NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1072

A Traveling Wave Maser for Deep Space Communication at 2295 and 2388 MHz

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Acknowledgment

The TWM systems described in this report are the product of the combined efforts of many people at the Jet Propulsion Laboratory. Thanks are due Jesse Cunningham, Paul Delano, Frank Shappell, and others of the JPL machine shop for the perfection of a machining process particularly suited to this TWM design. The successful cryogenic refrigerator, essential to the usefulness of the TWM, must be mentioned here; in this regard thanks are due to Dr. Walter Higa, Ervin Wiebe, and Rex Quinn.

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Abstract

A tunable traveling wave maser has been used for deep space communications at 2295 MHz and for planetary radar at 2388 MHz. Machining techniques that enable a comb-structure maser to be fabricated from a single piece of copper have been developed. Excellent surface finish and close tolerances result in low loss at the signal frequency. Coupling and loading techniques are described. Gain adjustment trim coils are used to trade gain for additional bandwidth. An external overcoupled cavity is used with the pump klystron to provide pump power for operation at a signal frequency of either 2295 or 2388 MHz. The maser operates in a closed-cycle helium refrigerator at 4.4°K, and refrigeration is also used to cool the signal input coaxial transmission line. An in-line quarter-wave thermal short circuit is used to transfer heat from the coaxial center conductor. This has reduced the equivalent input noise temperature of the maser to 5°K.

A Traveling Wave Maser for Deep Space Communication at 2295 and 2388 MHz

I. Introduction

A continuous effort to improve performance characteristics of maser systems has been carried out by the Jet Propulsion Laboratory (JPL) since 1960, with emphasis on reliability and ease of use in the field. JPL has used masers in field applications since 1961 (Refs. 1–4); the first installation of a traveling wave maser (TWM) in a closed-cycle helium refrigerator was completed in September 1963 at the Goldstone Venus Deep Space Station (DSS). In February 1966, a new tunable TWM (2275 to 2415 MHz) in a new closed-cycle helium refrigerator (Ref. 5) was installed on the 210-ft-diameter paraboloidal antenna (Mars DSS) at Goldstone. In June 1966, a second tunable TWM of the same design was installed in the planetary radar system on the 85-ft Venus DSS antenna.

The new TWM's (ruby-loaded comb structures) provide more than 32 db net gain over a tunable range from 2275 to 2415 MHz. An equivalent input noise temperature of 5°K at the waveguide interface has been measured at 2388 MHz (during evaluation of the Venus DSS TWM). In a uniform magnetic field, the instantaneous bandwidth is about 14 MHz. Gain adjustment trim coils can be used in conjunction with the permanent magnet to trade gain for additional bandwidth. In the center of the tuning range, a bandwidth of approximately 50 MHz can be obtained at 27 db net gain and 4.2°K refrigerator temperature (slightly lower than the normal operating temperature of 4.4°K). A single VA 246R klystron oscillator with an external overcoupled cavity provides pump power for operation at either 2295 or 2388 MHz (space probe tracking and planetary radar frequencies, respectively).

The two new maser/refrigerator systems are used continuously in the field and, by January 1, 1967, they had accumulated a total run time of 10,000 hours without incident.

II. Description

The development of machining techniques that improve the performance of masers has resulted in a traveling wave maser structure that can be fabricated from a solid piece of copper. There are no joints that might result in loss of microwave signal power or restrict heat transfer from the maser material to the cooled flange of the TWM. The use of a shaper, a machine that removes metal through a scraping process, has produced an excellent surface finish and a uniformity of 0.0001 in. in the most critical area of the comb structure. The use of electric-discharge machining for metal removal between the fingers of the comb has enabled the fabrication of structures with close intervals and long finger length. Figure 1 shows a product of the improved fabrication process. The TWM is shown prior to the installation of rubies, isolators, and coaxial input and output lines. Tuning screws are required only at the ends of the comb, where the last fingers encounter end effects.

Resistive losses in the comb structure at the signal frequency have received primary consideration in structure designs. Usable net gain, effective noise temperature, bandwidth, and gain stability are degraded by excessive loss. Resonant slowing provides the electrical length necessary for high gain. Since the attenuation of signal power due to resistive losses is proportional (in db) to the electrical length, the attenuation and length must be compared during structure evaluation. Figure 2 is a block diagram of the test equipment used for measuring the electrical length of a TWM.

