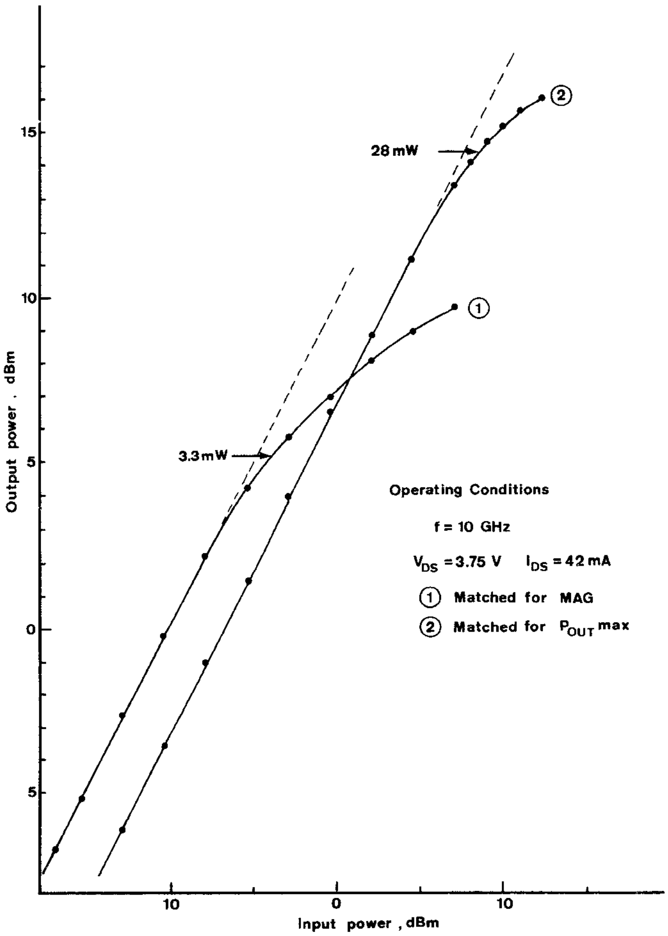

Fig. 7. Power output performance of a MESFET.

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Performance of GaAs MESFET's at Low Temperatures

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***Abstract*—The noise- and *s*-parameters of a GaAs MESFET with 1-μm gate length are characterized versus temperature. At room temperature, the noise figure measured at 12 GHz is 3.5 dB. At 90 K, the noise figure decreases to 0.8 dB (T_e = 60 K). The associated gain is 8 dB. The design of a cooled amplifier for the 11.7–12.2-GHz communication band is discussed. At 60 K, the three-stage amplifier exhibits 1.6-dB noise figure (T_e = 130 K) and 31-dB gain.**

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Introduction

At room temperature, thermal noise sources dominate the noise performance of GaAs MESFET's in microwave amplifiers [1], [2]. By cooling the MESFET's to 77 K, a significant noise reduction has been observed in the 1–2-GHz range [3]–[5]. Also, a 2-dB noise-figure reduction has been reported for a 6-GHz MESFET amplifier when cooled to 190 K [6]. The purpose of this short paper is to present MESFET characteristics versus temperature that are relevant to amplifier applications. Based on these device data, the design of a cooled communication amplifier is outlined and the amplifier performance data versus temperature are discussed.

MESFET Performance

The GaAs MESFET discussed in this short paper has been described in [7]. The gate is 1 μm long, 500 μm wide, and the channel is 0.2 μm thick. The active layer was grown by liquid-phase epitaxy directly on the (100) surface of a Cr-doped semi-insulating substrate. The criteria for the selection of the substrate are discussed in [8]. Tin was chosen as the donor impurity which has a negligible ionization energy (similar to sulfur [9]) at 1×10^{17} cm^{-3} doping density. Consequently, the free-carrier concentration in the channel is practically temperature independent.

To characterize the MESFET performance at low temperature, the transistor chip is mounted in a test fixture in which miniature coaxial lines[1] are directly contacting the gate and drain pads on the chip. The source is grounded with 40-pH lead inductance. At 12 GHz, this fixture exhibits less than 0.1-dB insertion loss at the input and output ports. The backside of the MESFET substrate is mounted on a heat sink yielding a thermal resistance of 100 K/W. Under low-noise operating conditions, 100-mW dc power is dissipated in the MESFET, raising the channel temperature approximately 10 K above the ambient temperature. The temperature of the heat sink (ambient temperature) was monitored close to the chip with a copper–constantan thermocouple. The test fixture was suspended above a liquid-nitrogen bath, and the temperature was changed by varying the distance between the fixture and the liquid-nitrogen level.

