X-Band Ultralow-Noise Maser Amplifier Performance

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Noise temperature measurements of an 8440-MHz ultralow noise maser amplifier (ULNA) have been performed at subatmospheric, liquid-helium temperatures. The traveling-wave maser was operated while immersed in a liquid helium bath. The lowest input noise temperature measured was 1.43 ± 0.16 K at a physical temperature of 1.60 K. At this physical temperature, the observed gain per centimeter of ruby was 4.9 dB/cm. The amplifier had a 3-dB bandwidth of 76 MHz.

I. Introduction

NASA's Deep Space Network uses low-noise ruby maser amplifiers for deep space telecommunications and to support radio and radar astronomy. Many deep-space mission communication links would not be possible without the low noise temperature performance that masers provide.

Currently, typical specifications of a DSN X-band (8420 MHz) maser system under normal operating conditions are 45 dB of net gain (1.4 dB/cm), over 100 MHz of instantaneous bandwidth, and a noise temperature at the input of 3.5 K, referenced to the room temperature flange. The required 4.5 K physical temperature of the maser is provided by a three-stage closed-cycle refrigerator (CCR). These maser-CCR packages are normally mounted near the vertices of large, tippable, parabolic antennas. The work presented in this article uses these specifications as a baseline for comparison.

Further cooling of a maser amplifier results in significant improvements in noise temperature and gain. At X-band, the input noise temperature is proportional to the physical temperature, while the electronic gain in decibels (excluding circuit losses) is inversely proportional to the physical temperature (both to a first-order approximation). Thus, immersing a maser amplifier in a bath of superfluid helium (below 2.17 K) will result in a threefold increase in the gain in decibels and a threefold decrease in the noise temperature (e.g., from 3.5 to 1.2 K at 8400 MHz).

Several 34-m beam waveguide (BWG) antennas are being implemented in the DSN that will provide, in contrast to present DSN antennas, a relatively large nontipping location for the maser and feed components. For these antennas, the use of a superfluid helium cryostat becomes very practical as a means to cool the maser (and its feed components). This is necessary in order to achieve a very low system noise temperature, while simultaneously increasing maser gain.

In order to provide the lowest front-end system noise temperature for its deep space telecommunications downlink, the Jet Propulsion Laboratory has developed and demonstrated superfluid helium-cooled maser amplifiers for the DSN. This article describes laboratory noise tem-

perature and gain measurements made on an ULNA maser centered at 8440 MHz in subatmospheric liquid helium. A brief discussion on the limits of X-band ULNA technology is also presented.

II. Theory

The noise power of a maser amplifier at a given physical temperature is discussed by Siegman in [1]. An extension of this discussion by Shell, et al. in [2] yields the following equation for the theoretical noise temperature of a maser amplifier:

$$T_{amp} =$$

$$\frac{\left(G_{net}^{ratio} - 1\right)}{G_{net}^{ratio}} \frac{hf}{k} \left[\frac{G_{elect}^{(dB)}}{G_{net}^{(dB)}} \frac{r}{r - 1} + \frac{L_0^{(dB)}}{G_{net}^{(dB)}} \frac{1}{\left(e^{\frac{hf}{kT_0}} - 1\right)} \right]$$

(1)

where

G_{net}^{ratio} = net electronic gain ratio, unitless

h = Planck constant = $6.6262 \times 10^{-34} J - s$

f = operating frequency, Hz

k = Boltzmann constant = $1.3806 \times 10^{-23} J/K$

$G_{elect}^{(dB)}$ = electronic gain, dB

r = inverted spin population ratio, unitless

$L_0^{(dB)}$ = forward insertion loss, dB

T_0 = maser physical temperature, K

Using Eq. (1), the expected noise temperature of a maser at the input to the cryogenic system can be calculated. Assuming an electronic gain of 39 dB, a net gain of 34 dB, a forward insertion loss of 5.0 dB, an inverted spin population ratio of 2.32, and a maser amplifier physical temperature of 1.6 K, the expected noise temperature is 1.02 K.

The maser noise temperature in Eq. (1) consists primarily of two noise-generating mechanisms. The first term is related to the spontaneous emission of photons by the ruby spin system, while the second is due to dissipative losses in the microwave circuitry. It is interesting to note that as the maser physical temperature (and the ruby spin temperature) approaches zero, the gain and inverted spin

population ratio terms each approach unity, while the conductor loss term goes to zero. Thus, Eq. (1) takes the limiting form of the equivalent quantum-noise temperature as discussed by Oliver in [3]

$$T_{MQL} = \frac{h}{k} f$$

(2)

At 8400 MHz, the quantum-noise temperature limit is 0.40 K. Thus, quantum noise accounts for almost half of the total noise associated with this maser amplifier.