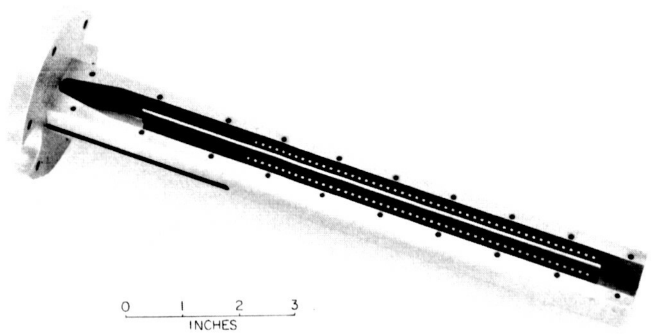

Fig. 1. One-piece copper maser comb structure fabricated with improved process

The pattern that results on the X–Y recorder is shown in Fig. 3. In-phase and out-of-phase signal voltage addition causes peaks and nulls to occur. The difference in frequency between two adjacent peaks or nulls is inversely proportional to the difference in electrical length of the two signal paths between the directional couplers. The electrical length L_e of the TWM is given by the expression

$$L_e = \frac{c}{\Delta f} = \frac{300\text{ m}}{\Delta f} \tag{1}$$

where

c = velocity of light

and

$\Delta f = \frac{\Delta\omega}{2\pi}$ = the frequency difference in MHz between two adjacent peaks or nulls