The noise figure and associated gain of the GaAs MESFET were measured at 12-GHz versus ambient temperature. At each temperature, the gate bias and the RF tuning at the gate and drain[2] were adjusted for minimum noise figure. The solid curves in Fig. 1 show the result. The noise figure decreases from 3.5 dB at 300 K to 0.8 ± 0.5 dB at 90 K. This performance demonstrates the ultralow-noise capability of cooled GaAs MESFET's at frequencies as high as 12 GHz. The rate of noise-figure decrease is particularly large between 300 and 200 K, which makes thermoelectric cooling an attractive technique for improving noise performance. The gain associated with the minimum noise figure changes from 7.4 dB at 300 K to 8.3 dB at 90 K. With decreasing temperature, the reverse bias on the gate had to be increased to achieve lowest noise performance. At the optimum gate bias, the ratio of the actual drain current, I_{DS}, to the current at zero gate voltage, I_{DSS}, remained approximately independent of temperature for most FET's tested. Using this rule, the optimum gate bias can be determined from simple drain-current measurements on a cooled MESFET providing that the optimum bias at room temperature is known.

The dashed curves in Fig. 1 show the MESFET's noise figure and

[1] The inner conductor has a 100-μm diameter.
[2] The transistor is operated in common-source configuration.

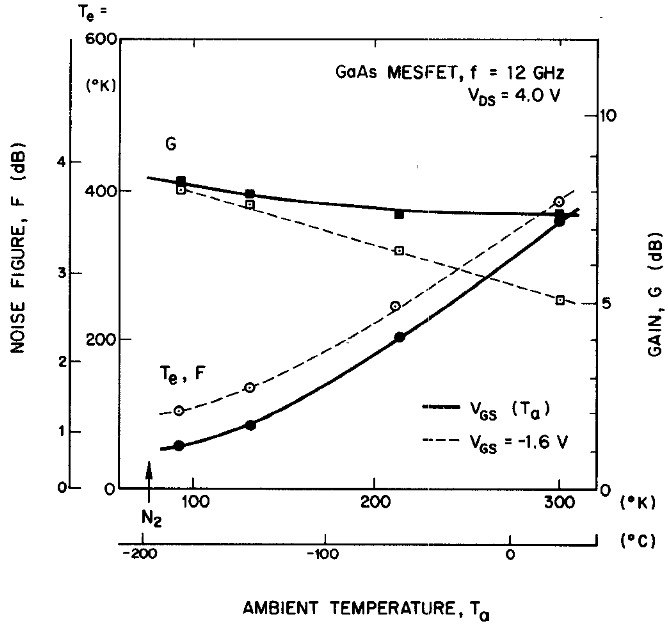

Fig. 1. Minimum noise figure, equivalent input noise temperature, and associated power gain of the GaAs MESFET versus ambient temperature. The source and load impedances and the gate bias, V_{GS}, were optimized at each temperature (solid line). Also, measurements with constant bias and fixed impedances were performed (broken line).

