A Cooled 1- to 2-GHz Balanced HEMT Amplifier[1]

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The design details and measurement results for a cooled L-band (1 to 2 GHz) balanced high-electron-mobility-transistor (HEMT) amplifier are presented here. The amplifier uses commercially available packaged HEMT devices (Fujitsu FHR02FH). At a physical temperature of 12 K the amplifier achieves noise temperatures between 3 and 6 K over the 1- to 2-GHz band. The associated gain is approximately 20 dB.

I. Introduction

Cryogenically cooled high-electron-mobility-transistor (HEMT) amplifiers have realized noise temperatures as low as the operating frequency (in GHz) of the amplifier up to 43 GHz [1,2]. These amplifiers have now become the standard for radio astronomy applications. Cooled HEMT amplifiers are also used as the first intermediate frequency (IF) stage in millimeter-wave superconductor-insulator-superconductor (SIS) and Schottky mixer systems. In these receivers the noise performance of the IF amplifier is very important because the mixer is usually lossy.

Most millimeter-wave receiver systems built for radio astronomy use an L-band (1 to 2 GHz) IF amplifier with a bandwidth of approximately 500 MHz and a noise temperature of approximately 4 K [3,4]. In a typical 115-GHz SIS receiver the IF amplifier contributes approximately 30 percent of the total receiver noise. A bandwidth of 500 MHz is barely sufficient for observations of sources with high velocity dispersion and it limits the capability of systems to observe several molecular transitions simultaneously. Increasing the receiver bandwidth by using a higher frequency IF amplifier is not acceptable because this would increase the IF noise contribution and therefore degrade the sensitivity of the system. The authors' approach to this problem has been to develop a 1-GHz bandwidth L-band cooled HEMT amplifier, while retaining < 6-K noise temperature.

A significant problem in the design of a wideband cooled amplifier is obtaining scattering parameters (*s*-parameters) and noise parameters for transistors at cryogenic temperatures. For this work, no facilities were available for measuring low-temperature *s*-parameters, but the HEMT noise parameters were measured at a physical temperature of 12 K. The absence of *s*-parameter information precluded the design of a feedback amplifier, so a bal-

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anced configuration was adopted. This has the advantage of providing a good input match even though the amplifiers in the two arms of the balanced circuit are poorly matched. However, there are disadvantages. The loss of the input hybrid degrades the noise temperature, and coupling errors in the hybrids and differences between the amplifiers reduce the gain and result in a noise contribution from the input load. In the amplifier described here these effects degrade the noise temperature by less than 1 K.

II. Noise in a Balanced Amplifier

The noise contributions in a balanced amplifier are explored in Fig. 1. Each hybrid directs a fraction c of the input power to the 0-deg port and the remaining power to the 90-deg port. The deviation from quadrature at the outputs is θ. To simplify the analysis, the amplifiers are assumed to have similar gains but different transfer function phases. In practice, this situation can be approached by selecting similar devices and by adjusting the bias.

The power gain of the balanced amplifier (with the input terminated in a matched source and the output terminated in a matched load) is

$$G = 2gc(1-c)(1+\cos\phi) \tag{1}$$

where g is the power gain of each amplifier in the balanced structure and ϕ is the phase difference between the amplifier transfer functions. The output noise temperature with the input terminated in a matched source at 0 K is

$$T_{out} = gT_o\left[(2c^2-2c+1)-2c(1-c)\cos\phi\right]+gT_a \tag{2}$$

where T_o is the physical temperature of the input hybrid termination and T_a is the input equivalent noise temperature of each amplifier. The first term is the contribution from the input hybrid termination and the second term represents the noise generated by the amplifiers. Note that the noise from the two amplifiers is uncorrelated. The input noise temperature of the balanced amplifier is

$$T_n = \frac{T_{out}}{G}$$

$$T_n = \frac{T_o[(2c^2-2c+1)-2c(1-c)\cos\phi]+T_a}{2c(1-c)(1+\cos\phi)} \tag{3}$$

The loss of the input hybrid can be modeled as an attenuator at the amplifier input. Loss in the output hybrid affects only the overall gain (and hence the noise contribution of the next stage). With an input hybrid loss L, the noise temperature of the balanced amplifier is

$$T_n' = T_o(L-1)+LT_n \tag{4}$$

where T_n is given by Eq. (3). As an example of what might be achieved, a balanced circuit containing amplifiers with $T_a = 4$ K, $\phi = 5$ deg, hybrids with coupling errors of 1 dB ($c = 0.40$), and excess loss of 0.1 dB would have a noise temperature of 5.09 K at a physical temperature of 12 K. If the input load were at 4 K instead of 12 K, the noise temperature would be 4.73 K.