The slowing factor S is given by

$$S = \frac{L_e}{L_0}$$

where

L_0 = physical length of the TWM

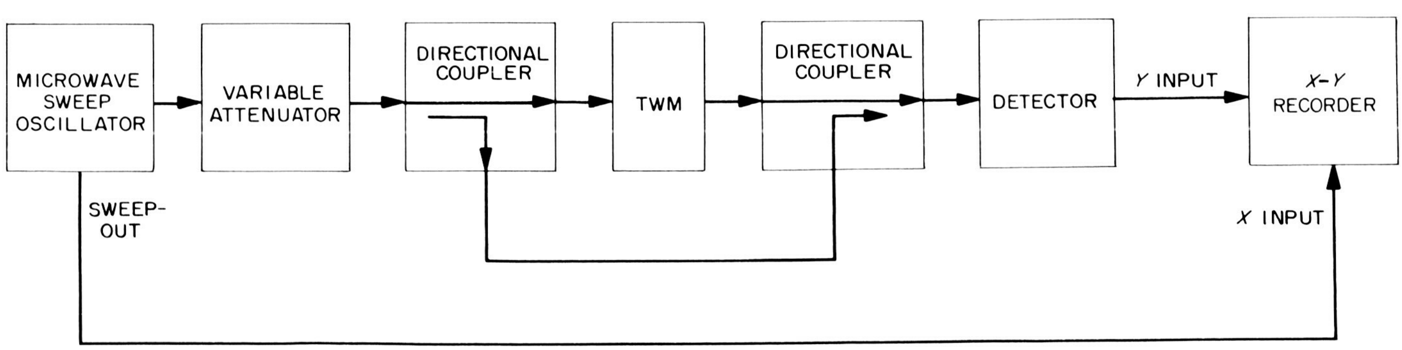

Fig. 2. Method for measurement of TWM electrical length

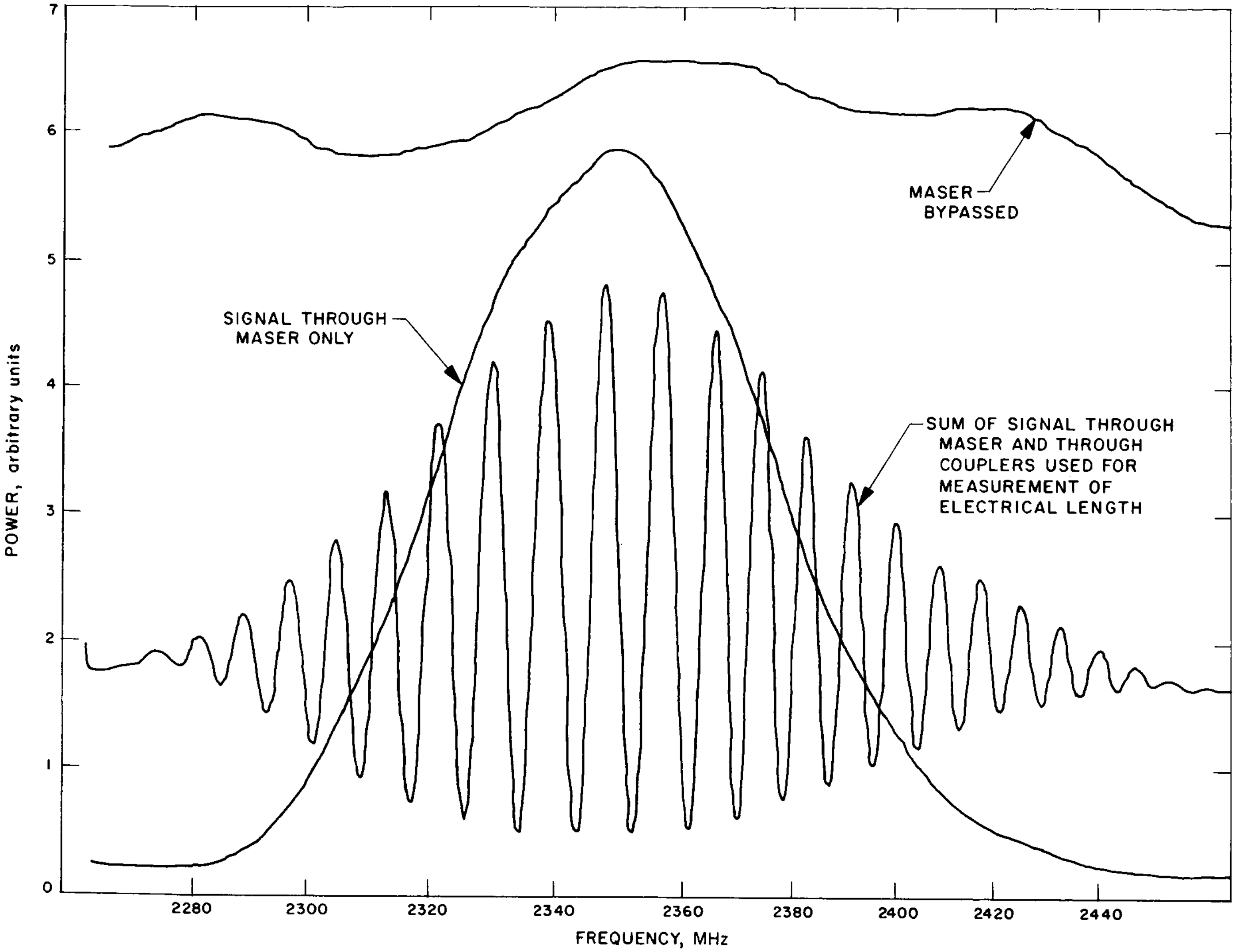

Fig. 3. An X–Y recording of TWM bandpass and electrical length

Alternatively, it is possible to solve for S in the usual terminology as follows:

$$S = \frac{c}{v_g} = \frac{c}{\dfrac{\Delta\omega}{\Delta\beta}}$$

where

$$v_g = \frac{\Delta\omega}{\Delta\beta} = \text{group velocity}$$

and

$$\beta = \text{phase change coefficient}$$

Hence, if $\Delta\omega_n$ is measured between the $(n + 1)^{\text{th}}$ and n^{th} maxima (or minima), then

$$\Delta\beta = \beta_{n+1} - \beta_n$$

$$\Delta\beta = \left(\beta_0 + \frac{2(n+1)\pi}{L_0}\right) - \left(\beta_0 + \frac{2n\pi}{L_0}\right)$$

or

$$\Delta\beta = \frac{2\pi}{L_0}$$

Therefore,

$$S = \frac{2\pi c}{\Delta\omega L_0} = \frac{c}{\Delta f L_0}$$

in agreement with the previous result. It should be noted that β_0 above is undetermined in this method; however, if ω_n is plotted as function of $(\beta_n - \beta_0)$, it is possible to obtain the ω vs β curve for the structure. This curve, whose slope is equal to the group velocity v_g, is of great importance in determining the useful bandwidth of the maser structure. A large frequency range with constant v_g is required for a distortion-free amplifier.

The curves in Fig. 3 marked "maser bypassed" and "signal through maser only" illustrate the TWM bandpass in comparison with the measurement of electrical length. The variable attenuator setting has been changed to give a convenient scale factor for each curve.