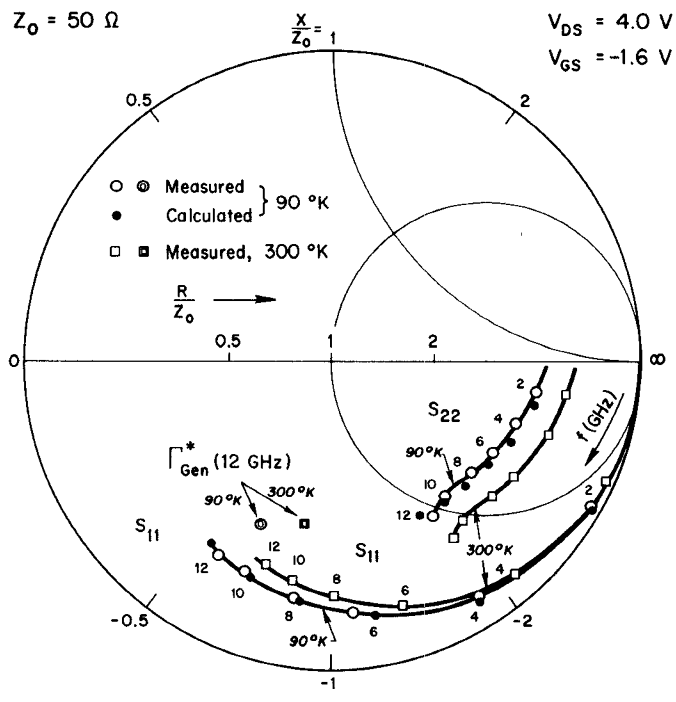

Fig. 2. Optimum generator reflection coefficient, Γ_{gen}, for minimum noise figure at 90 and 300 K ambient temperature. In this figure, the complex conjugate of Γ_{gen} is shown at 12 GHz. In addition, the measured s-parameters, s_{11} and s_{22}, are plotted versus frequency at the two temperatures. At 90 K, s-parameters calculated from the equivalent circuit (Fig. 4) are also shown.

gain versus temperature for constant gate bias and constant generator and load impedances. The gate bias ($V_{GS} = -1.6$ V), which yields minimum noise figure at 90 K, was chosen and the MESFET was tuned for minimum noise figure at room temperature. This could be a practical procedure in tuning the first stage of a cooled amplifier. However, this procedure does not lead to the minimum noise figure at 90 K, as illustrated in Fig. 1.

The variation in the optimum generator impedance versus temperature must also be considered. The generator impedances are shown in Fig. 2 for operation at 90 and 300 K. At the lower temperature, the optimum reactance is 20 percent smaller and the resistance 24 percent smaller. The MESFET's input impedance shows approximately the same relative change (Table I). The gate-to-source capacitance C_{gs}, shown in Fig. 4, increases by

TABLE I
ELEMENT VALUES IN THE EQUIVALENT CIRCUIT OF FIG. 4 THAT PROVIDE THE BEST AGREEMENT BETWEEN CALCULATED AND MEASURED s-PARAMETERS AT 300 AND 90 K

Parameter P	P (300°K)	P (90°K)	$\frac{P(90) - P(300)}{P(300)}$	Parameter P	P (300°K)	P (90°K)	$\frac{P(90) - P(300)}{P(300)}$
C_{gs} (pF)	0.31	0.38	+0.23	g_m (mmho)	22	48	+1.2
R_i (Ω)	8.0	6.0	-	$\frac{g_m}{1+g_mR_s}$ (mmho)	21	43	+1.1
R_s (Ω)	3.0	2.5	-	τ_0 (ps)	1	1	-
R_g (Ω)	3.0	1.5	-	C_{dg} (pF)	0.038	0.029	-0.24
$R_i + R_s + R_g$ (Ω)	14.0	10.0	-0.29	C_{dc} (pF)	0.003	0.01	+2.3
R_{ds} (Ω)	350	240	-0.31	L_g (nH)	0.05	0.05	-
R_d (Ω)	4.0	3.5	-	L_d (nH)	0.05	0.05	-
C_{ds} (pF)	0.11	0.10	(-0.09)	L_s (nH)	0.04	0.04	-

Note: The bias voltages are: V_{DS} = 4.0 V and V_{GS} = −1.6 V.

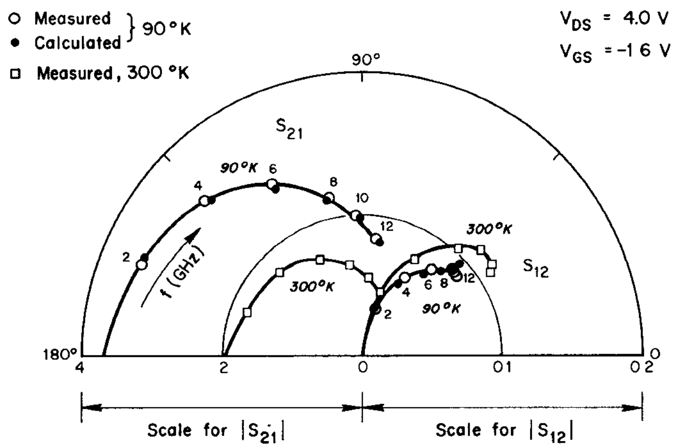

Fig. 3. Measured s-parameters, s_{12} and s_{21}, of the GaAs MESFET versus frequency at 90 and 300 K. At 90 K, s-parameters calculated from the equivalent circuit (Fig. 4) are also shown.

