Low Noise Receivers: Microwave Maser Development

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A traveling wave maser, tunable from 7750 to 8750 MHz, has been completed and tested in the laboratory. The maser is ready for installation on the 64-m-diameter antenna at the Deep Space Communications Complex at Goldstone, Calif. Gain, phase, and group delay stability were measured as a function of magnetic field, refrigerator temperature, power supply voltages and large interfering signals. Several features have been included in this maser to improve the stability performance. A superconducting magnet provides a very stable magnetic field. Push-push pumping results in complete pump saturation and reduced pump frequency stability requirements. Low pass filters at a temperature of 4.5 K reduce pump power radiation in signal waveguides.

The maser has 45 dB net gain and 17-MHz, 3-dB bandwidth with an equivalent input noise temperature of 6½ K at 8415 MHz and 8½ K at 7850 MHz. Simultaneous operation at two frequencies, separated by up to 500 MHz, is available at reduced gain.

I. Introduction

A new X-band traveling wave maser, ready for installation on the 64-m-diameter antenna at the Goldstone Deep Space Communications Complex, is described in this article. Improved stability performance (as compared with previously used X-band masers; see Refs. 1, 2, and 3) has been measured in the laboratory. The results of gain, phase, and group delay stability tests are reported.

II. Maser Description

The maser is a ruby-loaded comb structure similar to one previously described (Ref. 2). The entire package is shown in Fig. 1. A superconducting magnet provides a magnetic field adjustable from 0 to 5500 gauss. A closed-cycle helium refrigerator (CCR) is used to provide a 4.5 K operating environment for the maser comb structure and magnet. The klystron pump package contains two klystron oscillators and a power combiner for push-push operation. The pump package has been described previously (Ref. 4). The overall package weight (not including the feed horn shown in Fig. 1) is 70 kg. The maser may be operated in any position.

The maser and superconducting magnet are shown in Fig. 2; the CCR vacuum housing and radiation shields are not shown, and the magnet has been removed from the maser. The waveguide-to-coaxial-line transitions at the 4.5 K station (only the input side is shown) each contain 11 element coaxial low pass filters. The filter cutoff is 12 GHz. Rejection at the pump frequencies (18.4 to 19.6 GHz and 22.6 to 24.8 GHz) is more than 30 dB and the voltage standing wave ratio (VSWR) between 7700 and 8800 MHz is less than 1.2 to 1. The signal waveguides are of 0.064-cm-wall stainless steel with copper plating inside to reduce signal frequency loss. The waveguide low frequency cutoff is 6550 MHz.

Figure 3 shows the maser comb structure resting on the 4.5 K station of the CCR. Indium gaskets are used to provide intimate contact between the 4.5 K station, the maser flange, and the superconducting magnet assembly. Coils of wire, wound on the maser structure in a figure-eight pattern, are used to adjust the maser gain by changing the magnetic field shape. The field-shaping coil is controlled by a current-regulated power supply. The persistent mode (Cioffi-type) superconducting magnet and charging circuits were previously tested and reported by Berwin, Wiebe, and Dachel (Ref. 5).

III. Gain, Bandwidth, and Noise Temperature

Net gain of 45 dB is available at any frequency between 7750 and 8750 MHz. The measured equivalent input noise temperature is 10.5 K at 7750 MHz, 8.5 K at 7850 MHz, and 6.5 K from 8000 to 8650 MHz. Tuning across this range is accomplished from the maser control racks. The instantaneous 1-dB and 3-dB bandwidths (at 45-dB gain) are 10 and 17 MHz respectively. Gain vs frequency, with the maser tuned to 8415 MHz, is shown in Fig. 4. Current through the figure-eight field-shaping coil is used to adjust gain and bandwidth (measured values at a maser center frequency of 8415 MHz are shown in Table 1).

IV. Dual Frequency Operation

Current through the figure-eight field-shaping coil can be used to operate the maser at two frequencies separated by as much as 500 MHz. Additional pump sources must be used to pump both signal frequencies. The maser net gain is between 17 and 22 dB during dual frequency operation. Figure 5 shows the curves for maser net gain vs frequency response during dual frequency operation.