III. HEMT Device Noise Parameters

Device noise parameters for this work were obtained from measurements of the noise temperatures of several single-ended amplifiers each with a different input-matching network. The same HEMT device was used for the entire set of measurements. Previous work with GaAs field effect transistors (FETs) at L-band provided an estimate of the optimum source impedance so that it was necessary to explore only a small part of the source impedance plane in order to determine the HEMT noise parameters [5].

Different source impedances were provided using a cryogenically coolable test fixture. The input section consisted of a microstrip transformer realized on 60-mil thick RT/Duroid 6002[2] ($\epsilon_r = 2.94$) and a series chip inductor[3] close to the HEMT package. The output section was a 50-Ω microstrip line of the same substrate type. Connections to the HEMT device were simple pressure contacts which allowed easy removal of the input-matching network assembly. The input substrates were transferred to a different fixture fitted with sub-miniature series A (SMA) connectors to allow measurement of the source impedance presented to the HEMT.

Noise temperature measurements were made using the arrangement of Fig. 2. A cooled 20-dB attenuator at the amplifier input provides a cold load, and signals enter and leave the cryostat via low-loss coaxial lines. The losses of the lines, connectors, input bias network, and the 20-dB attenuator were measured at 12 K. These data along with measurements of the noise temperature of the receiver in

[2] RT/Duroid 6002 manufactured by Rogers Corporation, Microwave Materials Division, 100 S. Roosevelt Ave., Chandler, Arizona.

[3] Surface mount inductor series 1008CS manufactured by Coilcraft, 1102 Silver Lake Rd., Cary, Illinois.

Fig. 2 were used to calculate the noise temperature of the amplifier from measurements of the system noise temperature at the cryostat input. A solid-state noise source calibrated against liquid nitrogen and ambient loads was used for the measurements.

The amplifier noise temperature is related to the source impedance, $R + jX$, by

$$T = T_{min} + 290\frac{g_n}{R}\left[(R - R_{opt})^2 + (X - X_{opt})^2\right] \qquad (5)$$

where $R_{opt} + jX_{opt}$ is the optimum source impedance, g_n is the noise conductance, and T_{min} is the minimum noise temperature [6]. The noise parameters $\{R_{opt}, X_{opt}, g_n, T_{min}\}$ were obtained from the results of ten measurements of T with different source impedances using a least-squares fit to Eq. (5). Although the final amplifier was constructed using Fujitsu FHR02FH (200 μm × 0.25 μm) devices, the noise parameters were measured for a General Electric (GE) (300 μm × 0.25 μm) AlGaAs/GaAs HEMT in a standard 70-mil package [7]. Recent work with FHR02FH chips indicates that the packaged GE and packaged Fujitsu devices have very similar R_{opt} and X_{opt} values at L-band [8]. The measured noise parameters for the GE HEMT are summarized in Table 1. FHR02FH devices have g_n values approximately equal to 0.03 milliSiemens (mS) and are therefore less sensitive than the GE device to deviations from the optimum source impedance.

IV. Amplifier Design

The input-matching circuit for each arm of the balanced amplifier consists of a 71-Ω line ($\lambda/4$ at 1.5 GHz) and a 10-nH series inductor. This gives a good noise match over the 1- to 2-GHz band and is reasonably compact and low loss. The impedance of the transformer and the value of the inductor were chosen to minimize $\left[(R - R_{opt})^2 + (X - X_{opt})^2\right]$ over the 1- to 2-GHz band. Figure 3 shows measurements of the impedance presented by the matching circuit along with the optimum source impedance from Table 1. The calculated increase in noise temperature due to deviation of the source impedance from optimum is approximately 1 K. A single-ended amplifier was constructed with the input-matching circuit described above and a 50-Ω load at the output. The performance is shown in Fig. 4. As expected, the noise temperature increases by approximately 1 K at the band edges. Since the gain shows only a gentle slope across the band, no attempt was made to adjust the output match.