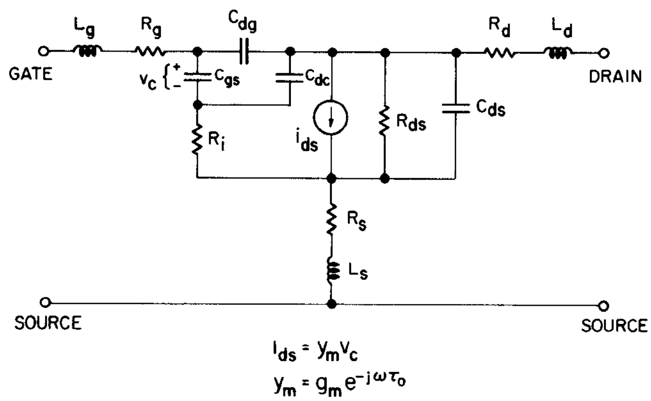

Fig. 4. Equivalent circuit for the GaAs MESFET. Element values for operation at 90 and 300 K are listed in Table I.

23 percent; and the sum of the intrinsic, source, and gate resistances, $R_i + R_s + R_g$, decreases by 29 percent. This latter change reflects the effect of an increasing electron drift mobility (+20 percent) and a larger conductive cross section in the active layer[3] at lower temperature.

The measured s-parameters of the MESFET are shown in Figs. 2 and 3 versus frequency for the two ambient temperatures, 90 and 300 K. They are described very accurately by the equivalent circuit illustrated in Fig. 4. Circuit-element values that yield best agreement between calculated and measured s-parameters are listed in Table I. The table also shows the change of each circuit component with temperature, which leads to the following discussion.

Between 300 and 90 K, the drain resistance, R_{ds} at $V_{GS} = -1.6$ V, decreases by 31 percent while the capacitance in parallel, $C_{ds} + C_{dc}$, remains constant. At $V_{GS} = 0$, R_{ds} decreases only by 20 percent. The temperature sensitivity of R_{ds} depends on the gate voltage. As the gate is reverse biased and V_{GS} approaches the cutoff voltage, $V_{GS(\text{off})}$,[4] the temperature variation of $V_{GS(\text{off})}$ (Fig. 5) causes R_{ds} to be more strongly temperature dependent; i.e., the widening of the conductive cross section in the active layer becomes more effective.

The parameter that varies most significantly with temperature is the intrinsic transconductance g_m. Between 300 and 90 K, g_m increases by 120 percent; a change also reflected in the variation of the forward transfer coefficient s_{21} (Fig. 3). g_m is related to the (extrinsic) low-frequency transfer admittance, $|y_{fs}|$, by

$$|y_{fs}| = \frac{g_m}{1 + g_m R_s}.$$

$|y_{fs}|$, as determined from the s-parameters, is listed in Table I, and values measured at 1 MHz are plotted in Fig. 5. The data agree within 10 percent. The temperature variation of g_m between

[3] The conductive cross section is larger because the measured cutoff gate voltage has increased (Fig. 5).

[4] $V_{GS(\text{off})}$ is defined as the gate voltage that reduces the drain current to 1 mA. $V_{GS(\text{off})}$ is temperature dependent because the depletion-layer width at the active layer to substrate interface apparently decreases with lower temperature for the particular MESFET investigated. The diffusion voltage of the Schottky barrier is practically temperature insensitive as reported in [11] and verified here with s_{11} measurements at $V_{GS} = V_{DS} = 0$.

