# X-kind Ultra-Low Noise Maser Amplifier Performance

G. W. Glass, D. L. Johnson, G. G. Ortiz

Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, California 91109-8000

## Abstract

Noise temperature measurements of an 8440 MHz ultra-low noise maser amplifier (ULNA) have been performed at sub-atmospheric, liquid helium temperatures. The traveling wave maser operated while immersed in a liquid helium bath. The lowest input noise temperature measured was 1.23 ± 0.16 K at a physical temperature of 1.60 kelvin. At this physical temperature the observed gain per unit length of ruby was 4.6 dB/cm, and the amplifier had a 3 dB-bandwidth of 76 MHz.

## Introduction

NASA's Deep Space Network (DSN) 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.

The required 4.5 kelvin physical temperature of the maser is provided by a three-stage closed cycle refrigerator. These maser-CCR packages are normally mounted at the vertex of large, tippable, parabolic antennas. Under normal operating conditions an X-band maser system typically provides 45 dB of net gain (1.4 dB/cm), over 100 MHz of instantaneous bandwidth, and a typical input noise temperature of 3.5 K, referenced to the room temperature flange.

Further cooling of a maser amplifier results in significant noise temperature and gain improvements. At X-band the input noise temperature is approximately proportional to the physical temperature, while the electronic gain in decibels (excluding circuit losses) is approximately proportional to the inverse physical temperature (both to first order). Thus, immersing a maser amplifier in a bath of superfluid helium (sub 2.17 kelvin) will result in an increase of three times the gain in dB and a decrease in the noise temperature by one-third (e.g., from 3.5 K 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 a maser (and its feed components) to achieve a very low system noise temperature while simultaneously increasing the maser gain.

In order to provide the lowest front-end system noise temperature for its deep space telecommunication downlink, the Jet Propulsion Laboratory (JPL) has developed and demonstrated a superfluid helium cooled maser amplifier for the DSN. This paper describes laboratory noise temperature and gain measurements made on an ULNA maser centered at 8440 MHz in sub-atmospheric liquid helium. A brief discussion on the limits of the X-band ULNA technology is also presented.

## Theory

The noise power of a maser amplifier at a given physical temperature is discussed by Siegman [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:

$$T_{amp} = \frac{(G_{net}^{ratio} - 1)}{G_{net}^{ratio}} \frac{hf}{k} \left[ \frac{G_{elect}^{(dB)}}{G_{net}^{(dB)}} \frac{r}{r - 1} + \frac{I_0^{(dB)}}{G_{net}^{(dB)}} \frac{1}{(e^{\frac{hf}{kT_0}} - 1)} \right] \qquad (1)$$

where $G_{net}^{ratio}$ = net electronic gain ratio, unitless
$h$ = Planck constant = $6.6262 \times 10$”’ {’.] $s$
$f$ = operating frequency, 117
$k$ = Boltzmann constant = $1.3806 \times 10^{23}\ J/K$
$G_{elect}^{(dB)}$ = electronic gain, dB
$r$ = inverted spin population ratio, unitless
$I_0^{(dB)}$ = forward insertion loss, dB
$T_0$ = maser physical temperature, kelvin.

Using eqn. (1) the expected noise temperature of a maser at the cryogenic input 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 2.8, and a maser amplifier physical temperature of 1.6 kelvin, the expected noise temperature is 1.02 K.

The mast]' noise temperature in eqn. ( 1 ) is comprised of' two primary noise mechanisms. The first term is related to the spontaneous ('mission of photons by the ruby spins while the second is due to conductor losses in the microwave circuitry. It is interesting to note that as the maser physical temperature (and ruby spin temperature) approach 7.('1'(), the gain and inverted spin population ratio terms each approach one while the conductor loss term goes to 7.('1"(). Thus ['() II. ( 1 ) takes the limiting form of' the equivalent quantum noise temperature as discussed by Oliver in [3]

$$T_{N\,IQI} = \frac{h}{k} f . \tag{2}$$

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 gain in dB is

$$G_{dB} = 27 \frac{SN}{Q_m} \tag{3}$$

Where $S$ is the slowing factor, $N$ is the circuit length in free space, 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 proportional to temperature. Assuming the gain of a maser amplifier at a physical temperature of 4.2 kelvin is 10 dB, the expected gain of this amplifier once its temperature has been lowered to 1.6 kelvin is 25 dB.