The 90-deg hybrids in the balanced amplifier are 6-finger Lange couplers [9]. These are realized on the same 60-mil RT/Duroid 6002 substrate as used for the matching networks. At room temperature, the measured coupler insertion loss is approximately 0.2 dB, the coupling error is < 0.5 dB, and the deviation from phase quadrature is < 2 deg.

A schematic of the complete balanced amplifier is shown in Fig. 5 and the construction details are indicated in Fig. 6. To ensure good thermal coupling to the box, the HEMT devices are clamped to posts which protrude through the circuit board. The bias circuits are configured to allow independent biasing of the two HEMTs, although in practice this has not been necessary.

V. Results

Two prototype balanced amplifiers were constructed with Fujitsu FRH02FH HEMTs, and the noise temperatures and gains at a physical temperature of 12 K are shown in Figs. 7 and 8. Both amplifiers have noise temperatures in the range of 3 to 6 K. For these measurements the bias of both HEMT devices was adjusted to minimize the noise temperature. In Figs. 7 and 8, both transistors have the same bias. No other tuning was done, so the results indicate typical performance for a production amplifier. Some improvement in noise temperature might be obtained by adjusting the values of the inductors in the matching networks.

Input and output return losses were measured for one amplifier at 12 K and these data are shown in Fig. 9. The worst-case input return loss is 13 dB, but over most of the band the return loss is better than 15 dB. All the results were obtained with no illumination of the HEMTs.

VI. Conclusions

This article was a description of a 1- to 2-GHz cooled balanced HEMT amplifier. At a physical temperature of 12 K the amplifier has a noise temperature in the range of 3 to 6 K and a gain of approximately 20 dB. The amplifier was designed primarily as a wideband IF amplifier for millimeter-wave radio astronomy, but it also has applications in wideband L-band receiver systems.

References

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Table 1. Noise parameters for the GE HEMT

Frequency, GHz	R_{opt}, Ω	X_{opt}, Ω	g_n, mS	T_{min}, K
1.0	100 ± 20	160 ± 20	0.07 ± 0.03	4.5 ± 1
1.5	80 ± 10	160 ± 20	0.07 ± 0.03	3.5 ± 1
2.0	80 ± 20	120 ± 20	0.13 ± 0.09	4.5 ± 1

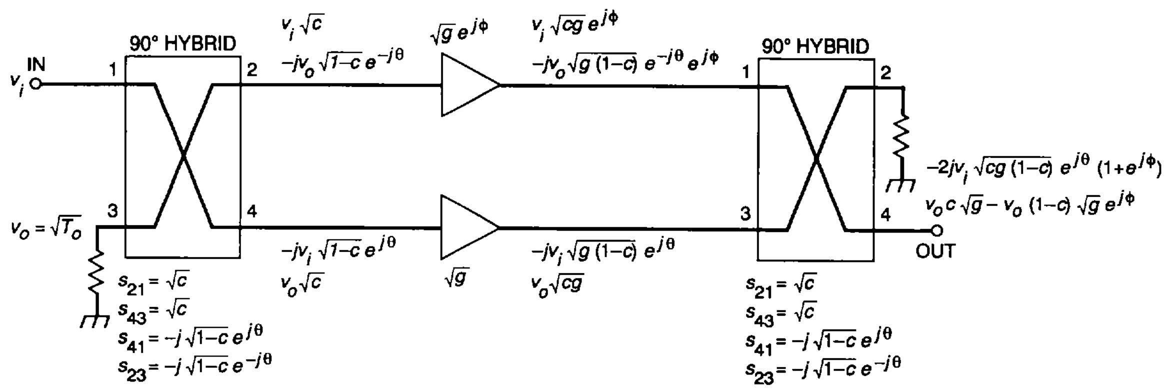

Fig. 1. Voltages in a balanced amplifier. The italicized terms indicate voltages due to input v_i. The other terms indicate noise voltages due to the input hybrid termination. The time dependent and delay terms have been omitted.