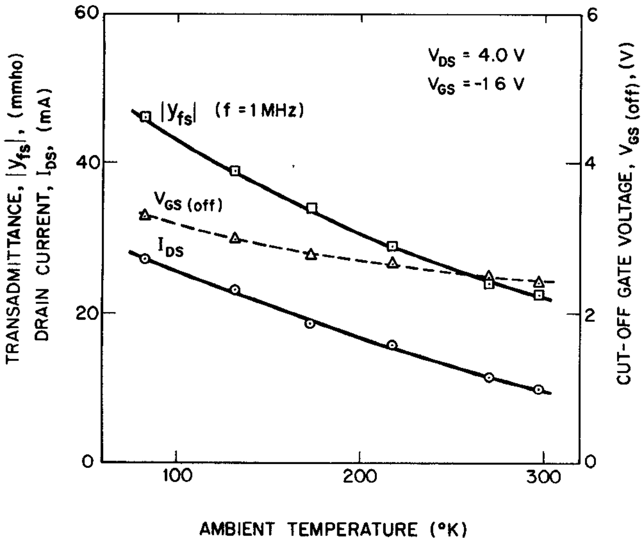

Fig. 5. Drain current, I_{DS}, transadmittance, $|y_{fs}|$, and cutoff gate voltage, $V_{GS(off)}$, of the GaAs MESFET versus ambient temperature.

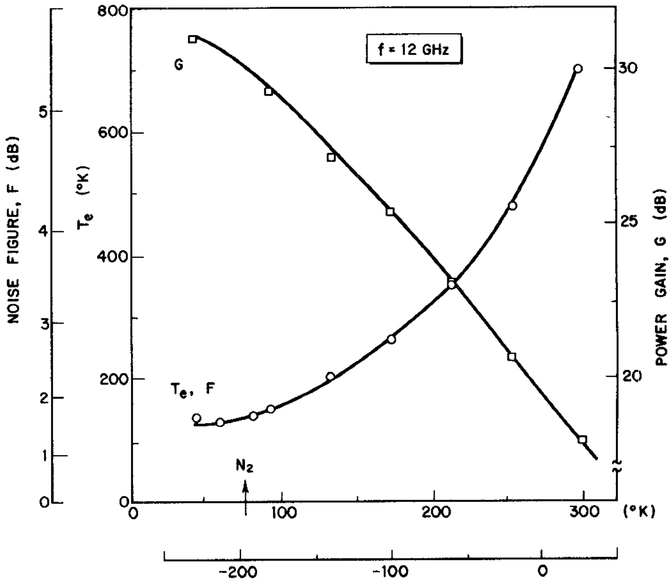

Fig. 6. Noise figure, equivalent input noise temperature, and power gain of the amplifier versus ambient temperature.

300 and 90 K can be traced to the following changes in the active-layer properties: a) the measured carrier drift mobility increases by 20 percent, b) the calculated peak drift velocity rises by 60 percent [10], and c) the cutoff gate voltage increases by 35 percent. On the basis of the parameter variations a) and b), a 45-percent increase in g_m is theoretically estimated with the simple model discussed in [12]. This calculated change agrees fairly well with measurements made at $V_{GS} = 0$. At this bias, the temperature dependence of $V_{GS(off)}$ can be neglected in a first-order approximation.

At the lower temperature, the drain-to-gate feedback capacitance, C_{dg}, is smaller (-24 percent) and the capacitance of the dipole layer in the channel [13], C_{dc}, is considerably larger. These changes are primarily due to the higher drain current ($+165$ percent, Fig. 5) at 90 K which results in a larger electron accumulation in the channel.[5] The negative space-charge, in turn, causes the depletion layer under the gate to widen toward the drain, thus reducing the drain-gate feedback capacitance.

Cooled Amplifer Design and Performance

Based on the measured temperature characteristics of the GaAs MESFET, an amplifier was designed for operation at 90 K ambient in the 11.7–12.2-GHz U.S. satellite communication band [14]. The amplifier consists of three low-noise stages with sapphire microstrip matching networks. The transistor chips are mounted directly on the ground plane of the amplifier package which is an effective heat sink. The gate bias of the first stage is adjusted to the optimum value for operation at 90 K, as discussed in the previous section. The noise match at the input port is accomplished with a low-loss structure of three elements: a cascaded transmission line next to the gate, a series interdigital capacitor, and an open-circuited shunt line.[6] The network is designed and tuned for lowest noise figure at room temperature. Then the tuning is slightly changed to compensate for the shift in optimum generator impedance at 90 K (Fig. 2). The second and third stages are operated under bias and tuning conditions yielding higher gain than the first stage with an acceptable noise figure. No compensation is made for the variation in the MESFET's output impedance versus temperature (Fig. 2). The complete integrated circuit is enclosed in a waveguide below cutoff; the amplifier package is filled with helium and hermetically sealed.

