X-Band Traveling Wave Maser Amplifier

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Laboratory tests on three X-band maser amplifiers have been completed. Gain, phase and group delay measurement data indicate that the maser stability performance will meet the design goals. A new method of remote gain adjustment has been achieved with the X-band maser amplifiers. The maser amplifiers have 45-dB gain over a minimum of 50-MHz 1-dB bandwidth and a noise temperature of 8 kelvins from 8400 to 8440 MHz.

I. Introduction

Three X-band traveling wave maser amplifiers (masers) have received final laboratory test and have been installed in the 64-meter antenna deep space stations of the Deep Space Network. Preliminary design parameters and testing of the maser and associated system were presented in earlier reports (Refs. 1 and 2). This report describes maser design refinements, performance, noise temperature, gain, phase, and group delay stability.

II. Maser Performance Improvements

The new X-band masers described here achieve a flat bandwidth (within 1 dB) of more than 50 MHz at 45-dB gain; this is more than 5 times the 1-dB bandwidth of previously reported tunable X-band masers (Ref. 3) at 45-dB net gain. The instantaneous bandwidth of a maser is determined by the maser material linewidth, the shape (or uniformity) of the magnetic field required for maser operation, and the electronic gain at which the maser operates. A thorough discussion of methods for increasing the bandwidth of a maser can be found in *Microwave Solid State Masers* by S. E. Siegman (Ref. 4). Siegman shows that operation of a maser using ruby (linewidth $\simeq$ 50 MHz) in a uniform magnetic field at high gain (more than 40 dB) results in a 3-dB bandwidth of less than 20 MHz. Attempts to increase bandwidth always result in substantial gain reductions. Considerable effort has been given to the task of optimizing the gain versus bandwidth trade-off. Bandwidth and gain value adjustment of previous masers (Ref. 5) was achieved by a combination of iron shim and field staggering coils. The previous methods are time consuming and require different shims or field staggering coil placement for each maser structure. A dual set of field spreading figure-eight coils was designed for gain and bandwidth adjustment; one full-sized set of coils covers the full length of the maser comb structure (for bandwidth adjustment), and the second half-sized set of coils is used for gain level adjustment. The dual coils are shown in Fig. 1. The dual figure-eight coil arrangement provides remote and independent adjustment of bandwidth and gain to desired specifications. Figure 2 shows gain versus frequency at five gain/current control setting. The gain can be adjusted within reasonable limits (± 3 dB at 45-dB gain) without changing the bandwidth. This results in minimal change in the phase and group delay characteristics of the maser as the maser gain is adjusted. This field staggering method improves the noise performance across the maser bandpass by minimizing slow-wave circuit losses prior to signal amplification. All signal frequencies are given some amplification as early as possible in the traveling wave maser structure (as shown in Fig. 2) by providing several repeated cycles of field stagger tuning along the maser's total length. The new X-band maser has a relatively flat equivalent noise temperature versus frequency performance as shown in Fig. 3. A previously used pump frequency modulator circuit (for S, X, and Ku-band uniform field masers, Ref. 6) was modified for use in the X-band maser with wide bandwidth and dual-frequency klystrons. The modulator (shown in Fig. 4) provides a 100-kHz sinewave with 26-V peak-to-peak output. The sinewave is applied to the reflector of both the 24- and 19-GHz pump klystron tubes through individual modulation level control potentiometers. Modulation of the pump frequency was previously used to improve maser gain stability in uniform field masers (Ref. 7). The new X-band field staggered maser requires pump frequency modulation to achieve the required gain over the extra wide bandwidth. The improvement in gain bandwidth with modulation of the pump frequency was previously reported (Ref. 1).