## System Description

A diagram of the noise/{:ai]] measurement setup with the maser amplifier in place is shown in Fig. 1. The maser is contained in 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 half 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 maintain a low radio frequency (RF) loss. The lower half 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 II-A maser structure [4]. This structure was modified for stable operation at 1.5 kelvin. The principal modification was to increase the reverse loss provided by the resonant YIG isolator from 37.5 to 74 dB. Further details with respect to the existing X-band ULNA structure and its modifications can be found in [5].

The bath temperature is reduced below 4.2 kelvin by reducing 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 2,600 LPM (92 CFM) evacuates the dewar to a pressure of 800 Pa. Once a stable operating temperature (vacuum pressure) is maintained, as measured 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 kelvin. Noise temperature measurements were made over a band of frequencies at a variety of temperatures by cooling the cryostat to its lowest temperature and then allowing the cryostat to slowly warm.

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 ($T_{hot}$, referred to the maser input) was a noise diode with an ENR value of 13 dB [8]. The attenuator is super-cooled in the helium bath while the noise diode is outside the dewar. This technique has the advantage of reducing the value of $T_{hot}$ and $T_{cold}$, yet maintaining a large Y-factor. An added benefit is the good input match that the pad presents to the noise source and the maser. The maser under test did not have enough 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 still have enough dynamic range so as not to overload when reading $T_{hot}$.

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

$$T_{eff} = \phi + L(L_p - 1)T_p + LL_pT_e + \frac{(\phi + T_f L)}{G_e}. \qquad (3)$$

(Eqn. (3) is derived in appendix 1.) The last term in eqn. (3) is negligible compared with the preceding terms so to first order it may be excluded. Our interest is in determining the noise temperature of the maser at the input flange, $T_e$, therefore solving eqn. (3) for $T_e$ yields

$$T_e = \frac{\left[T_{eff} - \phi - L(L_p - 1)T_p\right]}{LL_p}. \qquad (4)$$

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

## Measurement Results

The first measurement determined the RF loss ($2L$) and noise temperature contribution ($2\phi$) of the input and output waveguide lines. The first measurement setup consisted of a through coaxial line between the input and output waveguide lines. At a constant physical temperature of 1.60 kelvin noise and loss measurements were performed. At 8400 MHz, the noise temperature contribution of the input line ($\phi$) and the input line loss ($L$) were 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 kelvin 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 eqn. (4) the maser input noise temperature, $T_e$ equals 1.23 ± 0.16 K. Differentiating eqn. (4) yields the error in $T_e$,

$$dT_e = \frac{\partial T_e}{\partial T_{eff}} dT_{eff} + \frac{\partial T_e}{\partial \phi} d\phi + \frac{\partial T_e}{\partial L} dL + \frac{\partial T_e}{\partial L_p} dL_p + \frac{\partial T_e}{\partial T_p} dT_p . \qquad (5)$$

The most significant source of error in these measurements came from the attenuator physical temperature component. Thus, the better the bath temperature is known the more accurate the noise temperature measurement is.

In 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 kelvin. 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 vacuum pumps.

Noise temperature and gain per unit length results are presented for a range of frequencies between 8350 and 8500 MHz and for a range of superfluid temperatures. Maser noise temperature and gain per unit length results at 8400 MHz are plotted as a function of physical temperature in Figures 2 and 3 respectively.

Maser gain was measured at several different temperatures as the bath temperature was cooling to 1.6 kelvin. A 7-dB increase in maser gain was measured (from 28 dB to 35 dB at 8400 MHz) upon cooling from 2.2 to 2.17 kelvin. This result, shown graphically in Figure 4, is due to the onset of superfluidity at 2.17 kelvin, which, with its very high effective thermal conductivity, ensures that the maser ruby temperature is equal to the bath temperature. This effect is due to a change of the dominant mechanism of heat transfer out of the ruby lattice, from conductive to convective cooling. These test results suggest that above 2.17 kelvin the ruby operates at a temperature about 0.5 kelvin higher than that of the bath temperature. At the lowest temperature, 1.6 kelvin, the maser exhibited a net gain of 43 dB, with a bandwidth of 76 MHz centered at 8400 MHz, as shown in Fig. 5.

## Conclusion

The noise performance of an 8400 MHz maser amplifier has been measured in normal and superfluid liquid helium. The measured results agree with theory within the root mean square error. A value of 1.23 ± 0.16 K was measured while the predicted value is 1.04 K.