The resulting amplifier performance versus temperature is documented in Figs. 6 to 9. At 300 K, the noise figure of the amplifier is 5.2 dB. The noise figure versus temperature curve has a steep slope at room temperature (Fig. 6). The slope decreases at lower temperatures, and at 60 K a lowest noise limit of 1.6 dB is reached[7] (equivalent input noise temperature $T_e = 130$ K). At lower temperature, e.g., 40 K, no further noise figure decrease is observed. Better noise performance can be obtained with an improved design. Based on 0.8-dB device noise figure (Fig. 2), 8.3-dB associated gain, and 0.2-dB loss in each of the matching circuits at the two ports, an amplifier noise figure of 1.2 dB is estimated at 90 K ambient temperature. This compares with 1.8 dB for the reported amplifier whose input and output matching circuits exhibited 0.5-dB loss. If the ultimate noise figure is not required, thermoelectric cooling of the amplifier is an economical and reliable approach for noise reduction. Cooling the first stage to 200 K and the following stages to 250 K is feasible and makes the 3.2-dB noise figure at 12 GHz possible (Fig. 6). In communication satellites, the use of radiation coolers for low-temperature (90 K) MESFET operation is of great interest.

Between 300 and 90 K, the gain of the amplifier increases by 11.5 dB from 17.8 to 29.3 dB. This gain variation is primarily due to the FET's increasing transconductance plotted in Fig. 7.

[5] The strong dependence of C_{dg} on I_{DS} is also experienced when the gate voltage is changed. At 90 K, C_{dg} is decreasing from 0.029 pF at 27 mA ($V_{GS} = -1.6$ V) to 0.007 pF at 110 mA ($V_{GS} = 0$). Notice that the smaller capacitance is obtained for the smaller drain-to-gate voltage, $V_{DS} - V_{GS}$.

[6] The series capacitor performs three functions: a) it is an element in the RF matching network, b) it acts as a dc block, and c), in conjunction with the bias network, it provides a high-pass filter which is required to protect the burn-out sensitive gate from surge pulses. The open-circuited stub can be easily adjusted in its location, length, and characteristic impedance and is, therefore, a convenient tuning element.

[7] The noise performance of this amplifier was measured independently at Hewlett-Packard and at the National Radio Astronomy Observatory in Charlottesville, VA. The noise figures as measured by the two laboratories agreed well with a maximum difference of 0.2 dB.

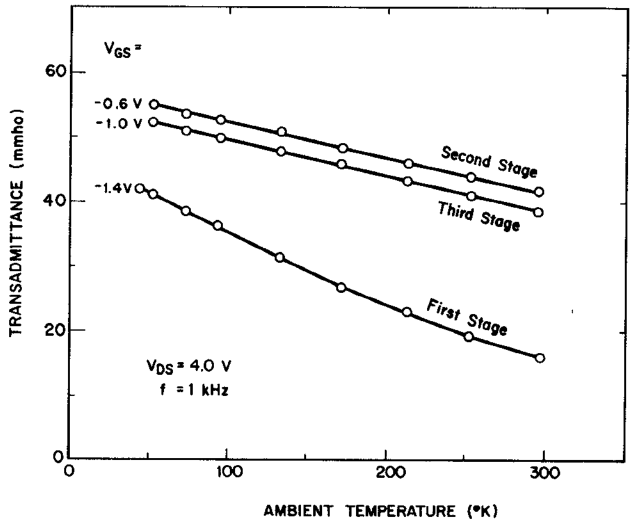

Fig. 7. Transadmittance versus ambient temperature for the MESFET's operated in the three amplifier stages.

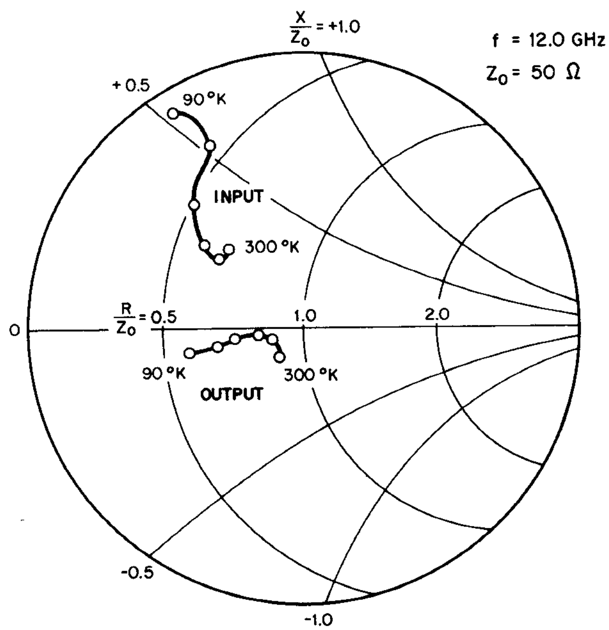

Fig. 8. Amplifier input and output impedances versus ambient temperature.