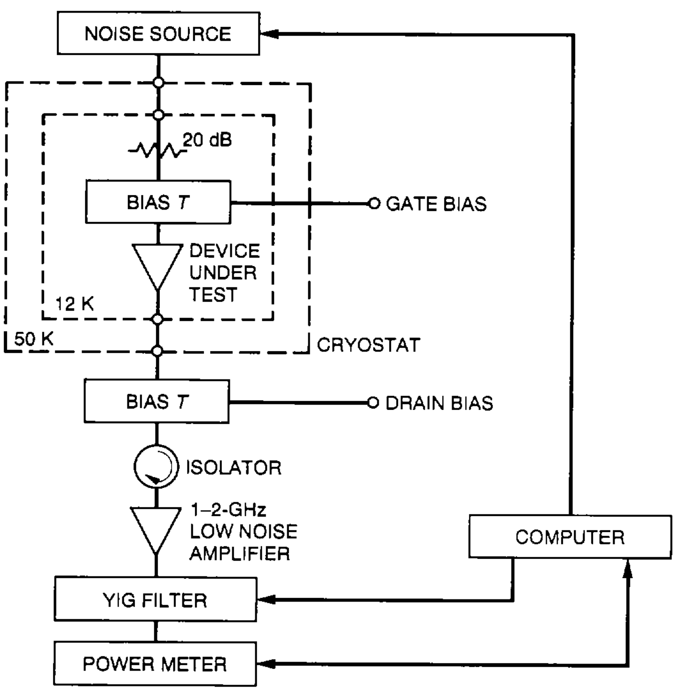

Fig. 2. Noise temperature measurement system.

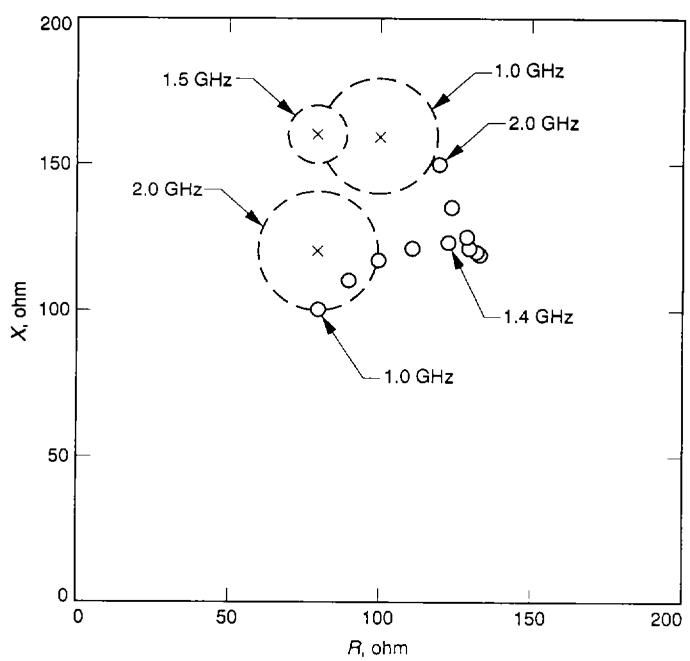

Fig. 3. Measured impedance of the amplifier input-matching circuit at 100-MHz intervals (solid circles) and the optimum source impedance from Table 1 (dashed circles). The size of the dashed circles indicates the uncertainty in the optimum source impedance measurements.

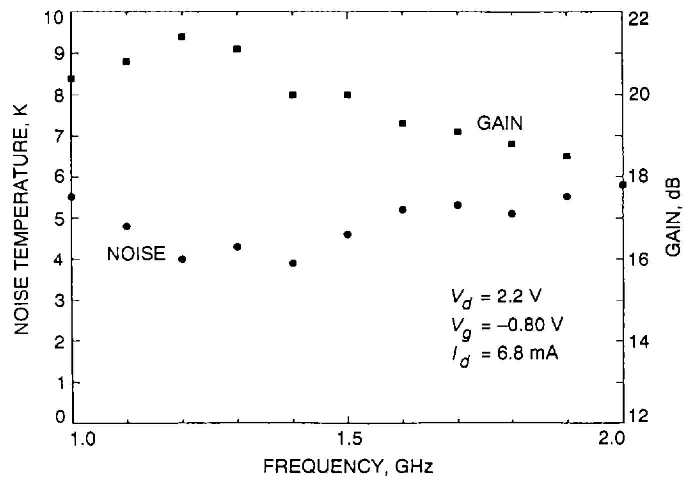

Fig. 4. Performance of a single-ended amplifier with a GE HEMT. The noise temperature uncertainty is ±1.5 K, where V_d = voltage at drain, V_g = voltage at gate, and I_d = current at drain.

