CRYOGENICALLY COOLED GaAs FET AMPLIFIER WITH A 1.1-dB NOISE FIGURE AT 5.0 GHz

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Abstract

A 4.5 to 5.0 GHz gallium arsenide field-effect transistor (GaAs FET) amplifier cryogenically cooled to 20 K is described. A noise figure of 1.1 dB maximum is achieved over the band. Gain per stage is approximately 10 dB. A noise analysis is performed to predict noise figure dependence on the physical temperature of the amplifier.

Summary

Introduction

The GaAs FET is presently providing outstanding performance in low-noise microwave amplifiers from 3.5 to 14.0 GHz. By cooling the FET, a substantial reduction in noise figure may be realized since most of the noise generated by the FET is thermal in nature. Unlike the bipolar transistor, whose gain drops with decreasing temperature, the FET gain increases, producing the desirable effect of further increasing the output signal-to-noise ratio (SNR) for a given fixed input SNR.

A GaAs FET amplifier cryogenically cooled to 20 K was designed and constructed to cover the 4.5 to 5.0 GHz range. Its intended application is for radio astronomy use. The amplifier has a noise figure of 1.1 dB maximum (80 K) over most of the band at the cold temperature. The room temperature noise figure is approximately 3.3 dB maximum. Amplifier gain per stage increased from 8 dB at room temperature to approximately 10 dB at 20 K. Gain curves, with temperature as a parameter, are presented.

In an effort to acquire an ability to predict (albeit roughly) the noise figure at a particular temperature, an analysis of a simplified GaAs FET noise model was performed. Key results of this work are presented.

Noise temperature measurements were made on the GaAs FET amplifier at several temperatures from 20 to 300 K. These data were plotted along with the values predicted from the analysis. The measured data show good correlation with the theory presented.

Amplifier Description

The amplifier is shown in Fig. 1. It utilizes microstrip circuitry etched on a 0.025-inch thick alumina substrate. The GaAs FET is the NEC 24406. Extensive S-parameter and two-port noise parameter measurements were made on the GaAs FET before the circuit design was started. Presenting the optimum source impedance for minimum noise figure to the GaAs FET is critical to the success of the design. The design was carried out using room temperature transistor data and compensated for the effects of the lower temperature. Generally, the transistor impedances and reverse transducer gain are fairly constant with temperature. However, the forward gain changes markedly with changes in temperature. The bias points had to be altered to maximize the forward gain at the lower temperature. In addition, some minor frequency compensation had to be performed to maintain the requisite gain flatness.

The input and output impedances are of necessity different from 50 ohms. Voltage standing-wave ratios (VSWR's) of 4:1 to 7:1 are generally measured with GaAs FET amplifiers in this frequency range. The high VSWR's are a result of the noise match and stability requirements. Two cryogenic isolators were integrated with the amplifier so that the input/output VSWR's would be under 1.3 to 1.

A severe problem is destructive stresses that build up at electrical connections at the cold temperature due to the incompatibility of the coefficients of contraction of the various materials and components which comprise the complete amplifier. Careful choices of materials and construction techniques alleviated this problem.

Proper heat sinking of the transistor was necessary to ensure that the transistor was cooled to the same temperature as the amplifier housing. The method of mounting the transistor has a large impact on this.

Key Results of Noise Analysis

Fig. 2 shows the noise model analyzed. Fig. 3 shows the simplified equivalent circuit of the FET with the channel noise represented as a current generator in parallel with a conductance. State-of-the-art microwave FET's approach this model because the parasitics that degrade noise figure have been minimized. Some of the parasitics include contact resistance, gate leakage current, and inductance in the source connection.