From data in Fig. 7, a gain increase of 12.2 dB is calculated. The reflection coefficients at the input and output of the amplifier are plotted in Fig. 8. The input VSWR rises from 1.7 at 300 K to 4.0 at 90 K. The amplifier output is approximately matched at 300 K. The output VSWR reaches 1.8 at 90 K. Fig. 9 illustrates the gain and noise figure versus frequency. The relatively small changes of the MESFET reactances prevent a frequency shift of the band center versus temperature.

Conclusion

It has been shown that GaAs MESFET's with 1-μm gate length are capable of very low-noise performance (NF = 0.8 dB at 12 GHz) when operated at liquid-nitrogen temperature. The MESFET's transconductance increases appreciably with decreasing temperature, raising the RF gain. The input and output impedances of the transistor are fairly insensitive to temperature

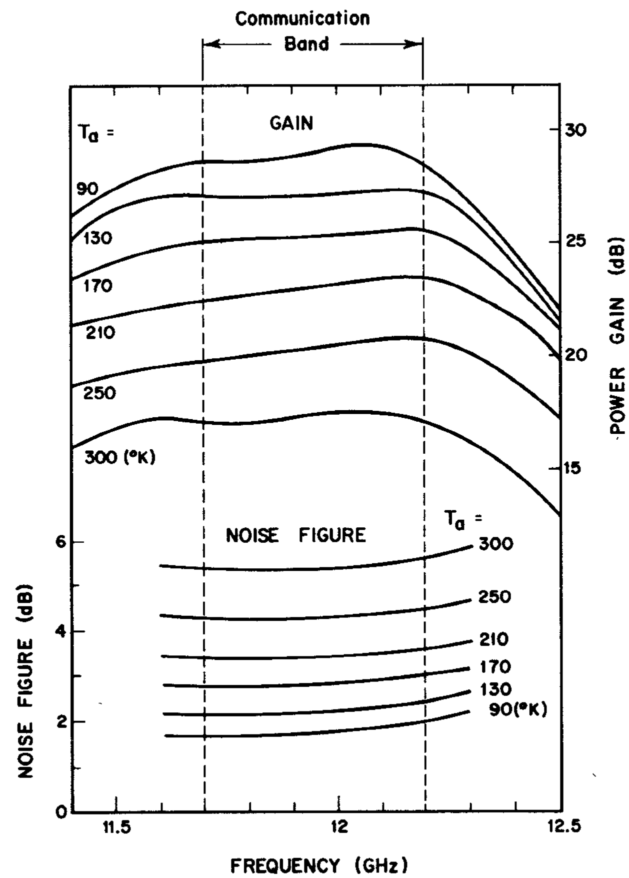

Fig. 9. Amplifier gain and noise figure versus frequency with ambient temperature as a parameter.

variations. A three-stage amplifier was built, yielding 1.6-dB minimum noise figure at 12 GHz when operated at 60 K ambient. A 1.2-dB noise figure is estimated for an improved MESFET amplifier version operating at 90 K ambient temperature. This noise figure compares with 1.8 dB for uncooled and with 0.7 dB (T_e = 50 K) for cryogenic parametric amplifiers [15]. The MESFET's +10-dBm output power at 1-dB gain compression compares with −15 dBm [16] for the parametric amplifier. Bandwidths of 4 GHz have been demonstrated for low-noise MESFET amplifiers in *C* [17] and *X* band [7], [18] as compared to a 2-GHz bandwidth realized with parametric amplifiers at 10 GHz [16], [19]. In addition, a gain-versus-temperature slope of <0.1 dB/°C and gain stability of <0.1 dB/h are achieved without special care using FET's. Cooled GaAs MESFET amplifiers with their simple circuitry and relatively low cost are, therefore, expected to compete effectively with parametric amplifiers at frequencies up to 12 GHz.