The telemetry needs of the DSN for outer planet missions, as well as 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 customers needs into the next century.

## Prologue

This X-band maser amplifier has recently been used at Deep Space Station-13, a Beam Wave Guide Antenna, in Goldstone, California. This maser was a key element in receiving a radar signal bounced off the 4179 Toutatis asteroid [9]. Because of this masers outstanding performance, astronomers at JPL have obtained the sharpest images yet of an Earth-approaching asteroid.

## Acknowledgments

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9.

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2. Noise temperature versus physical temperature graph at 8440 MHz.

3. Maser gain per unit length ruby versus physical temperature graph at 8440 MHz.

4. Increase in maser gain over a range of frequencies as a function of physical temperature near the lambda point. This suggests that above 2.17 kelvin the ruby operates at a temperature about 0.5 kelvin above the bath temperature.

5. Maser gain bandpass curve with the physical temperature at 1.60 kelvin. The maser exhibits a net gain of 43 dB, with a bandwidth of 76 MHz centered at 8400 MHz.

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Maser Noise Temperature Results, K

| Freq, MHz<br>Phys Temp, K | 8350 | 8375 | 8400 | 8425 | 8450 | 8475 | 8500 |
|---|---|---|---|---|---|---|---|
| 1.600 | 1.27 | 1.27 | 1.22 | 1.50 | 1.93 | 2.35 | 3.62 |
| 1.700 | 1.30 | 1.42 | 1.43 | 1.56 | 2.06 | 2.80 | 11.22 |
| 1.800 | 1.42 | 1.61 | 1.61 | 1.81 | 2.30 | 3.10 | 13.61 |
| 1.900 | 1.54 | 1.72 | 1.76 | 2.06 | 2.54 | 3.39 | 16.83 |
| 2.000 | 1.81 | 1.96 | 1.99 | 2.35 | 2.84 | 3.92 | 19.17 |
| 2.101 | 2.08 | 2.18 | 2.25 | 2.63 | 3.04 | 4.09 | 18.79 |

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Maser Gain per Unit Length Results, dB/cm

| Freq, MHz<br>Phys Temp, K | 8350 | 8375 | 8400 | 8425 | 8450 | 8475 | 8500 |
|---|---|---|---|---|---|---|---|
| 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 |

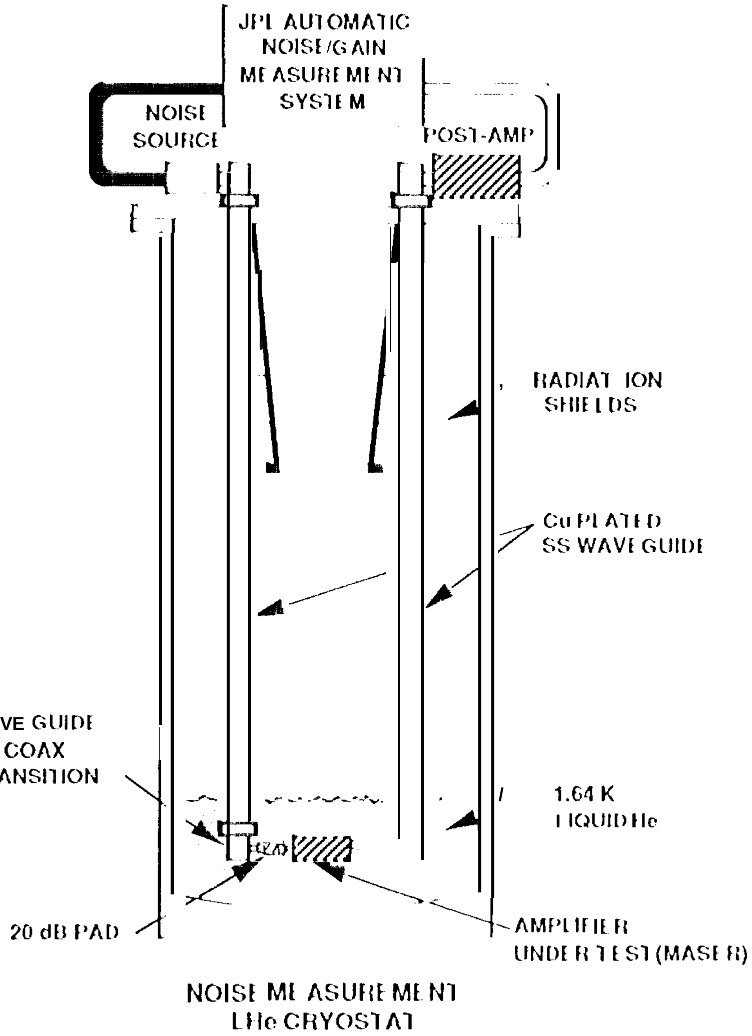

Figure 1.
Diagram of the noise/gain measurement system with maser amplifier installed.