V. Large Signals and Gain Compression

The maser was subjected to signal levels up to 1 mW to determine gain compression (saturation) sensitivity. Figure 6 shows the signal level (as a function of frequency) which causes a 3-dB reduction in maser gain. The maser was adjusted for a net gain of 45 dB at 8420 MHz prior to the test. Figure 7 shows maser gain compression as a function of signal power level at the maser center frequency. Power levels shown are at the maser input.

Two large signals at the maser center frequency, spaced 1 MHz apart, were used to saturate the maser. A level of −28 dBmW at the maser input reduced the net gain to unity. A spectrum analyzer was used to test for mixing products; the system could detect signals 60 dB below the level of the −28 dBmW test signals. No mixing products were observed.

VI. Stability Measurements

Gain, signal phase, and group delay stability measurements were made using a Hewlett-Packard network analyzer. Figure 8 shows the gain and signal phase shift vs frequency; a test signal was swept through the maser bandpass to produce the curve. The reference channel path contained a delay line of approximately 16 m equivalent free space length. The maser group delay at 8415 MHz (at 45 dB net gain) was measured to be 63.9×10^{-9} s (equivalent free space length of 19.17 m).

Changes in maser gain, group delay, and signal phase are caused by changes in the magnetic field, refrigerator operating temperature, and pump frequency and power. Figure 9 shows gain and group delay changes as the refrigerator temperature is changed from 4.32 to 4.76 K. Peak-to-peak signal phase changes were less than 5 deg. The total phase slope change was 0.6 deg/MHz. The measured data were recorded and are shown at two gain levels; the figure-eight field-shaping coil was used to set the specific gain values tested.

Large group delay changes are caused by magnetic field shape changes. Figure 10 shows group delay changes as the maser net gain is changed with the field-shaping coil. Figure 11 shows changes in gain and group delay as a function of average magnetic field strength. A 1-gauss change in magnetic field produces a 2.5-MHz maser center frequency change. The magnetic field for 8415 MHz operation is 4940 gauss. A 1-gauss change results in a 0.25-dB gain reduction, a 0.40×10^{-9}-s group delay change (12 cm free space distance) and a 28-deg signal phase shift. These changes emphasize the need for a very stable magnetic field. Measurements in the laboratory and on a moving antenna show the superconducting magnet to be 30 times less sensitive to external magnetic fields than permanent magnets previously used with S- and X-band masers (Refs. 2, 3, and 6).

The effects of pump klystron changes are summarized in Table 2. Gain, signal phase, and group delay changes are shown as results of changes in klystron tuning, beam voltage and current, and reflector voltage. Complete pump transition saturation due to push-push pumping (Ref. 7) causes the maser performance to be relatively insensitive to pump frequency or power changes. Long-term phase and gain stability records with the maser operating in the laboratory (fixed position and constant ambient temperature) showed no detectable gain change (resolution 0.1 dB), 4 deg peak-to-peak signal phase change, and 1.9×10^{-11}-s group delay change (0.57 cm free space distance) during a period of 12 h.

A summary of parameters affecting maser stability is shown in Table 3. The listed variations in pump frequency, power supply voltages, refrigerator temperature, and magnetic field are based on data from maser systems operating on the 64-m-diameter antenna at the present time. The predicted instability combines laboratory test data in this article with the previously measured maser system data. The various instabilities are expected to add in a random manner. The total expected gain, phase, and group delay changes include the effects of antenna motion during a 12-h time period. The total rms changes are as follows: ± 0.12 dB gain, ± 1.1 deg phase, and $\pm 0.08 \times 10^{-9}$ s group delay.

VII. Conclusion

Laboratory test data show the new X-band maser performance to be superior to previously used X-band masers in gain, bandwidth, noise temperature, and stability. The use of push-push pumping, pump frequency filters in the signal waveguides, and a superconducting magnet is responsible for the improved performance.