The transconductance is a function of transistor operating point and physical temperature. The mobility of the majority carriers in the channel is a function of temperature, and transconductance is directly proportional to the mobility. For physical temperatures greater than approximately 60 K, the mobility may be described by:

$$a(T_{FET})^{-x}$$

Where a is a constant, and the exponent x assumes a range of values depending on the material and doping level. Curves for mobility in a doped semiconductor as a function of temperature appear in the literature[1]. A frequently used value for the exponent is -3/2. From measurements made on actual transistors, it appears that the exponent is closer to -1/2. The mobility for a typical doped semiconductor is maximum at about 60 K and decreases below 60 K.

By postulating a function for the transconductance, g_m, of the form $K(T_{FET})^{-1/2}$ where T_{FET} is the GaAs FET temperature, we get the following result for the noise temperature, T_e, of the GaAs FET:

$$T_e = 290\left(\frac{0.6}{g_m R'}\right) \times \left(\frac{T_{FET}}{T_s}\right)^{3/2} \qquad (1)$$

T_e = electronics noise temperature, Kelvins

g_m = low frequency transconductance at temperature T_s (300 K for convenience)

T_{FET} = physical temperature of GaAs FET in degrees Kelvin

R' is given by:

$$\frac{R_s \left| 1 - \left(\frac{R_s}{R_s + j\omega L_1}\right)\right|^2}{\omega^2 C_{gs}^2 \left|Q\right|^2}$$

ω = Radian frequency, rad/second

R_s = 50 ohms

C_{gs} = Gate-source capacitance of FET

$\left|Q\right|^2 = \left|Z_{opt} + Z_{in}\right|^2$

Z_{in} = Input impedance of FET

Z_{opt} = Optimum source impedance for minimum noise temperature

L_1 is an inductance which is part of the matching network. At 4.7 GHz, R' is calculated to be approximately 15 ohms. The transconductance g_m is 26.5 mmho and T_s is 300 K.

The equation for T_e is plotted in Fig. 4 as a function of T_{FET}.

Noise Temperature Measurements

Noise measurements on the FET amplifier were performed using an AIL 20 K parametric amplifier having 15-dB gain as the second stage. The second stage contribution to the noise temperature measurements was no more than 10 K. Both the GaAs FET amplifier and the parametric amplifier were attached to the 20 K refrigerator station. An AIL Hot/Cold Noise Generator was used as the noise source.

Discussion of Results

Fig. 5 shows the gain response with temperature as a parameter. In Fig. 4, the noise temperature predicted by analysis is plotted along with the measured amplifier noise temperature data. The analysis is strictly not valid below 60 K since the transconductance no longer follows the postulated function. Fig. 6 is a plot of noise temperature versus frequency. These data were taken at 20 K. The output power at the 1-dB compression point was well in excess of +7 dBm. Input/output VSWR's were well below 1.3:1.

Conclusions

Data show that it is presently feasible to construct low-noise GaAs FET amplifiers with performance comparable to uncooled parametric amplifiers. Saturation powers well in excess of those associated with parametric amplifiers are easily attained. The simplicity of the approach makes the cooled GaAs FET an attractive candidate as a second stage to a parametric amplifier.

Using 1/2 micron GaAs FET's, it should be possible to realize noise temperatures under 50 K in this frequency range.

The first-order analysis presented in this paper for a simplified noise model of the FET yields results that correlate well with measurements.

Acknowledgements

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Reference

1. R. M. Rose, L. A. Shepard, and John Wulff, "The Structure and Properties of Materials," Volume IV, John Wiley and Sons, p 106-107.