The variable attenuator may be used to measure the insertion loss of the TWM. The one-piece comb structure has reduced copper losses at the signal frequency to a practical minimum.

Coupling the signal power to the slow-wave structure is accomplished by using a loop adjacent to the comb structure, as shown in Fig. 4. Adjustments are made by bending the loop, thereby changing the distance between the loop and the first resonant element. A screw located directly above the first element provides capacitive tuning. Figure 5 is a block diagram of the test

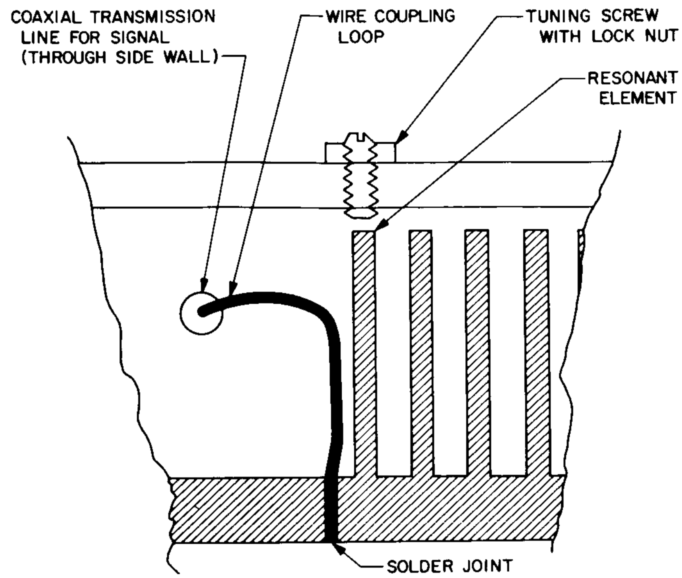

Fig. 4. TWM signal coupling loop

equipment used to indicate input and output match during the adjustment. Mismatched coupling at the TWM input can seriously degrade the equivalent input temperature of the amplifier. This noise temperature degradation is a function of refrigerator temperature and mismatch, as well as the equivalent input temperature of the TWM under matched conditions. The equivalent input temperature of a mismatched TWM, T_M, is given by

$$T_M = \frac{T_{M_0} + T_B \rho^2}{1 - \rho^2} \tag{2}$$

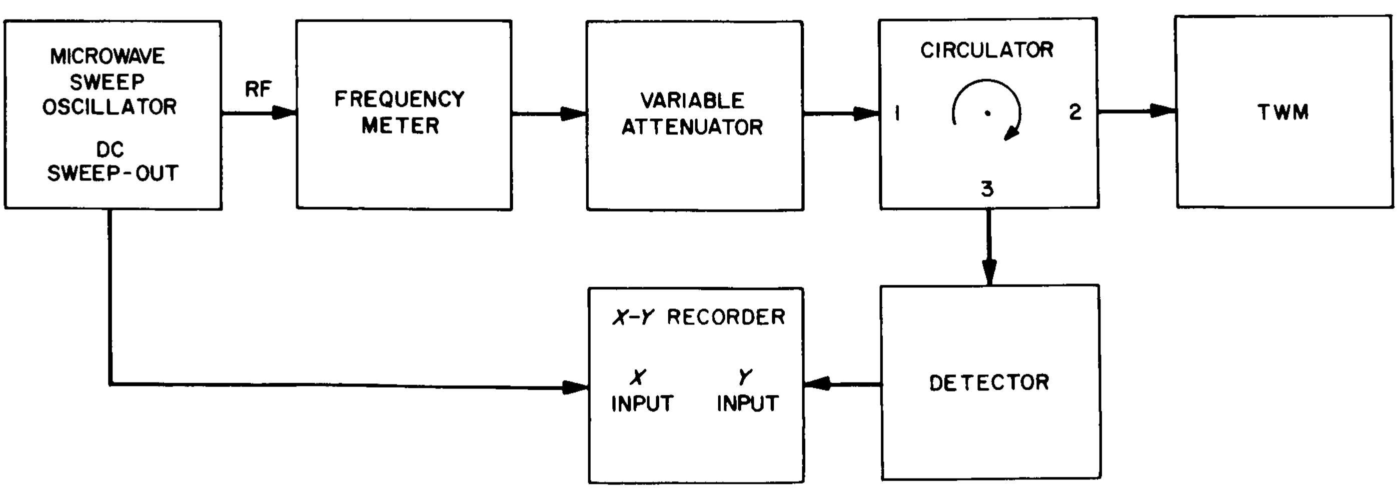

Fig. 5. Test setup for measuring reflected power

where

T_{M_0} = equivalent input temperature of TWM under matched condition

T_B = bath temperature

ρ = voltage reflection coefficient

The ratio T_M/T_{M_0} is

$$T_M/T_{M_0} = \frac{1}{1-\rho^2} + \frac{T_B}{T_{M_0}}\left(\frac{\rho^2}{1-\rho^2}\right) \tag{3}$$