Acknowledgment

The authors wish to thank Dr. D. Mellor for the design of the amplifier prototype and Dr. S. Weinreb and J. Davis of the National Radio Astronomy Observatory for noise measurements at low temperatures; especially for the amplifier performance characterization below 90 K.

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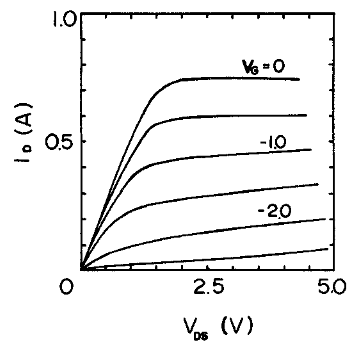

Fig. 1. Static current-voltage characteristics of a power FET with the gate-source voltage as a parameter. The vertical scale shows source-drain current I_{DS} (100 mA/div) and the horizontal scale shows source-drain voltage V_{DS} (500 mV/div).

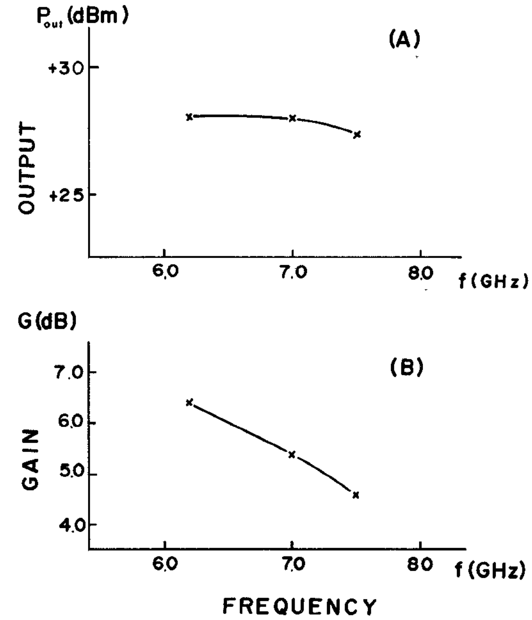

Fig. 2. Frequency response of an FET power amplifier. (a) Output power at 1-dB gain compression point. (b) Small-signal gain.

A 6-GHz Four-Stage GaAs MESFET Power Amplifier

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***Abstract*—A 6-GHz GaAs MESFET power amplifier with 1-W output power, 26-dB gain, and 8-dB noise figure is described. It is a fully integrated four-stage amplifier with an efficiency of 22 percent. The third-order intermodulation product is 31.5 dB below the carrier at an output power of 1 W.**

I. Introduction

Gunn and IMPATT diodes have been widely used as high-power devices in microwave oscillators and amplifiers for radio-communication systems in the frequency range beyond 6-GHz [1]–[3]. Considering the recent progress in the fabrication and performance of the high-power GaAs MESFET [4], this three-terminal device is expected to replace conventional two-terminal devices in system applications.

Many authors have reported low-noise and small-signal FET amplifiers [5], [6] and also high-power GaAs MESFET devices [7], [8]. This short paper describes the performance of a 6-GHz four-stage GaAs MESFET high-power amplifier which was fabricated on a Teflon-glass-fiber printed-boards with microstrip circuits. The bandwidth, the power variation with temperature, the third-order intermodulation, and the AM-to-PM conversion of the completed amplifier are discussed.

The four-stage amplifier has the following characteristics: the output power is +30.2 dBm with a gain of 26.2 dB and a noise figure of 8 dB. The 3-dB bandwidth is almost 200 MHz and the third-order intermodulation product is 31.5 dB below the carrier at an output power level of 1 W. The amplifier power efficiency exceeds 22 percent.

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II. A Microwave Power GaAs MESFET

A microwave high-power GaAs MESFET is composed of many small-signal FET's which are connected in parallel yielding a high drain current. Some characteristics of the GaAs MESFET's incorporated in this amplifier will be introduced. The static current-voltage characteristic of the FET was measured using a curve tracer to determine the dc bias point for class A common-source operation. Typical V_{DS}–I_{DS} characteristics are shown in Fig. 1. The frequency response of a high-power GaAs MESFET was measured, and is shown in Fig. 2. The output power at the 1-dB gain compression point remains almost constant over the