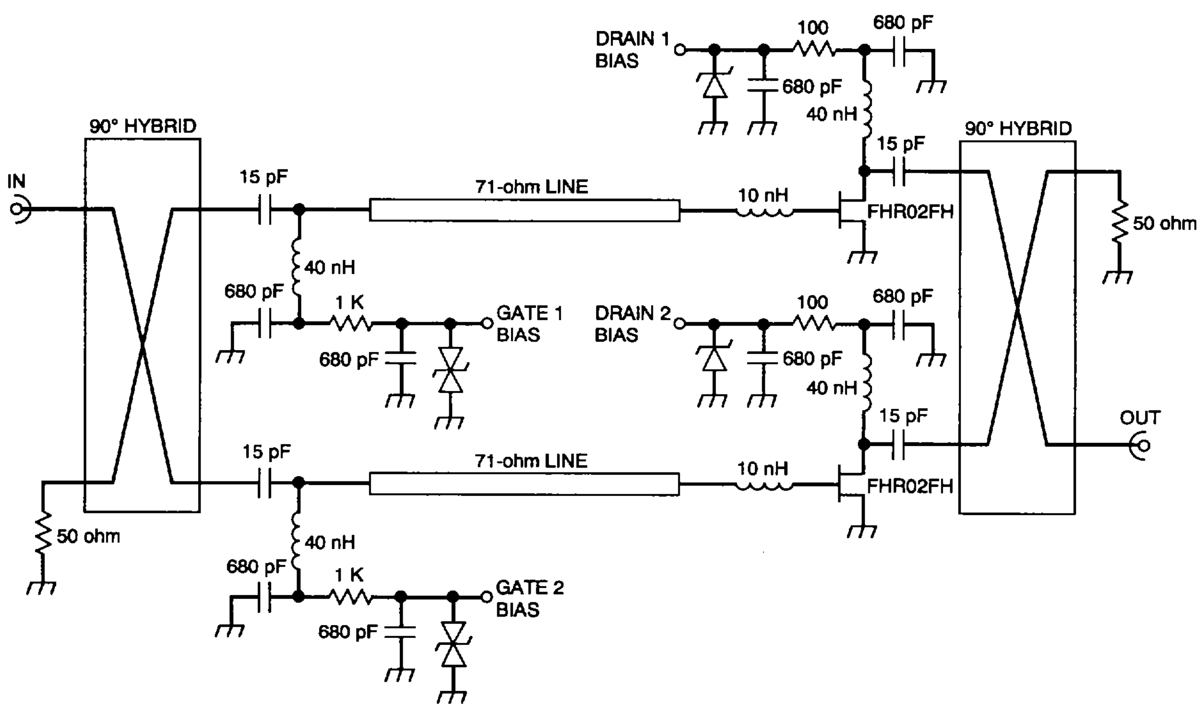

Fig. 5. Schematic of the 1- to 2-GHz balanced amplifier.

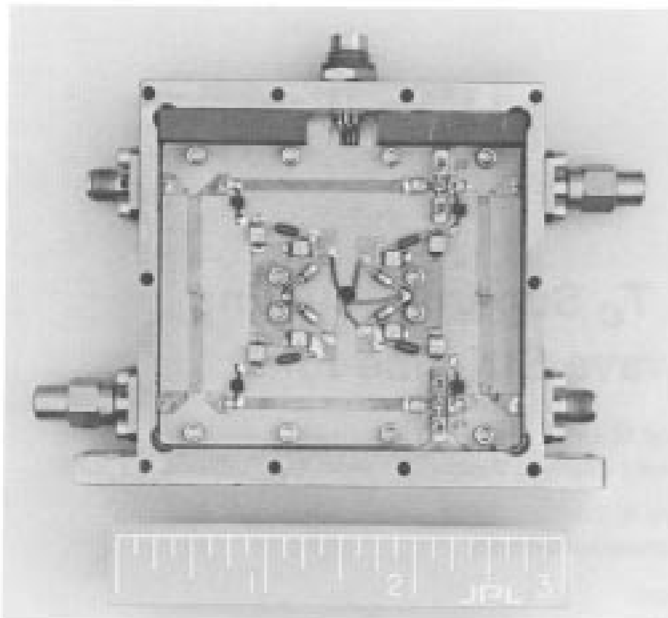

Fig. 6. Photograph of the 1- to 2-GHz balanced amplifier. (Scale shown in inches.)