Figure 6 shows the ratio T_M/T_{M_0} as a function of mismatch for three values of T_B/T_{M_0}. Figure 7 is an X–Y recorder plot showing the reflected power from the TWM signal connections. The matches shown are typical for a TWM that would cover a tuning range of approximately 130 MHz, centered at 2340 MHz. The VSWR from 2300 to 2400 MHz is approximately 1.4 to 1, and ρ^2 is 0.03.

Bandpass adjustment of the TWM is accomplished by changing the geometry of the maser material. Ruby, the material used, has a dielectric constant that varies from 10 to 12, depending on the C-axis orientation. Figure 8 shows the end view of a TWM, with ruby, clamps, and isolators in a typical configuration. The clamps are made of beryllium copper shim stock and are copper-plated to reduce resistive loss. In addition to the mechanical function of the clamp, its height is used to adjust the slowing factor, which can be increased by reducing the height of the clamp. Increasing the depth of the bevel shown on the "forward-side" ruby also increases the slowing factor. When the slowing factor is increased by adjusting the clamp or the ruby's shape, the bandpass (tuning range) of the TWM is reduced.

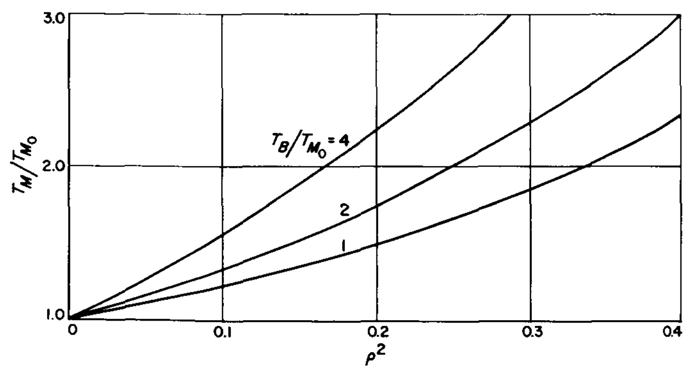

Fig. 6. Effect of mismatched input coupling on TWM equivalent input temperature

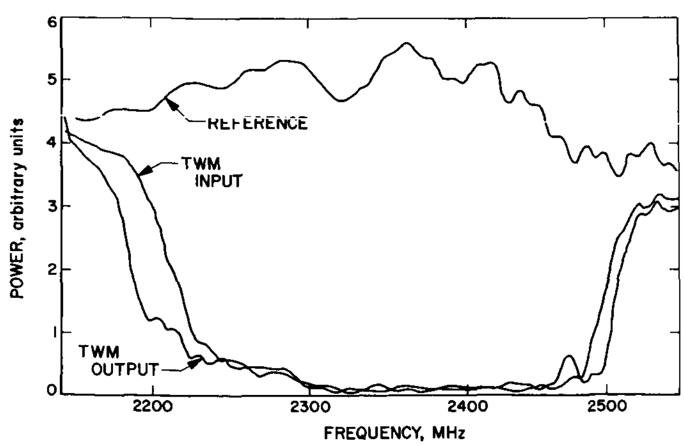

Fig. 7. Reflected power from TWM

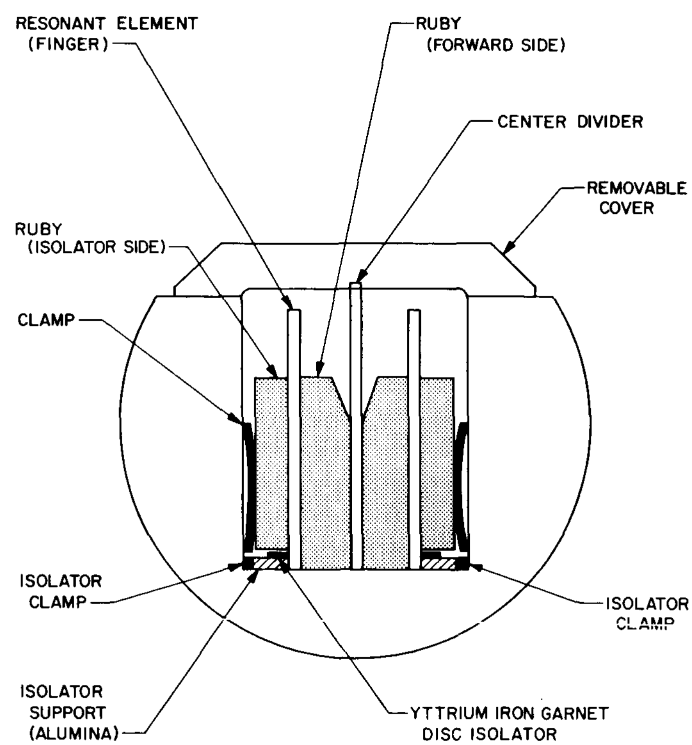

Fig. 8. End view of TWM

The center frequency of the TWM can be shifted by adjusting the height of the ruby slab. At 2300 MHz, a slab height of 0.475 in. is used with finger length of 0.720 in. The center frequency shifts at a rate of 4 MHz