III. Maser Phase and Gain Measurements

Gain, signal phase, and group delay stability measurements were made using a Hewlett-Packard network analyzer. Figure 5 shows the gain and total signal phase shift versus frequency; the reference and test channel paths were balanced to produce the same delay and phase shift with the maser bypassed. A test signal was then swept through the maser to produce the recording of maser gain and phase shift versus frequency. The maser group delay (t_d) is calculated from the phase change versus frequency change at any point within the bandpass. Reference 8 defines transit time of signals through a device as group delay in the following manner:

$$t_d = \frac{|d\phi|}{360\,|df|} \simeq \frac{1}{360}\frac{|\Delta\phi|}{|\Delta f|} \qquad (1)$$

where

t_d = group delay or signal transit time in seconds

$\Delta\phi$ = incremental phase shift in degrees

Δf = incremental frequency change which produces $\Delta\phi$

The group delay time through the maser, with 45-dB net gain, varies from 50×10^{-9} s at 8422 MHz to 55×10^{-9} s at 8402 and 8442 MHz. To obtain these group delay measurements accurately, the reference path delay time was increased, with additional cable length, to equal the time delay in the test signal path at the center of the maser bandwidth. This condition enables expansion of the phase scale and improves phase shift resolution. It was used to produce the recording (Fig. 6) of gain and signal phase shift versus frequency. Data from Fig. 6 were used to plot the group delay time change versus frequency shown in Fig. 7. This represents the group delay time difference between the maser and a nondispersive network with $t_d = 50 \times 10^{-9}$ s.

IV. Stability Measurements

Changes in maser gain, group delay, and signal phase are caused by changes in magnetic field, refrigerator operating temperature, and pump frequency and power. Twelve-hour predicted parameter changes for the pump klystron power supplies, field shaping power supplies, and refrigeration temperature (variable parameters) were determined from known voltage output stability versus time and temperature and refrigerator temperature stability.

The maser change in phase shift and gain versus frequency was recorded for each of the known variable parameters. The group delay change introduced by each variable parameter versus frequency is plotted in Figs. 8 and 9 based on the recorded data. This represents the predicted $\pm$ group delay time instability versus frequency for each of the separate variable parameters over any 12-h period in an environment temperature of 25 ± 10°C. The measured maser phase and gain changes, at three frequency points across the maser gain bandwidth 8402, 8422, and 8442 MHz, are listed in Table 1 for each of the separate variable parameters. The various instabilities are expected to add in a random manner. The total rms gain, phase change, and group delay time instabilities versus frequency are listed in Table 1 and shown in Fig. 10. The predicted total rms maximum changes for a 12-h period are as follows:

Gain	± 0.5 dB
Group delay time change	$\pm 0.27 \times 10^{-9}$ s
Phase change	± 5 deg

V. Conclusions

Laboratory test data show that the X-band maser system meets, and in most cases exceeds, the present design goals. The maser wide bandwidths and resulting additional pump frequency width requirements have resulted in the pump detuning factor being the major contributor to maser gain and group delay instability. The X-band maser requires a wider pump frequency range with flat power output characteristics in order to produce the wide-gain bandwidths with the desired stability. Future planned implementation of solid-state pump sources with appropriate modulation circuits should further improve the maser gain and phase stabilities. Effects of antenna movement on maser performance and solid-state pump investigation will be reported in future progress reports.

References

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Table 1. Predicted maser gain and phase stability for 12-h period and environment temperature of 25 ± 10°C (based on measured data)

Variable parameter	Parameter change	Gain change, dB			Signal phase change, deg		
		8402 MHz	8422 MHz	8442 MHz	8402 MHz	8422 MHz	8442 MHz
Beam V 24 GHz	±1 V	±0.01	±0.02	±0.07	±0.4	±0.6	+0.8 −0.6
Beam V 19 GHz	±1 V	+0.01 −0.08	+0 −0.55	+0.1 −0.2	+0.3 −0.7	+0.3 −1.0	+0.3 −1.2
Reflector V 24 GHz	±1 V	±0	±0.1	±0.3	+3.1 −2	+3.7 −2.5	+4.4 −2.9
Reflector V 19 GHz	±1 V	+0.05 −0.15	+0 −0.25	+0.03 −0.04	+1.3 −2.5	+0.9 −3.2	+1.2 −3.6
Bandwidth control supply current	±0.2 mA	∓0.02	∓0.06	−0.04 +0.03	±0.4	±0.2	+0.3 −0.4
Gain control supply current	±0.2 mA	−0.04 +0.02	−0.02 +0.01	−0.02 +0.01	+0.04 −0.08	±0	±0
Refrigerator temperature	±0.005 K	∓0.05	−0.06 +0.05	−0.05 +0.04	∓0.1	−0.06 +0.08	−0.06 +0.05
Total rms	As above	+0.07 −0.19	+0.12 −0.64	+0.33 −0.62	+3.4 −3.3	+3.9 −4.7	+4.7 −4.8

