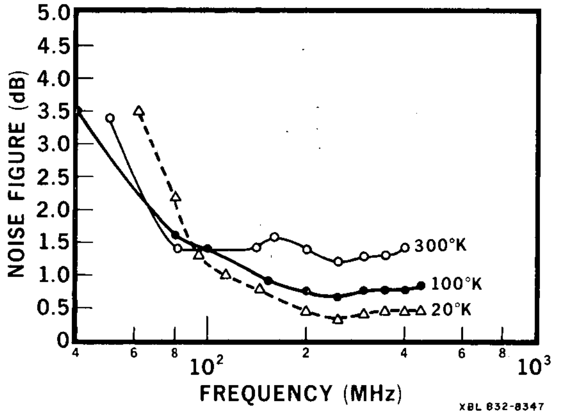


Fig. 2. Preamplifier noise figure as a function of frequency for MGF 1402 Field-Effect Transistors at ambient temperatures of 300K, 100K and 20 K.

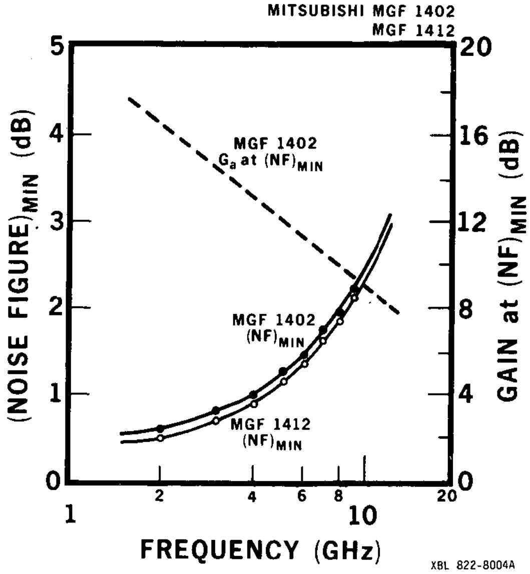


Fig. 3. Noise figure versus frequency for Mitsubishi MGF 1402 and 1412 transistors.

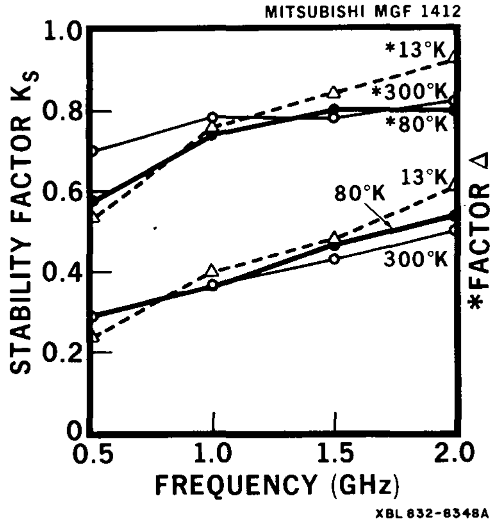


Fig. 4. Stability factor K_S and factor Δ as a function of frequency for MGF 1412 transistor.

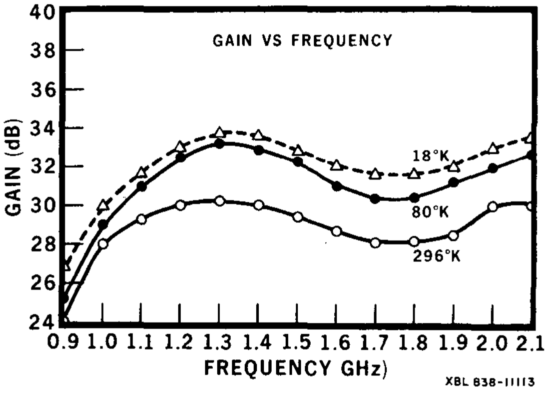
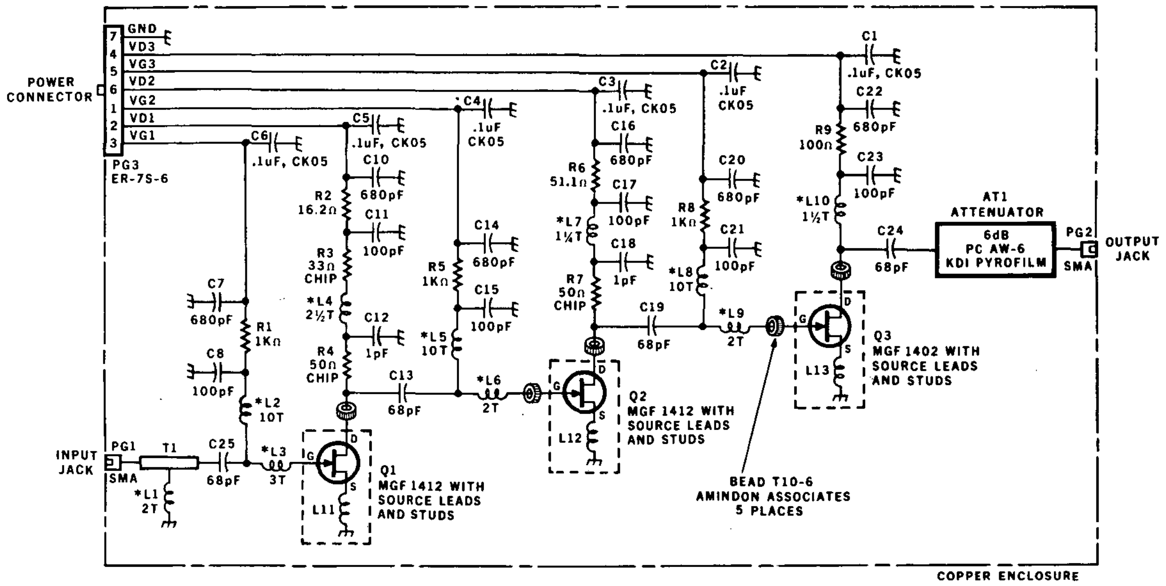