Maser gain expressions are also given in [1]. Considering only first-order temperature-dependent terms, the decibel gain is

$$G_{dB} = 27 \frac{SN}{Q_m}$$

(3)

where S is the slowing factor (the ratio of the velocity of light to the group velocity), N is the length of the circuit in free-space wavelengths, and Q_m is the magnetic Q. The Q_m term is directly proportional to temperature. Thus, the gain of a maser amplifier is inversely porportional to temperature. Assuming that the gain of a maser amplifier at a physical temperature of 4.2 K is 10 dB, then the expected gain of this amplifier at 1.6 K is 26 dB.

III. System Description

A diagram of the noise and gain measurement setup with the maser amplifier in place is shown in Fig. 1. The system is housed within a liquid-helium-filled dewar with the maser immersed in superfluid liquid helium. The input and output waveguides are cooled by the discharging helium vapors. The upper halves of the maser input and output waveguides are made of thin-walled stainless steel to minimize heat leak into the helium bath. These stainless steel waveguide sections are copper plated to a minimum thickness of three skin depths to ensure a low radio frequency loss. The lower halves of these waveguide sections are made of copper.

The most economical and expedient means of providing a maser amplifier for this system demonstration was to use an available Block IIA maser structure, described in [4]. This structure was modified for stable operation at 1.5 K. The principal modification was to increase the reverse loss provided by the resonant yttrium iron garnet (YIG) isolator from 37.5 to 74 dB. Further details about

the existing X-band ULNA structure and its modifications can be found in [5].

The bath temperature is reduced below 4.2 K by decreasing the vapor pressure above the helium bath in the dewar. Vapor pressure control is provided by two pumping ports at the top of the dewar connected to two helium-tight, single-stage Leybold-Hereaus S65B TRIVAC vacuum pumps. A combined pumping speed of 2600 lpm (92 cfm) evacuates the dewar to a pressure of 800 Pa. Once a stable operating temperature (vacuum pressure) is maintained, as monitored on high-precision carbon-glass resistors, noise and gain measurements can be performed.

Maser gain-bandpass measurements were made as the helium bath was slowly cooled from 2.20 to 1.60 K. Noise temperature measurements were made over a range of frequencies at a variety of temperatures by cooling the cryostat to its lowest temperature and then allowing the cryostat temperature to gradually increase.

The maser noise temperature and gain were measured using the Y-factor technique [6,7]. A cooled attenuator (20 dB) in front of the maser was used as the cold load (T_{cold}), while the hot load (T_{hot}), referenced at the maser input, was a noise diode with an excess noise ratio (ENR) value of 13 dB [8]. The attenuator is supercooled within the helium bath while the noise diode resides outside the dewar. This technique has the advantage of reducing the value of T_{hot} and T_{cold}, while maintaining a large Y-factor. An added benefit is that the pad presents a good input match to the noise source and the maser. The maser under test did not have sufficient gain for the receiver. So, a follow-up amplifier was connected at the output of the system to increase the gain. The follow-up amplifier was chosen such that the power meter could read the low noise powers of T_{cold} and yet have enough dynamic range to accommodate a measurement of T_{hot}.

The equation that defines the noise temperature of the entire system, referenced to the input flange of the cryostat, is given by

$$T_{eff} = \phi + L(L_p - 1)T_p + LL_pT_e + \frac{(\phi + T_rL)}{G_e} \quad (4)$$

The last term in Eq. (4) is negligible compared to the preceding terms, so to a first-order approximation it may be excluded. The noise temperature of the maser at the input flange, T_e, was solved for in Eq. (4), yielding,

$$T_e = \frac{[T_{eff} - \phi - L(L_p - 1)T_p]}{LL_p} \quad (5)$$

where T_{eff} is a measurable quantity; ϕ is the thermal noise contribution due to the input line; L is the line loss; L_p is the cryogenic 20-dB attenuator loss; and T_p is the physical temperature of the pad. All must be accurately measured. These quantities are obtained by performing three separate measurements of the noise and loss (or gain) contributions at the same physical operating temperatures.