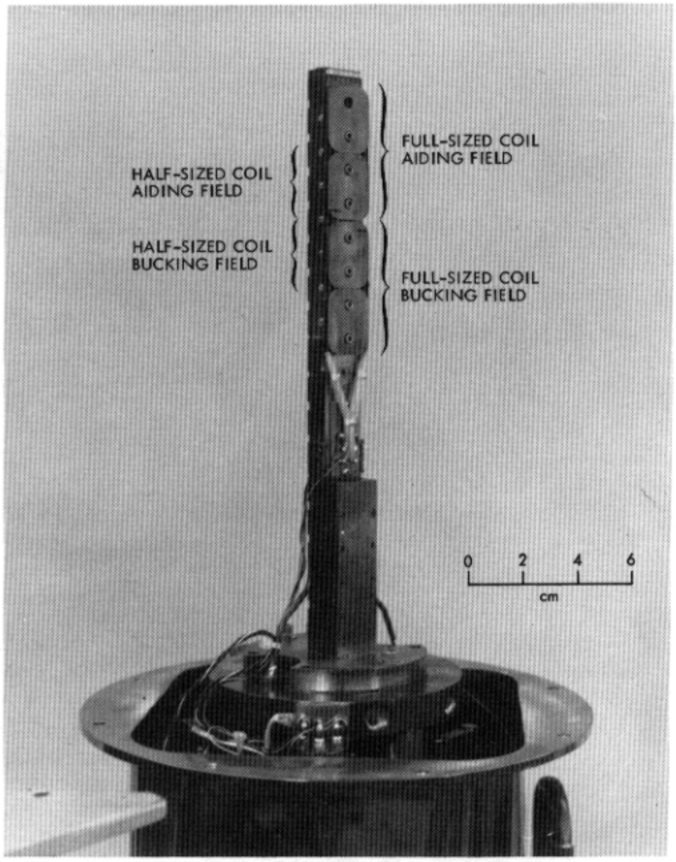

Fig. 1. Maser amplifier with field-shaping coils mounted on refrigerator

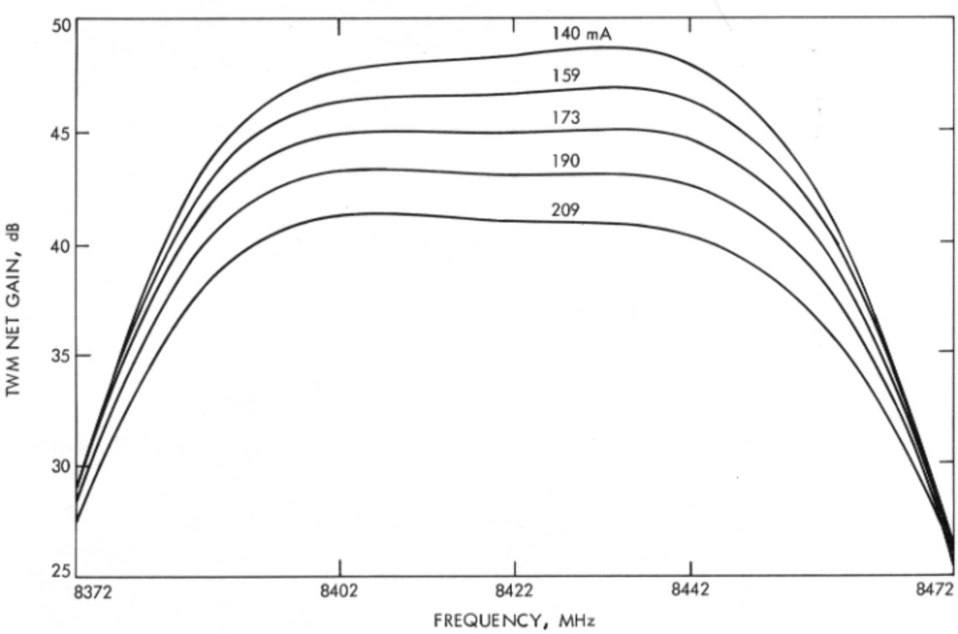

Fig. 2. Gain vs frequency at five gain control field-shaping coil current settings