References

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Table 1. Maser gain and bandwidth at 8415 MHz vs magnetic field shape

Net gain, dB	Bandwidth, MHz (1 dB)	Bandwidth, MHz (3 dB)	Field-shaping coil current, mA
57	8	13	180
45	10	17	270
35	14	26	300
30	23	35	315
25	42	53	330

Table 2. Pump system stability effects with maser at 45 dB net gain at 8415 MHz

Pump system change	Gain change, dB	Signal phase change, deg	Group delay change, 10^{-9} s	Equivalent free space path length, cm
24-GHz klystron, retune ± 10 MHz	-0.1	± 1.7	± 0.11	± 3.3
19-GHz klystron, retune ± 10 MHz	-0.2	± 2.2	∓ 0.09	∓ 2.7
24-GHz klystron, beam voltage, ± 30 V	-0.3	∓ 0.2	± 0.06	± 1.8
19-GHz klystron, beam voltage, ± 30 V	-0.7	<0.1	± 0.13	± 3.9
24-GHz klystron, reflector voltage, ± 20 V	-0.4	∓ 0.3	± 0.12	± 3.6
19-GHz klystron, reflector voltage, ± 20 V	-0.5	∓ 0.3	∓ 0.02	∓ 0.6

Table 3. Predicted maser system stability characteristics for 12 h on 64-m-diameter antenna at 8415 MHz

Variable parameter	Parameter change	Maser performance change			
		Gain, dB	Signal phase, deg	Group delay, 10^{-9} s	Equivalent free space distance, cm
Refrigerator temperature	± 0.005 K	∓ 0.08	<0.1	∓ 0.04	∓ 1.2
Average magnetic field strength	± 0.03 gauss	-0.01	± 1.0	-0.01	-0.3
Field-shaping coil current	± 0.2 mA	∓ 0.06	<0.1	∓ 0.06	∓ 1.8
24-GHz klystron pump frequency	± 2 MHz	-0.02	± 0.3	± 0.02	± 0.6
19-GHz klystron pump frequency	± 2 MHz	-0.04	± 0.4	± 0.02	± 0.6
Klystron power supply voltages	± 1 V	-0.04	<0.1	± 0.01	± 0.3
Random combination of variable parameters	As above	± 0.12 rms	± 1.1 rms	± 0.08 rms	± 2.4 rms