Fig. 6. Preamplifier gain as a function of frequency at ambient temperatures of 296 K, 80 K and 18 K.



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) ≈4T/0.1 INCH.

XBL 838-11111

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

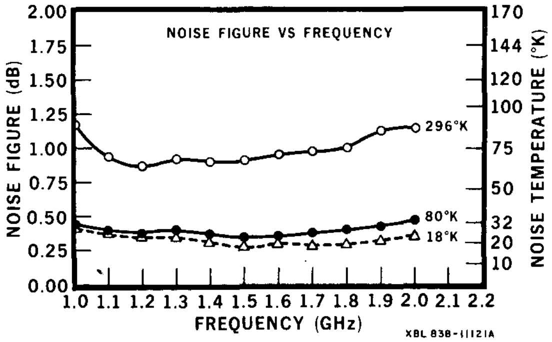


Fig. 7. Noise figure of the preamplifier as a function of frequency at ambient temperatures of 296 K, 80 K and 18 K.

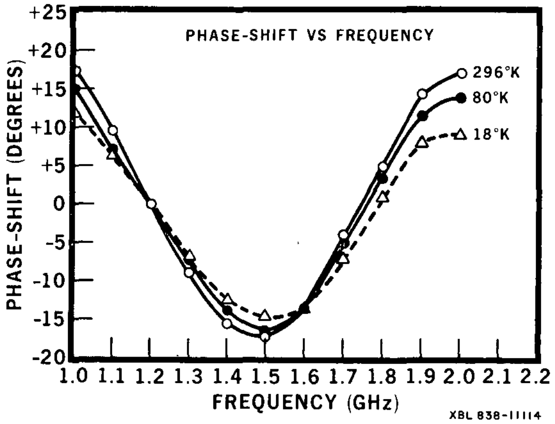


Fig. 8. Preamplifier phase-shift as a function of frequency at ambient temperatures of 296 K, 80 K and 18 K.

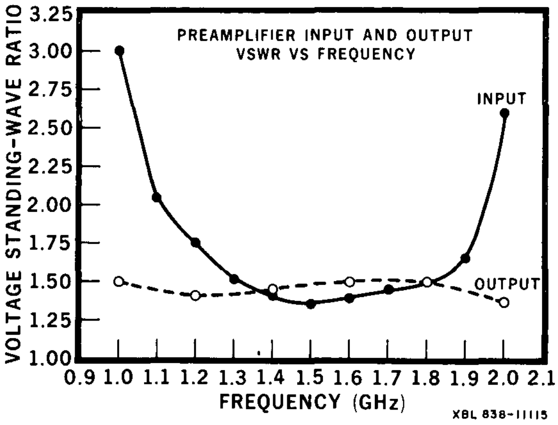


Fig. 9. Input and output Voltage Standing - Wave Ratio of the preamplifier.