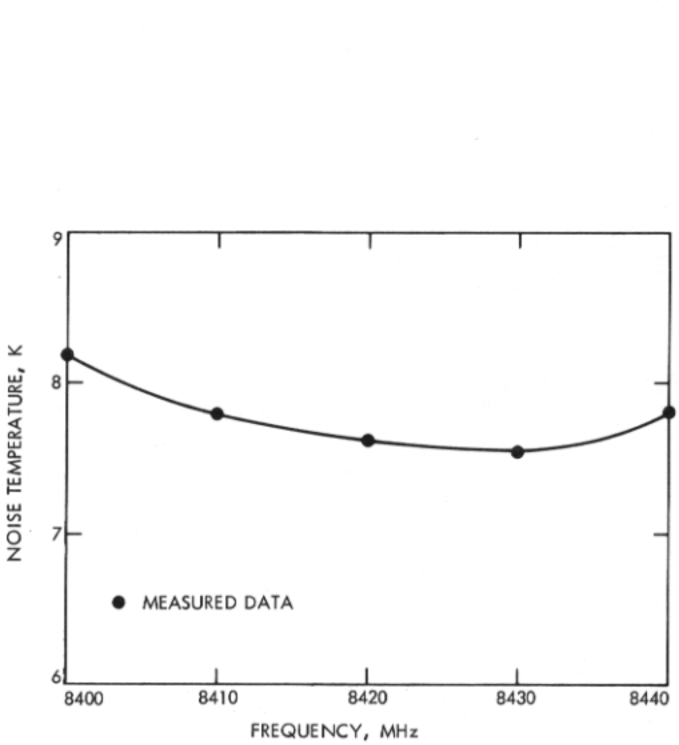

Fig. 3. Equivalent maser noise temperature vs frequency

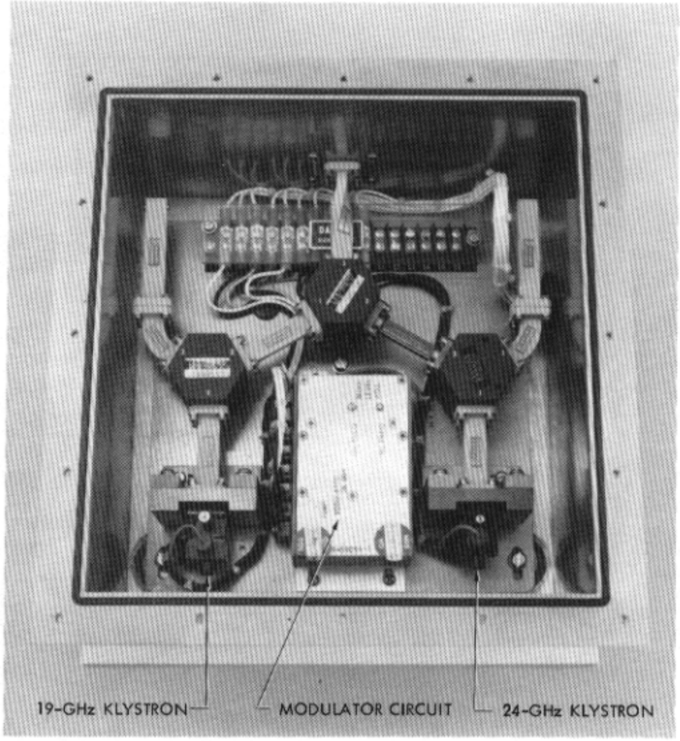

Fig. 4. Pump klystron assembly with modulator

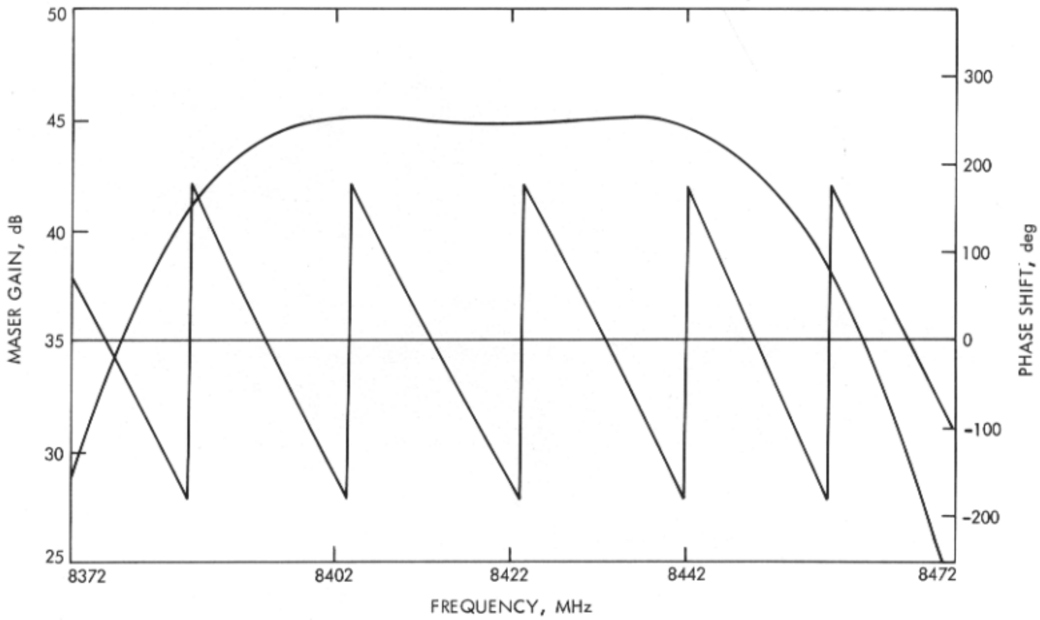