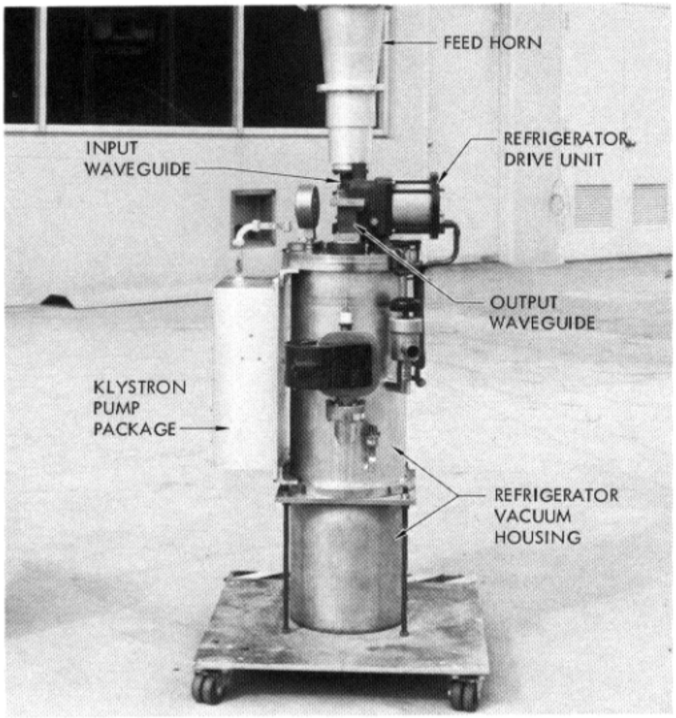

Fig. 1. X-band traveling wave maser assembly

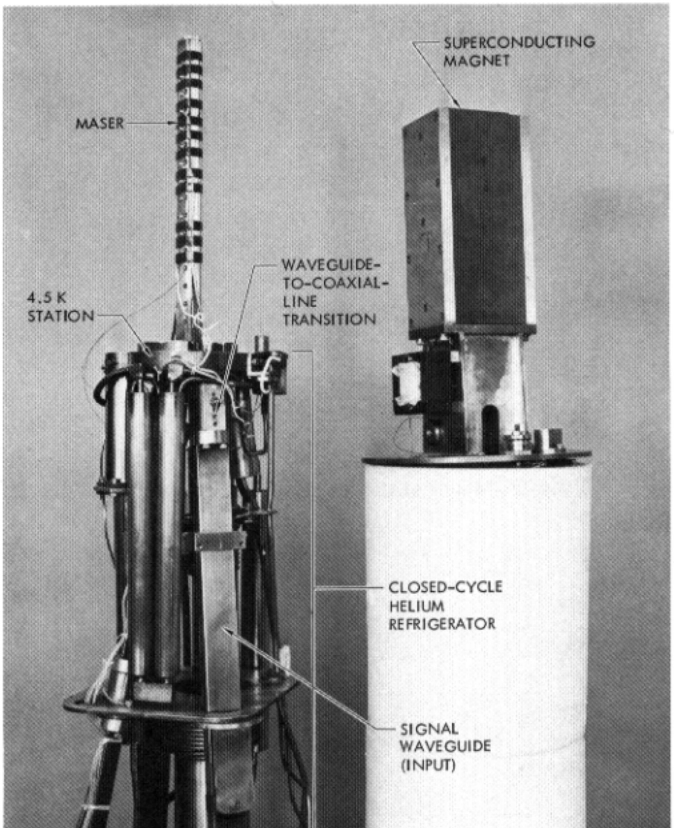

Fig. 2. Maser, superconducting magnet, and closed-cycle helium refrigerator

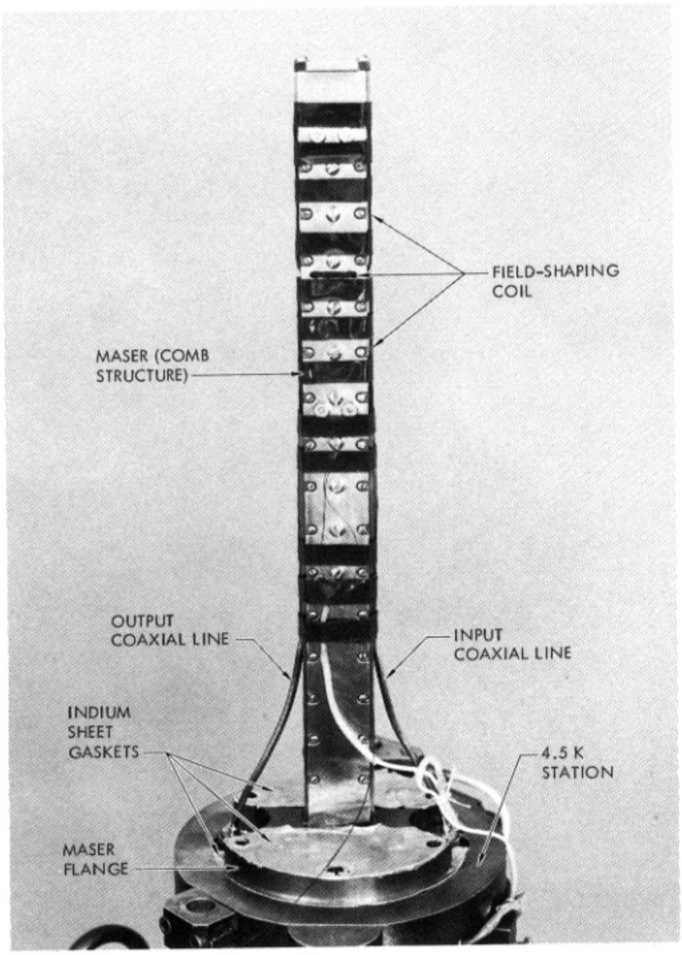

Fig. 3. Maser structure on 4.5-K heat station

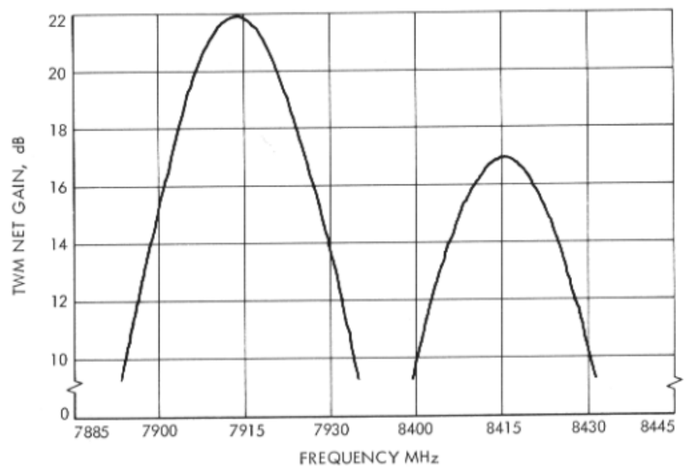