Two assumptions were made in the derivation of Eq. (4). The first is that the components are all linear, and the second is that $h\nu \ll kT$, where ν is the frequency of interest. The maser amplifier and all other components in the three measurements were linear. However, $h\nu/kT = 0.32$ is not negligible with respect to unity; therefore, a correction term, $T_c' \cong 0.024\nu$ (GHz), as explained in [9], may be added to T_e to determine the corrected amplifier noise temperature, T_c. For this measurement, $T_c' = 0.20$ K and $T_c = T_e + T_c' = 0.20$ K.

IV. Measurements and Results

The first measurement determined the RF loss ($2L$) and noise temperature contribution (2ϕ) of the input and output waveguide lines. The setup of the first measurement consisted of a through coaxial line between the input and output waveguide lines. At a constant physical temperature of 1.60 K, noise and loss measurements were performed. At 8400 MHz, the noise temperature contribution of the input line (ϕ) and the input line loss (L) were measured to be 29.26 ± 1.22 K and −0.89 ± 0.02 dB, respectively.

A 20-dB attenuator was installed between the input and output waveguide lines for the second measurement. A precision carbon-glass thermometer was attached to the attenuator to accurately monitor its temperature. This measurement determined the pad loss (L_p) at a known temperature (T_p). At 1.60 ± 0.05 K and 8400 MHz, the attenuator loss measured −20.09 ± 0.03 dB.

The maser was installed behind the 20-dB attenuator for the third measurement. Measured values of T_{eff} and the associated gain, G_e, were 382 K and 41.8 dB, respectively. Substituting data from the previous measurements and the value of T_{eff} from this third procedure into Eq. (4), the maser input noise temperature, T_e, equals 1.23 ± 0.16 K. Adding the correction term T_c' gives a corrected maser input noise temperature of 1.43 ± 0.16 K.

The theoretical estimate of the error in T_e is obtained by taking the differential of Eq. (5), which yields

$$dT_e = \frac{\partial T_e}{\partial T_{eff}} \, dT_{eff} \; + \; \frac{\partial T_e}{\partial \phi} d\phi \; + \; \frac{\partial T_e}{\partial L} dL$$

$$+ \; \frac{\partial T_e}{\partial L_p} dL_p \; + \; \frac{\partial T_e}{\partial T_p} dT_p \qquad (6)$$

The most significant error contribution in these measurements is in T_p, the attenuator physical temperature. Thus, the better the bath temperature is known, the more accurate the noise temperature measurement.

For each of these measurements, the temperature of the liquid helium bath was lowered below the normal boiling point (4.2 K) by pumping on the bath to reduce the vapor pressure of the liquid helium. In each case, the minimum bath temperature achieved was 1.60 K. The physical temperature was measured with a carbon-glass thermometer and verified with a vacuum pressure gauge. The lowest temperature achieved was limited by the helium boil-off rate and the pumping speed of the high-vacuum equipment.

Tables 1 and 2 present noise temperature and gain per unit length results, respectively, for a range of frequencies between 8350 and 8500 MHz and for a range of superfluid temperatures. Maser noise temperature measurements at 8400 MHz are plotted as a function of physical temperature in Fig. 2. In this plot, it is satisfying to note that a least-squares line through the data passes close to the maser noise temperature quantum limit at a physical temperature of 0 K.

Maser gain was measured at several different temperatures as the bath temperature was cooled to 1.6 K. The 8400-MHz results are shown graphically in Fig. 3. A 7-dB

increase (from 28 to 35 dB at 8400 MHz) in maser gain was measured upon cooling from 2.2 to 2.17 K. This result, shown graphically in Fig. 4, is due to the onset of superfluidity at 2.17 K. Superfluid helium has a very high effective thermal conductivity, ensuring that the maser ruby temperature is equal to the bath temperature. This effect is due to an increase by three orders of magnitude in the thermal conductivity at temperatures below the lambda point. The test results suggest that above 2.17 K the ruby operates at a temperature about 0.5 K higher than that of the bath.

At the lowest temperature of 1.6 K, the maser exhibited a net gain of 41.8 dB, with a bandwidth of 76 MHz centered at 8400 MHz, as shown in Fig. 5. The maser's ruby bar was 8.5 cm long, giving a maser net gain per centimeter of 4.9 dB/cm. Figure 6 shows a close comparison between measured data and the theoretical gain as a function of physical temperature.