Fig. 5. Maser gain and total phase shift vs frequency

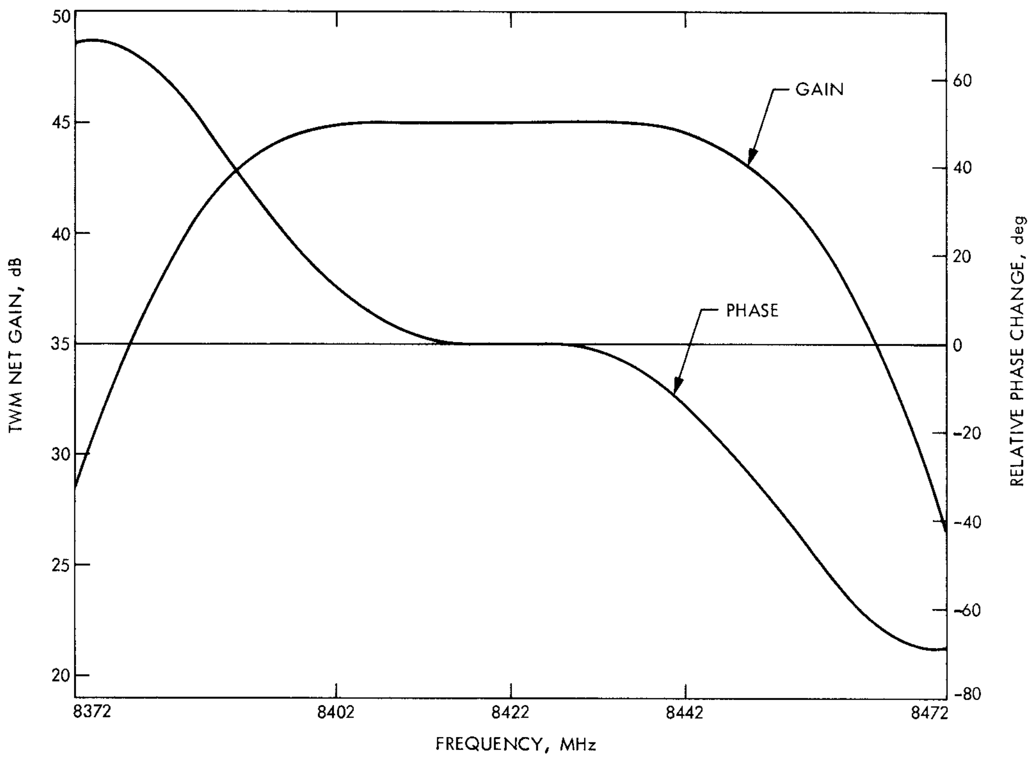

Fig. 6. Maser gain and relative phase change vs frequency

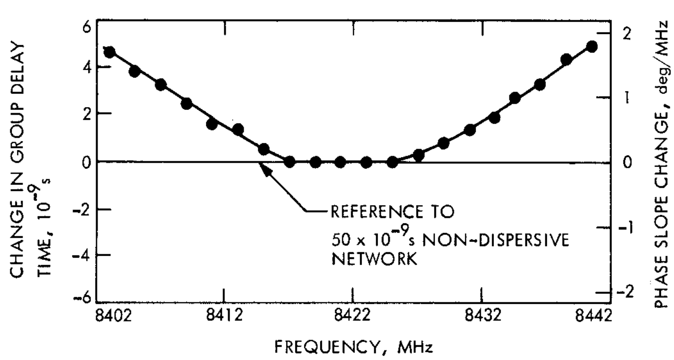