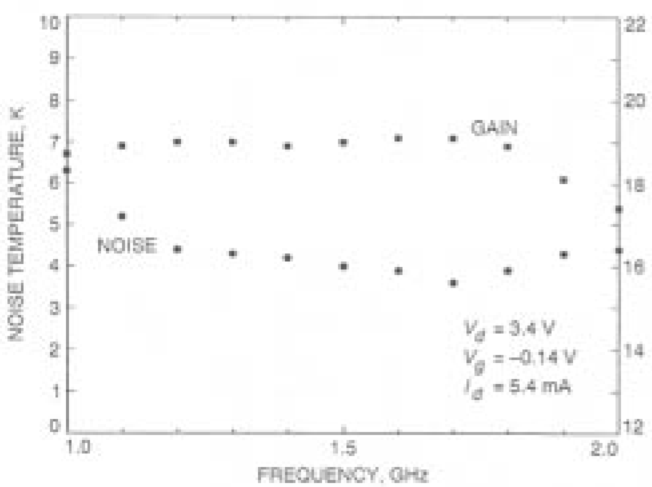

Fig. 7. Gain and noise temperature of balanced amplifier serial number 00 at a physical temperature of 12 K. The noise temperature measurement uncertainty is ±1.2 K.

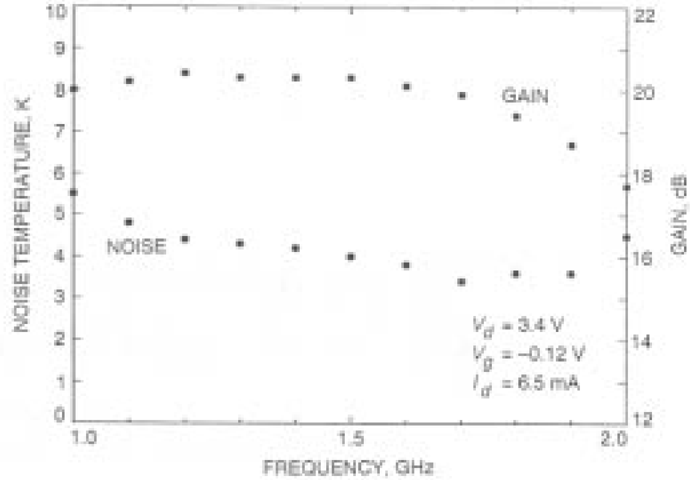

Fig. 8. Gain and noise temperature of balanced amplifier serial number 01 at a physical temperature of 12 K. The noise temperature measurement uncertainty is ±1.2 K.

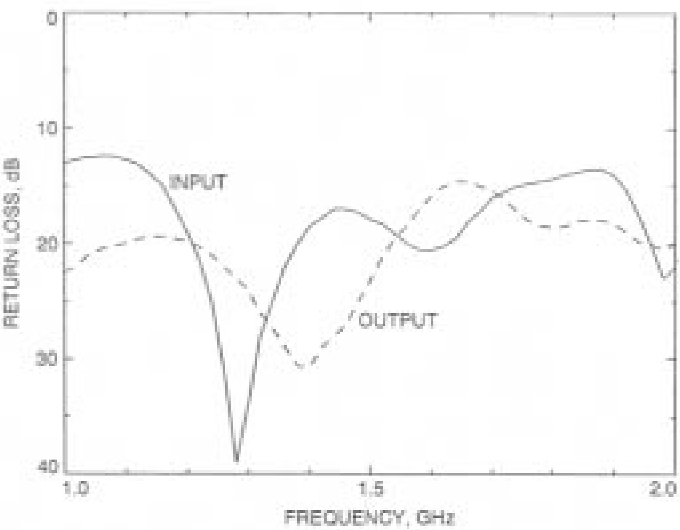

Fig. 9. Input and output return loss for amplifier serial number 00 at a physical temperature of 12 K.