V. Conclusion

The noise performance of an 8400-MHz maser amplifier has been measured in superfluid helium. The measured results agree closely with theory. A value of 1.43 ± 0.16 K was measured, while the theoretical value is 1.02 K. The associated maser gain measurement at the same frequency and physical temperature was 4.9 dB/cm, agreeing closely with theoretical predictions.

The telemetry needs of the DSN for outer planet missions, as well as for Mars surface exploration, can only be met with the lowest noise amplifiers. This maser technology, used in conjunction with beam waveguide antennas, will assist the DSN in meeting its needs into the next century.

Acknowledgments

References

[1] A. E. Siegman, *Microwave Solid State Masers*, New York: McGraw-Hill, 1964.

[2] J. S. Shell, R. C. Clauss, S. M. Petty, G. W. Glass, M. S. Fiore, J. J. Kovatch, J. R. Loreman, D. E. Neff, R. B. Quinn, and D. T. Trowbridge, "Ruby Masers for Maximum G/T_{op}," accepted for a special issue of the *Proceedings of the IEEE on the Design and Instrumentation of Antennas for Deep Space Telecommunications and Radio Astronomy*, scheduled to be published in February 1994.

[3] B. M. Oliver, "Thermal and Quantum Noise," *Proceedings of the IEEE*, vol. 53, no. 5, p. 436, May 1965.

[4] D. L. Trowbridge, "Block IIA Traveling-Wave Maser," *The Telecommunications and Data Acquisition Progress Report 42-87, vol. July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 158–164, November 15, 1986.

[5] D. L. Johnson, S. M. Petty, J. J. Kovatch, G. W. Glass, "Ultralow Noise Performance of an 8.4-GHz Maser-Feedhorn System," *The Telecommunications and Data Acquisition Progress Report 42-100, vol. October–December 1989*, Jet Propulsion Laboratory, Pasadena, California, pp. 100–110, Febuary 15, 1990.

[6] C. T. Stelzried, "Microwave Thermal Noise Standards," *IEEE Trans. on MTT*, vol. MTT-16, no. 9, pp. 646–655, 1968.

[7] N. Kuhn, "Accurate and Automatic Noise Figure Measurements with Standard Equipment," *IEEE MTT-S Int. Microwave Symp. Digest*, pp. 425–427, 1980.

[8] M. W. Pospieszalski, "On the Noise Measurement of Noise Parameters of Microwave Two-Ports," *IEEE Trans. on MTT*, vol. MTT-34, pp. 456–458, 1986.

[9] C. T. Stelzried, *The Deep Space Network-Noise Temperature Concepts, Measurements, and Performance*, JPL Publication 82-33, Jet Propulsion Laboratory, Pasadena, California, September 15, 1982.

Table 1. Maser noise temperature results.

Physical temperature, K	Frequency, MHz						
	8350	8375	8400	8425	8450	8475	8500
	Noise temperature, K						
1.600	1.47	1.47	1.42	1.70	2.13	2.55	3.82
1.700	1.50	1.62	1.53	1.76	2.26	3.00	11.42
1.800	1.62	1.81	1.61	2.01	2.50	3.30	13.81
1.900	1.74	1.92	1.66	2.26	2.74	3.59	17.03
2.000	2.01	2.16	1.80	2.55	3.04	4.12	19.37
2.101	2.28	2.38	1.96	2.83	3.24	4.29	18.99

Table 2. Maser gain per unit length results.