Fig. 4. Gain vs frequency for maser at 8415 MHz

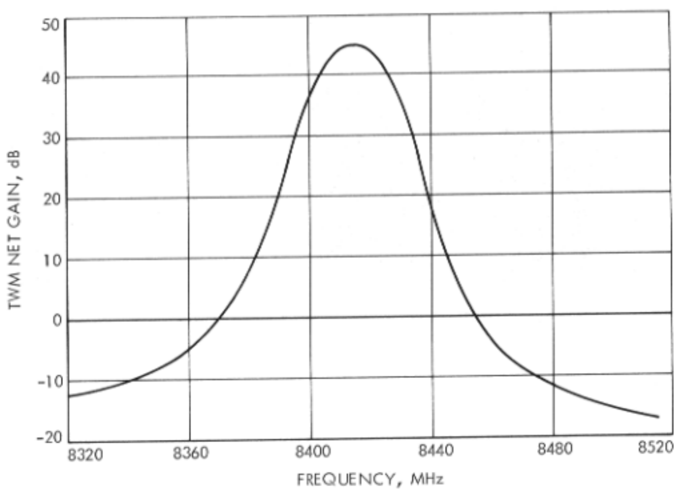

Fig. 5. Gain vs frequency for simultaneous operation at two frequencies

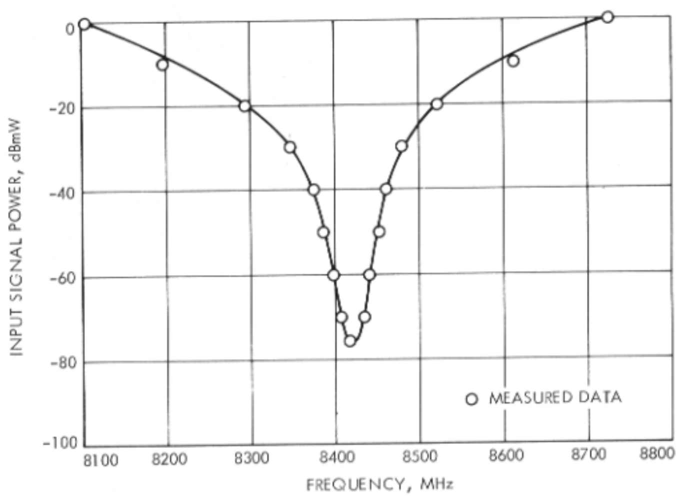

Fig. 6. Signal input power vs frequency for 3-dB maser gain compression