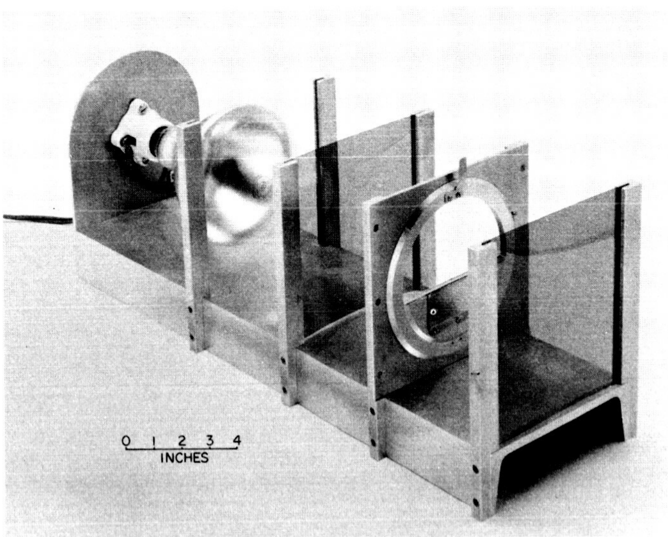

Fig. 9. Polariscope for ruby selection and orientation

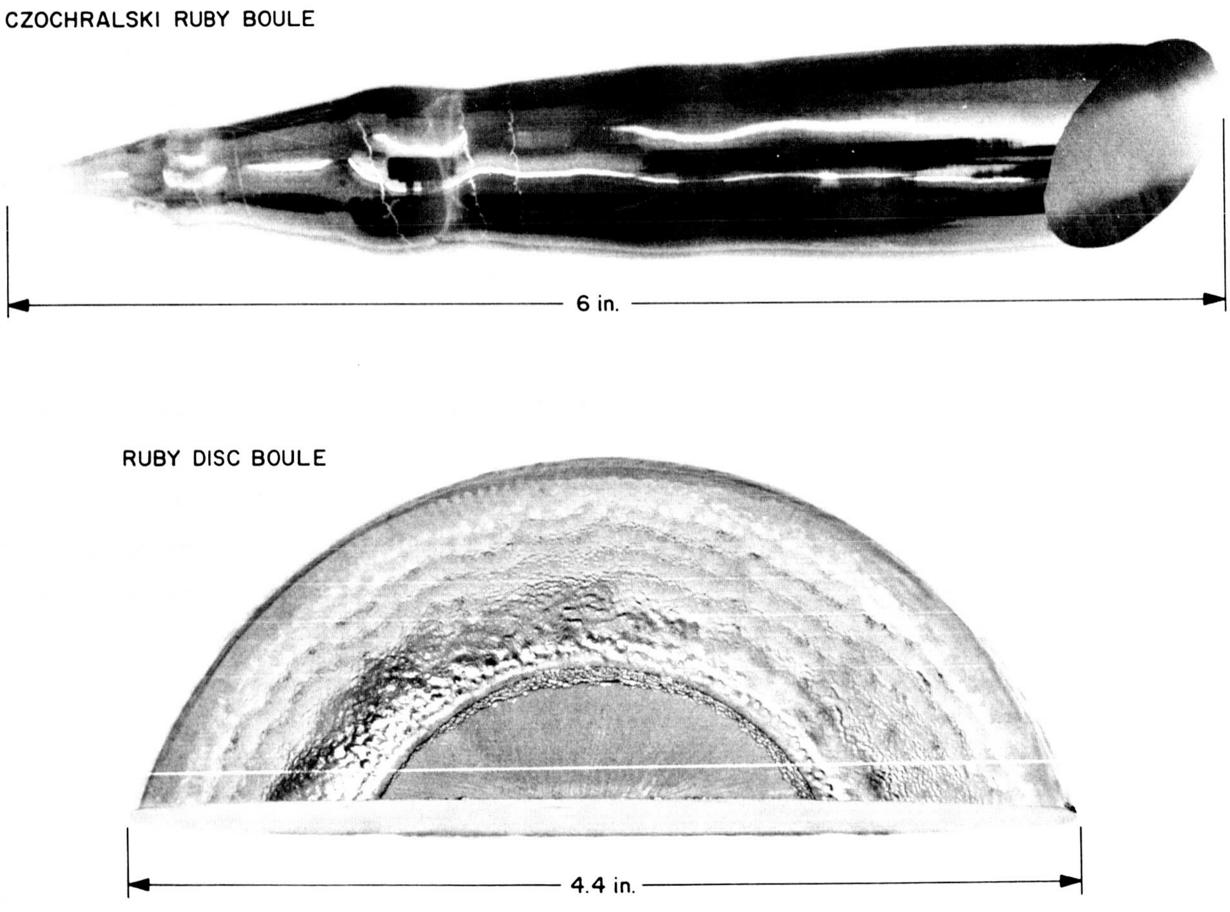

Fig. 10. Ruby boules used for TWM

per 0.001-in. change in slab height. The ruby should always rest on the base of the structure, where the RF magnetic field is maximum.

The selection of optimum-quality ruby is a vital step in the construction of a high-performance traveling wave maser. Visual inspection in polarized light enables one to observe flaws that degrade maser performance. Figure 9 shows the polariscope used to check and to properly orient the ruby slabs. Figure 10 shows two types of ruby boules used to supply slabs for the tunable TWM's. Figure 11 is a typical slab photo, showing flaws that degrade maser performance. Slabs are cut with the *C*-axis parallel to the longest edge. This "zero degree" orientation provides maximum gain, as has been previously noted by Okwit and Smith (Ref. 6).

III. Performance

Characteristics of a TWM that describe amplifier performance are net gain, forward loss, inversion ratio, and slowing factors. (Instantaneous bandwidth in a uniform magnetic field is determined by the material line width and amplifier gain.) A comparison of the Mars DSS TWM (No. 1) and the Venus DSS TWM (No. 2) is shown in Table 1. Although the comb structures are identical, slight changes in loading have changed the performance characteristics. Both magnetic field and pump frequency have been optimized to give maximum gain at the individual frequencies listed.

A uniform magnetic field of 2500 gauss is required for maser operation. This field is supplied by a 150-lb alnico magnet. The field strength may be adjusted electrically