Fig. 7. Maser group delay characteristic vs frequency

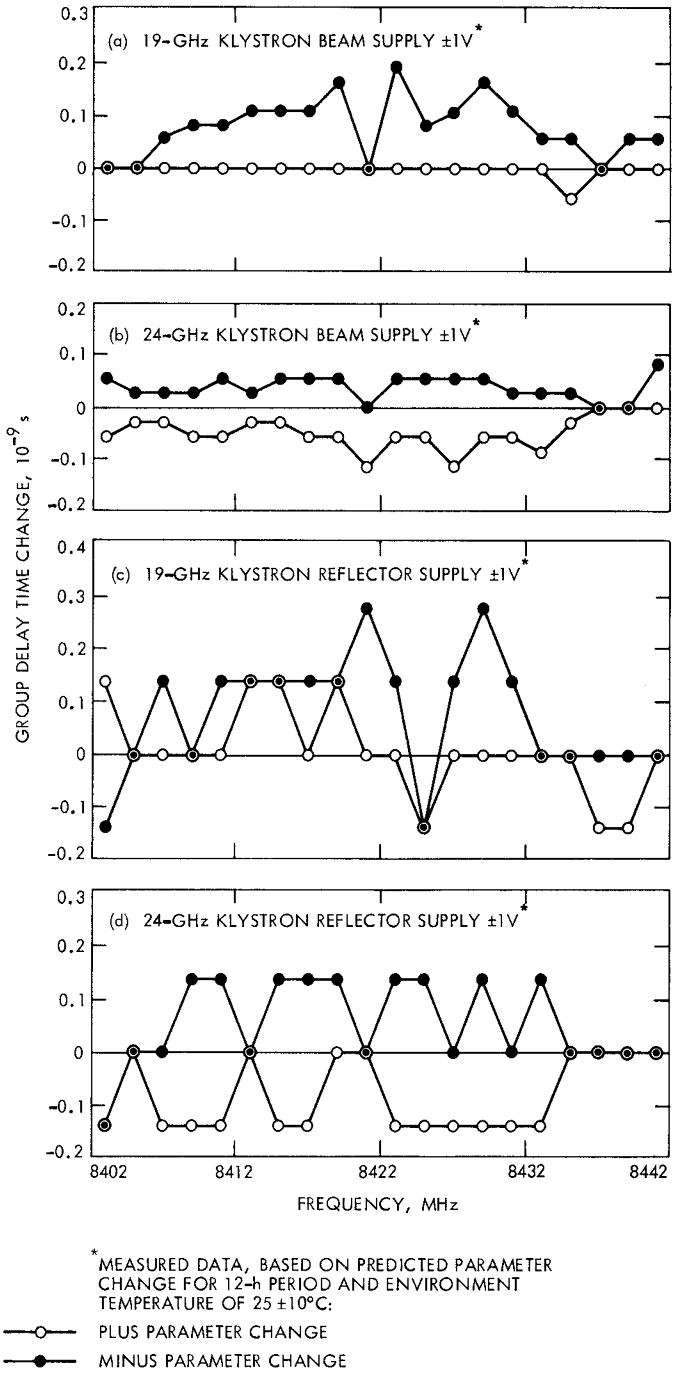

Fig. 8. Pump system effects on maser group delay stability

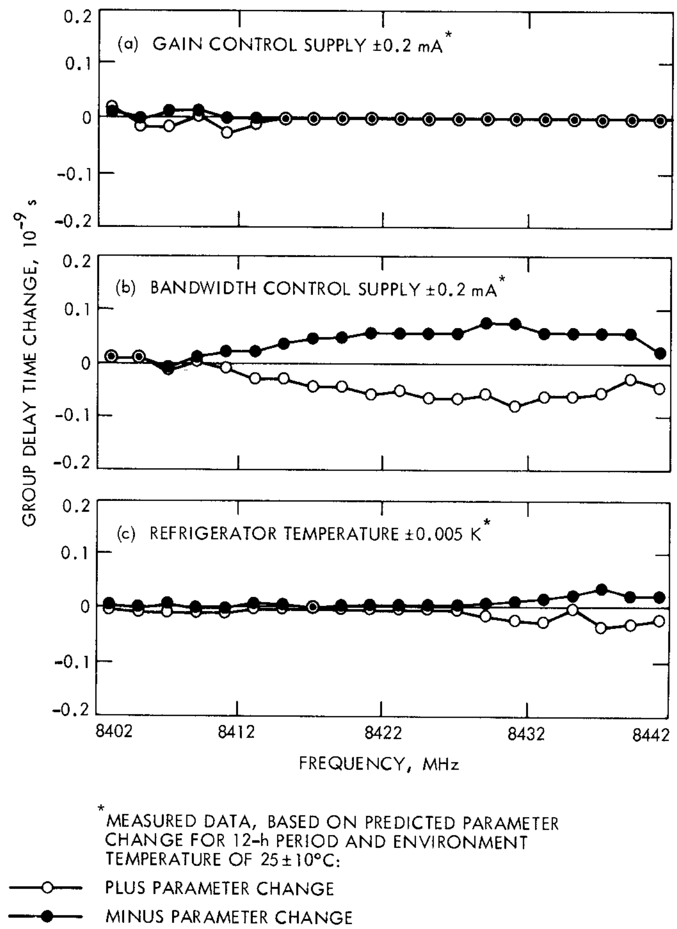

Fig. 9. Refrigerator temperature, gain, and