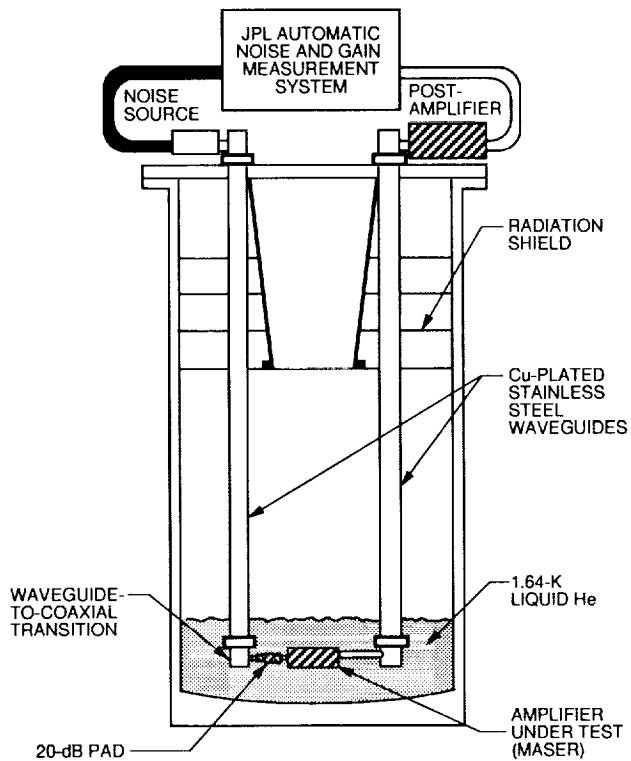| Physical temperature, K	Frequency, MHz						
	8350	8375	8400	8425	8450	8475	8500
	Maser gain per unit length, dB/cm						
1.600	4.67	4.86	4.92	5.18	4.43	4.48	2.45
1.700	4.24	4.32	4.28	4.16	3.58	2.44	1.06
1.800	3.97	4.05	3.99	3.90	3.36	2.29	0.96
1.900	3.72	3.79	3.72	3.65	3.14	2.12	0.83
2.000	3.45	3.53	3.49	3.44	2.95	1.94	0.73
2.101	3.22	3.31	3.29	3.22	2.77	1.81	0.64

Fig. 1. The noise and gain measurement system with the
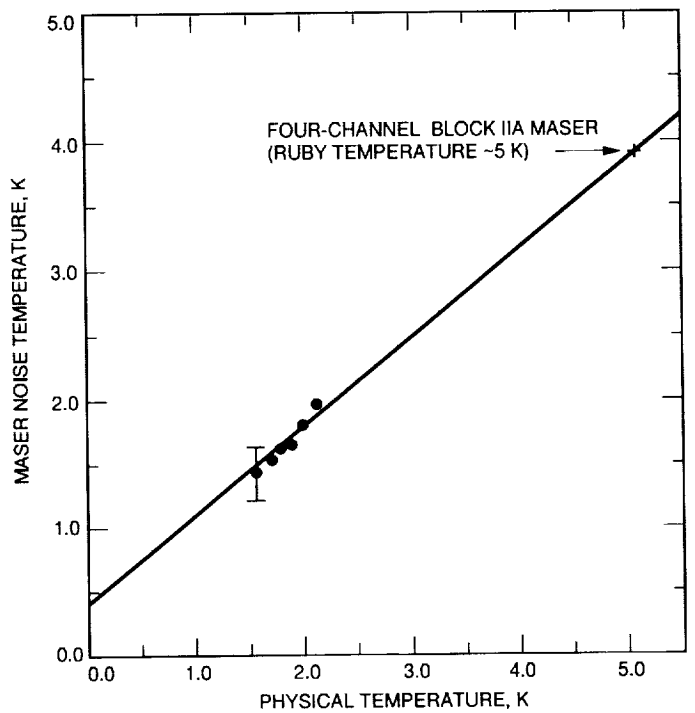maser installed.

Fig. 2. Measured noise temperature for an 8400-MHz maser
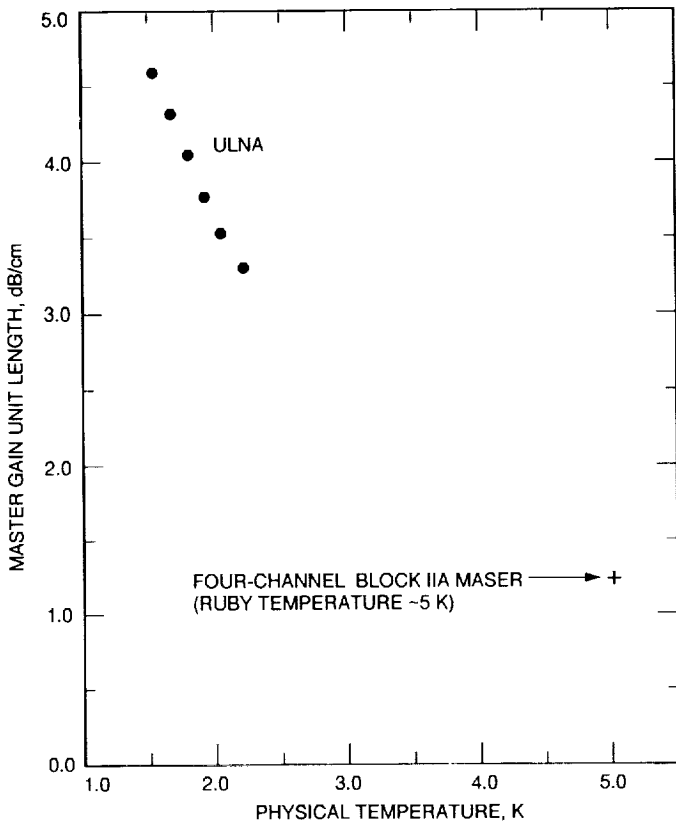ULNA as a function of physical temperature.