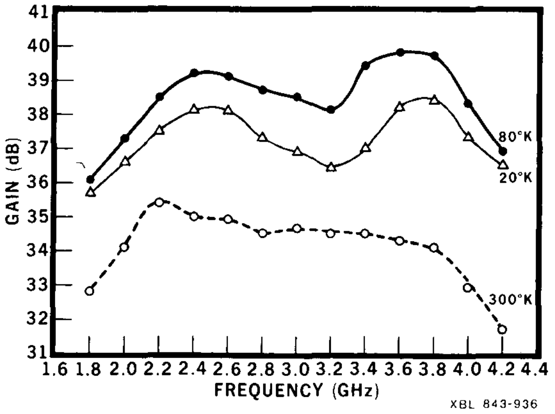
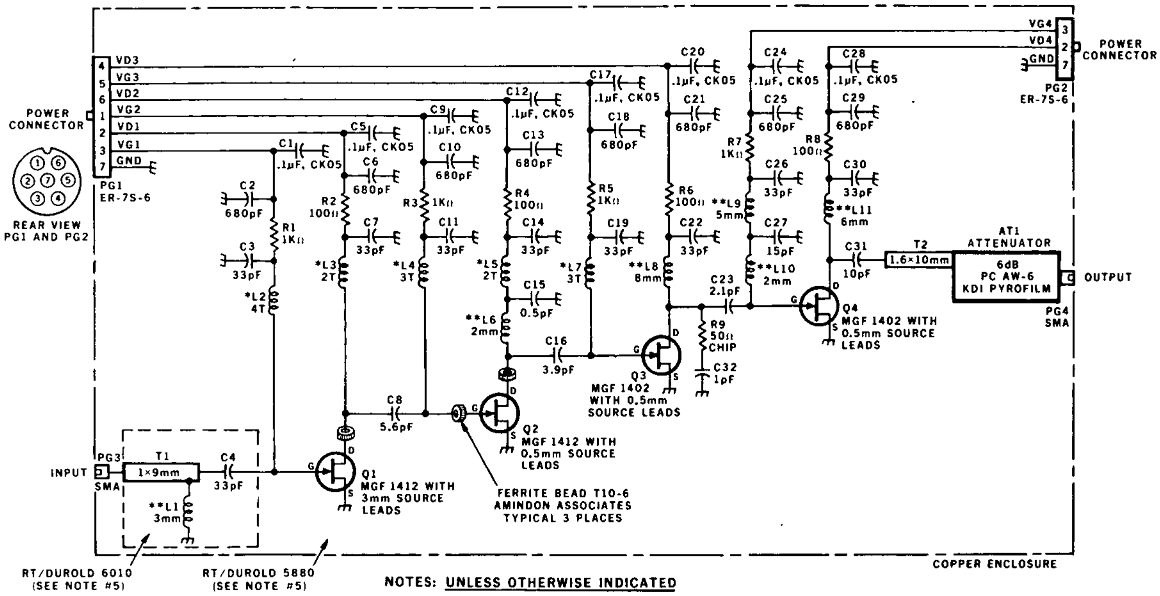


Fig. 11. Preamplifier gain as a function of frequency measured at an ambient temperatures of 300 K, 80 K and 20 K.



NOTES: UNLESS OTHERWISE INDICATED

1. CAPACITORS CHIP TYPE.
2. RESISTORS 1/8W 1% METAL FILM.

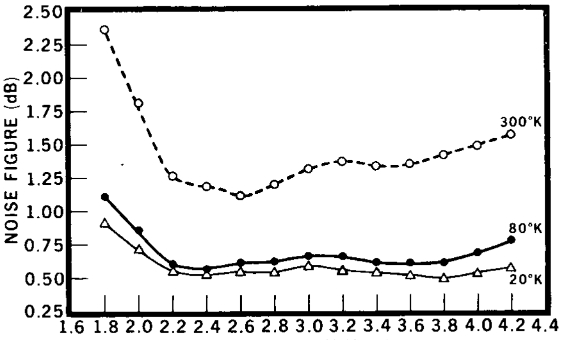
*3. COILS MADE OUT OF 0.25mm DIA. GOLD PLATED PHOSPHOR BRONZE WIRE USING 1mm DIA. WIRE AS A COIL FORM.

**4. STRAIGHT LENGTH OF 0.25mm DIA. GOLD PLATED PHOSPHOR BRONZE WIRE.

5. SUBSTRATE MATERIAL: RT/DUROLD 5880 EXCEPT T1, L1 AND C4 ON RT/DUROLD 6010 AS SHOWN ON SCHEMATIC.

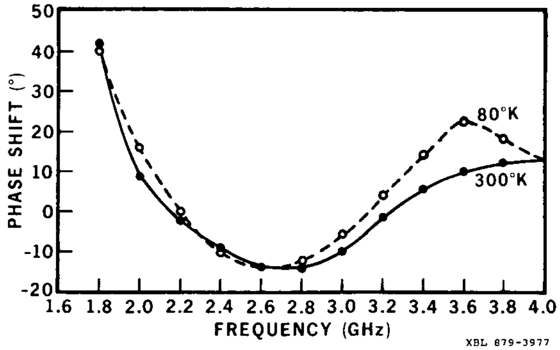
XBL 843-935

Fig. 10. Schematic diagram of the 2-4 GHz preamplifier.



XBL 843-940

Fig. 12. Preamplifier noise figure as a function of frequency measured at an ambient temperature of 300 K, 80 K and 20 K.



XBL 879-3977

Fig. 13. Preamplifier phase-shift as a function of frequency at ambient temperature of 300 K.

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