bandwidth control supplies effect on maser group delay stability

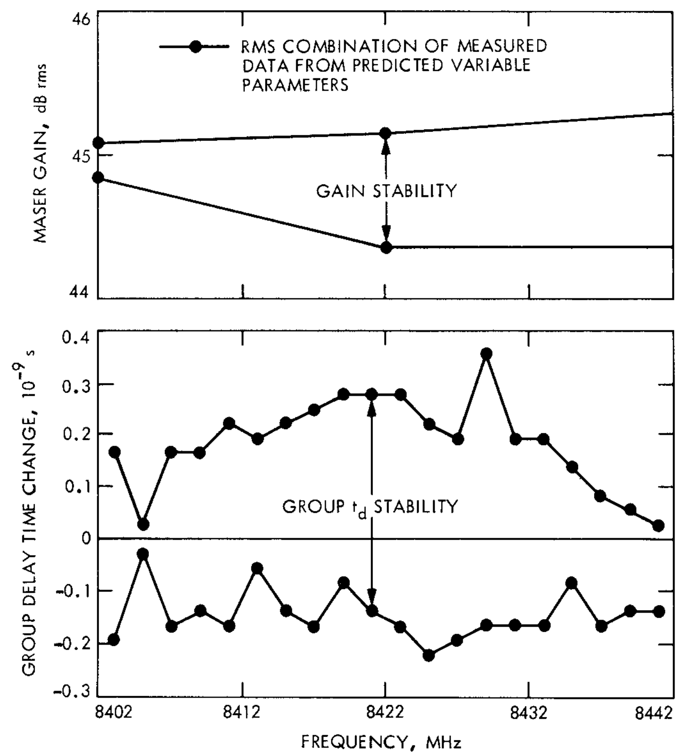

Fig. 10. Predicted maser system group delay and gain stability for 12-h period and environment temperature of 25 ± 10°C