## Noise Temperature
## 8.4 GHz Ultra Low-Noise Amplifier

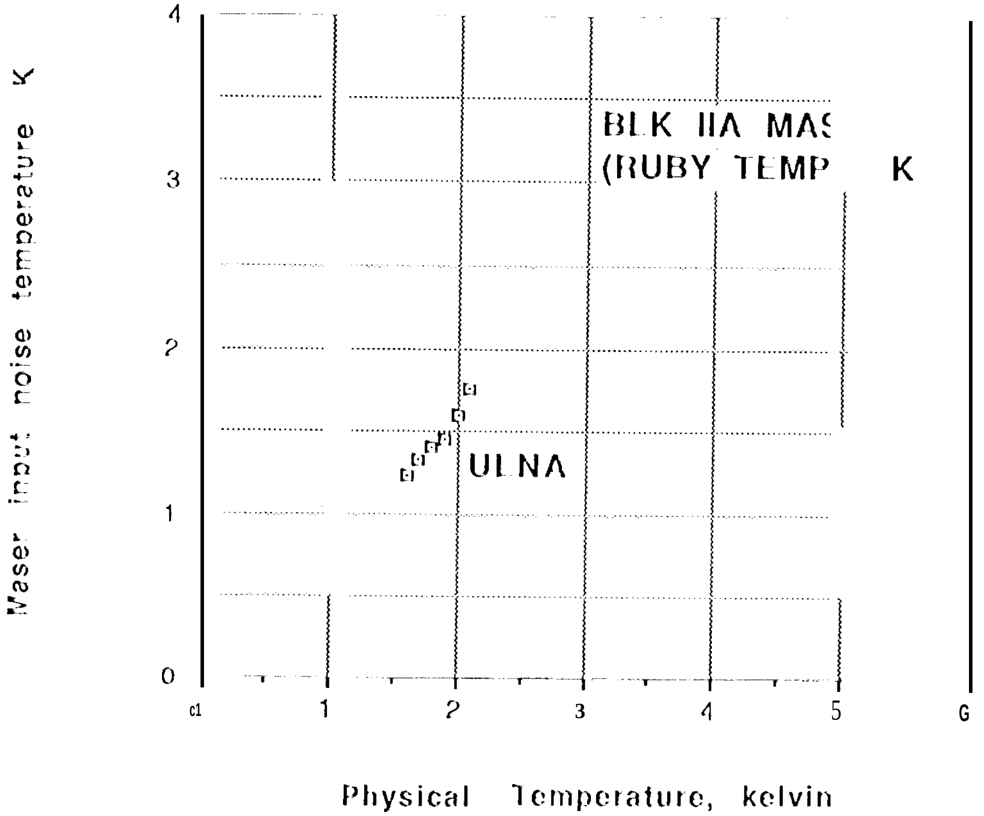

Fig 2

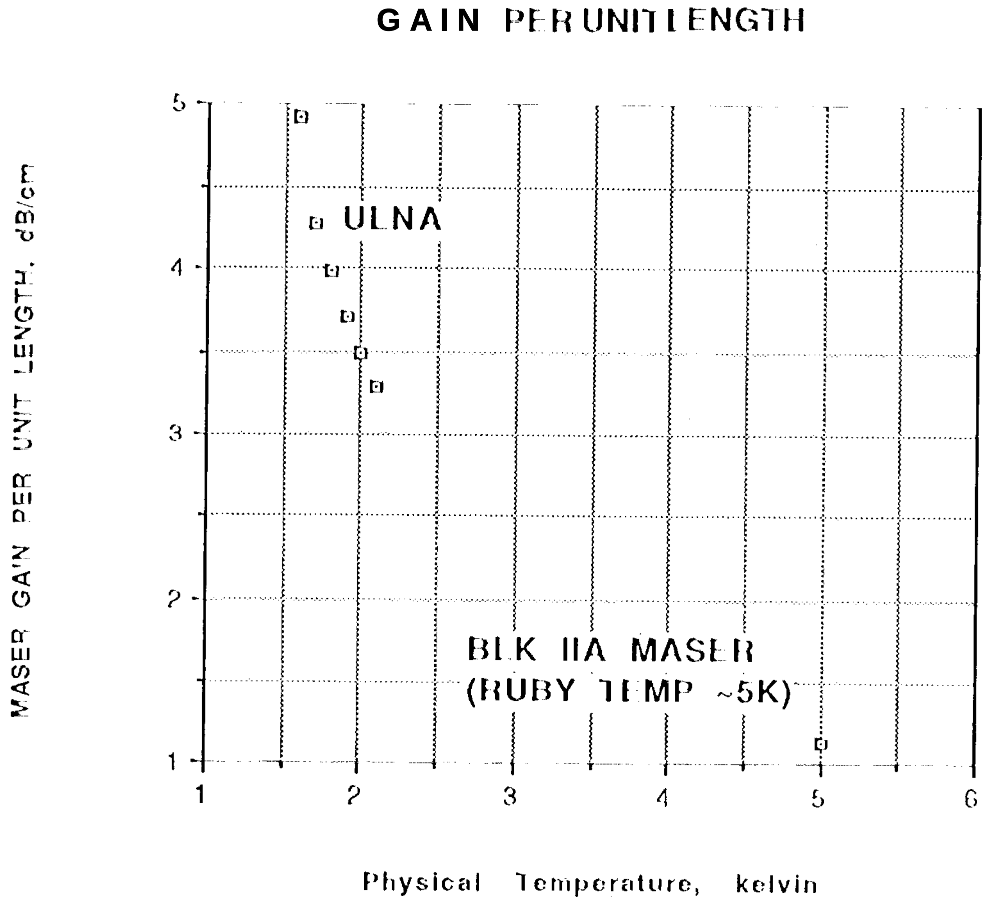
GAIN PER UNIT LENGTH
MASER GAIN PER UNIT LENGTH, dB/cm
5
4
3
2
1
ULNA
BLK IIA MASER
(RUBY TEMP ~5K)
1
2
3