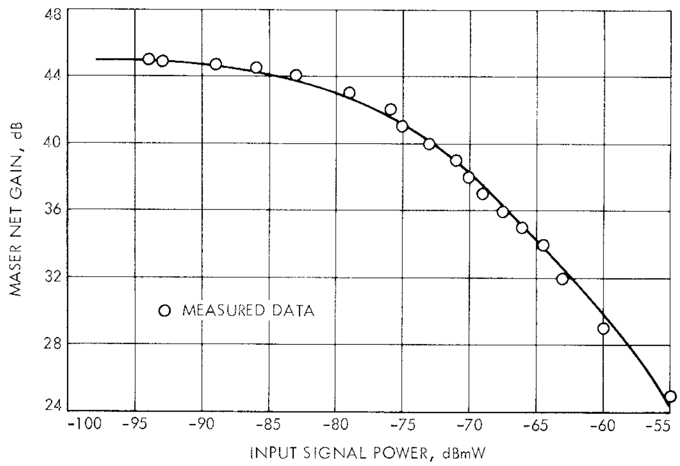

Fig. 7. Signal power vs gain at the maser center frequency

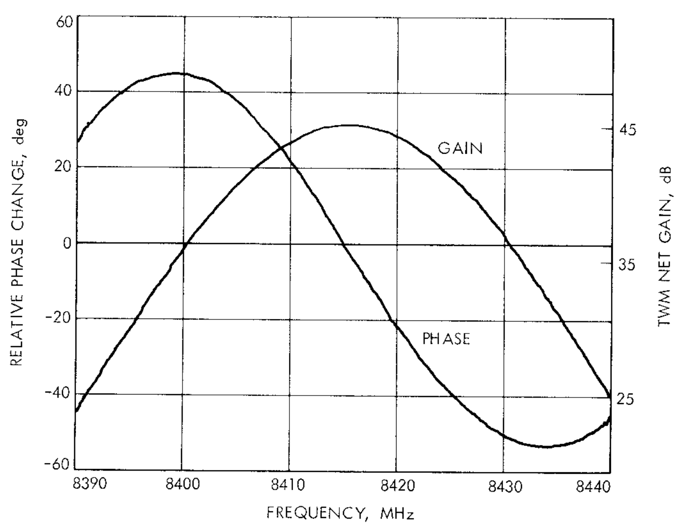

Fig. 8. Maser gain and phase shift vs frequency

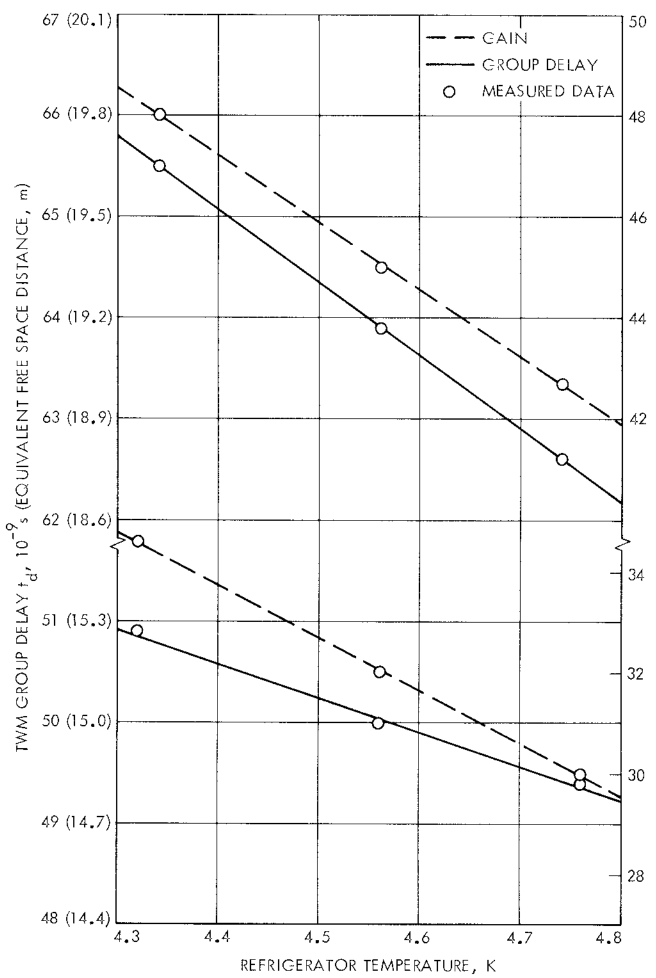

Fig. 9. Gain and group delay vs refrigerator temperature at two field-shaping coil current settings