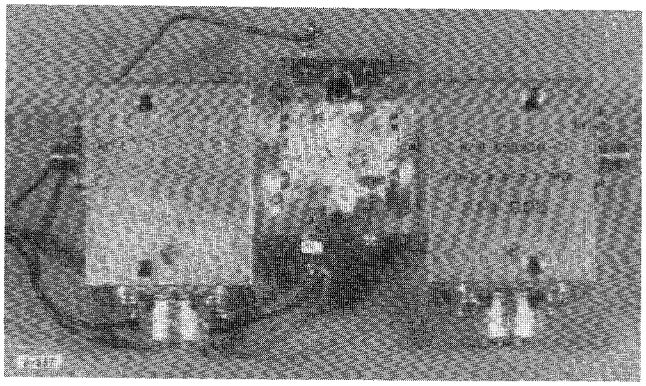

Fig. 1. Cooled GaAs FET Amplifier

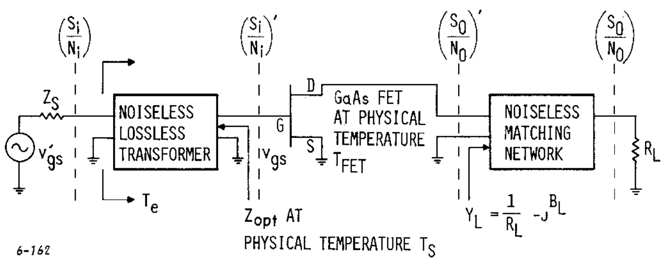

Fig. 2. GaAs FET Noise Model

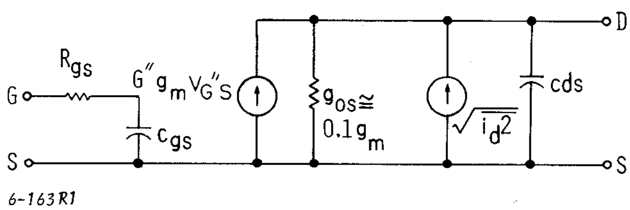

Fig. 3. Equivalent Circuit

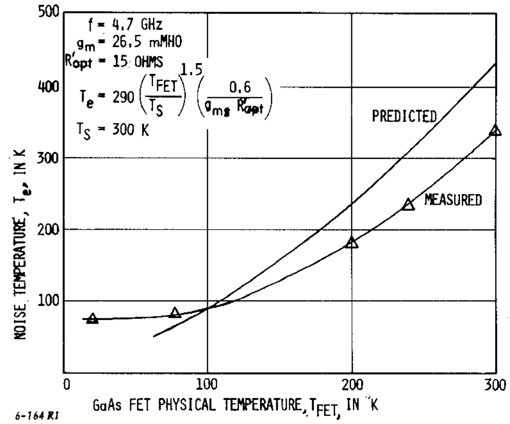

Fig. 4. GaAs FET Amplifier Noise Temperature

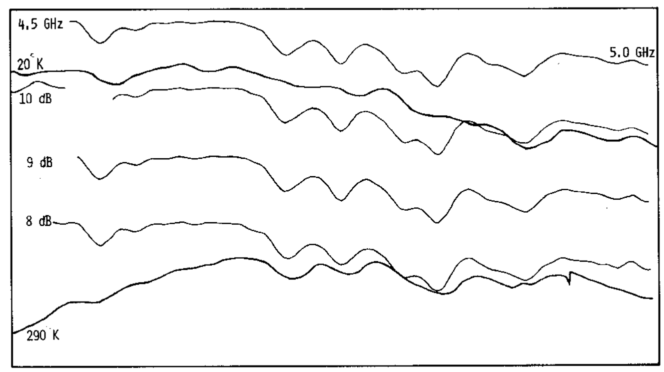

Fig. 5. Gain Response of GaAs FET Amplifier

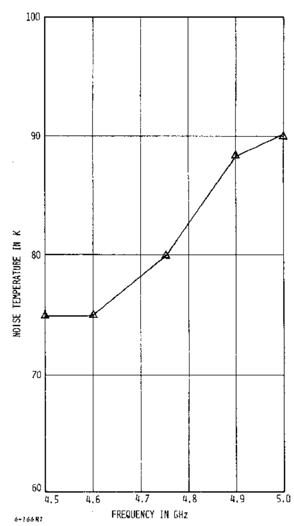

Fig. 6. Noise Temperature of GaAs FET Amplifier at 2 K

NOTES