4
5
6
Physical Temperature, kelvin

Fig 3

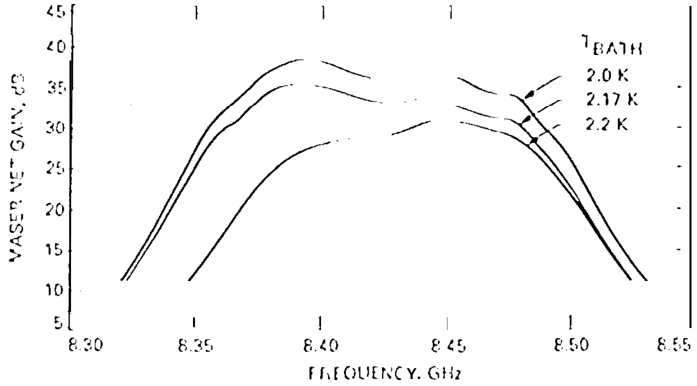

Fig. 4. Maser gain-bandpass as a function of temperature about the helium lambda point.

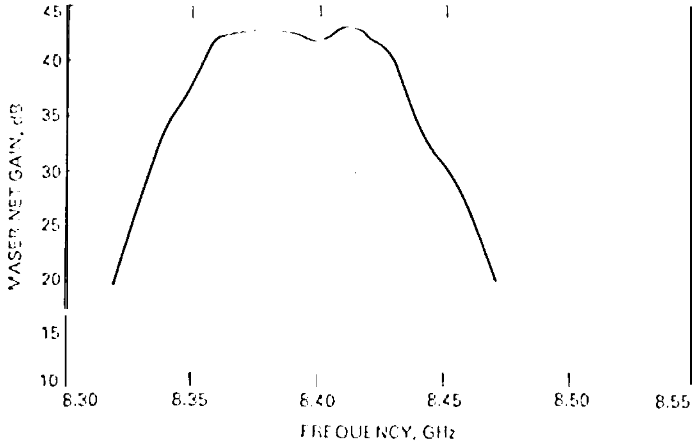

Fig. 5. Maser gain-bandpass at 1.64 K.