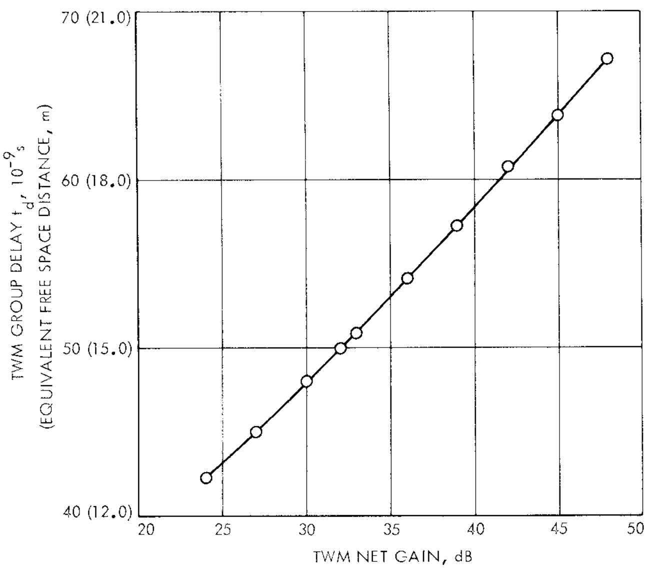

Fig. 10. Group delay vs net gain caused by field-shaping coil current changes

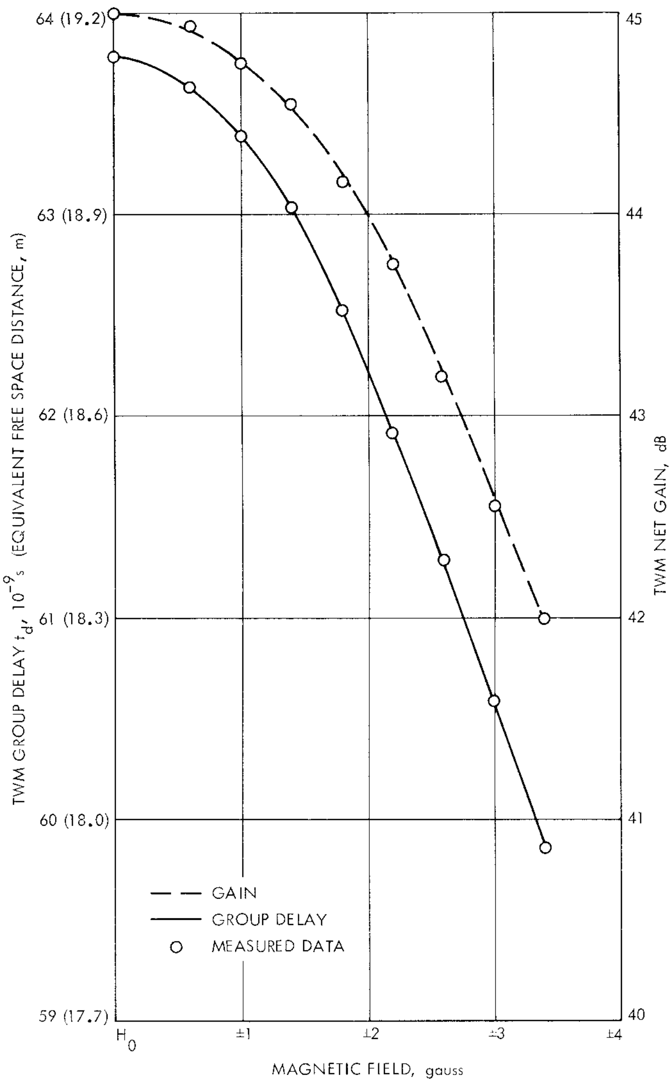

Fig. 11. Gain and group delay vs average magnetic field strength