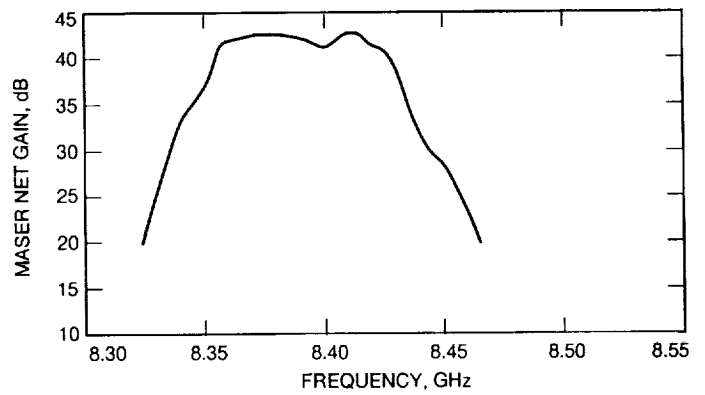Fig. 3. Maser gain at 8400 MHz with respect to physical temperature.
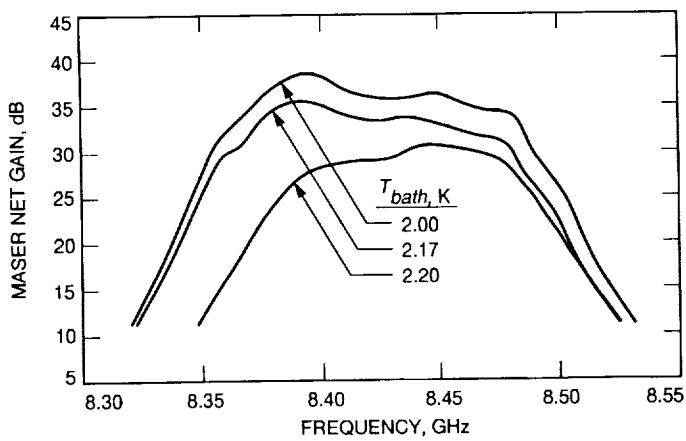

Fig. 4. Maser gain-bandpass as a function of temperature about the helium lamda point.

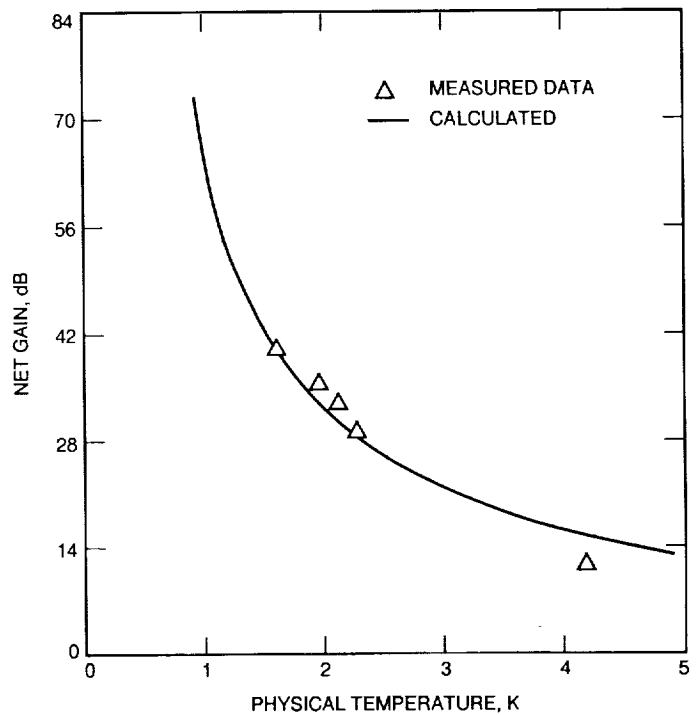Fig. 5. Maser gain-bandpass curve at 1.6 K.

Fig. 6. Comparison of theoretical and measured maser net gain as a function of physical temperature.