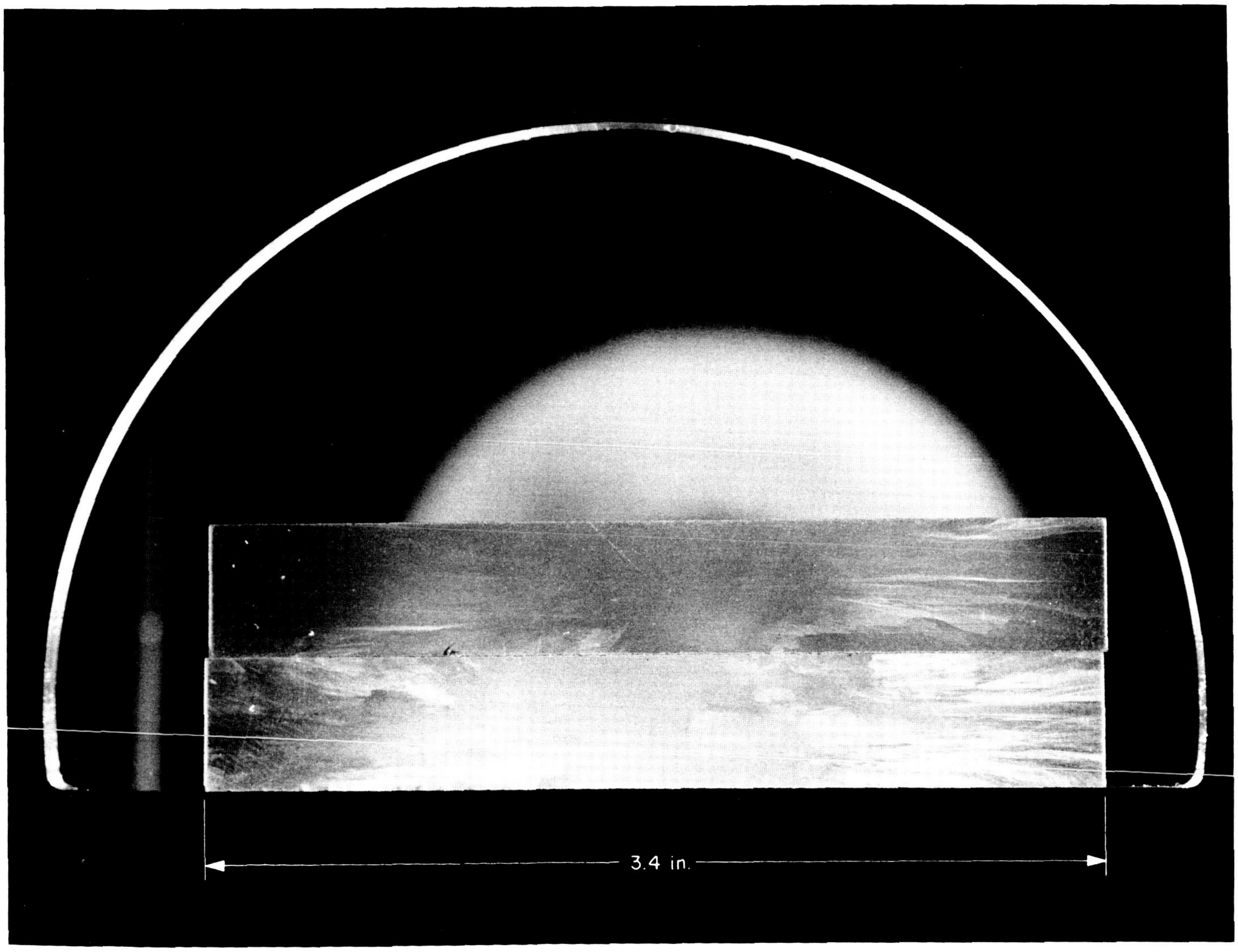

Fig. 11. Ruby slabs during inspection

Table 1. TWM performance comparison

Frequency, MHz	Net Gain, db		Loss, db		Measured inversion ratio		Slowing factor		Calculated[a] noise temperature, °K	
	No. 1[b]	No. 2[c]	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2
2265	—	45	—	—	—	—	—	105	—	—
2275	59	51	34	30	—	3.5	165	100	4.6	4.6
2285	62	52	27	22	3.4	3.4	125	100	3.8	3.7
2295	60	51	22	17	3.4	3.2	125	90	3.4	3.3
2305	58	50	19	14	3.4	3.2	125	85	3.2	3.0
2325	55	50	15	9½	3.4	3.0	115	85	2.9	2.6
2350	50	46	13	8½	3.5	3.1	110	85	2.7	2.5
2375	44	42	16	9½	3.6	3.1	110	85	3.3	2.7
2388	40	38½	18	10	3.6	3.0	110	85	3.7	3.0
2400	38	35	21	12	3.9	3.0	115	85	4.2	3.5
2415	34	32	25	14	3.9	—	125	85	5.1	4.0
2425	—	30	—	16	—	3.0	—	85	—	4.5

[a]Calculated for TWM at 4.4°K refrigerator temperature. Does not include input line contribution.
[b]TWM No. 1 for Mars DSS.
[c]TWM No. 2 for Venus DSS.

by the use of two trim coils. This adjustment determines the center frequency of operation for the maser.

In order to provide an efficient gain adjustment (one that trades excess gain for additional bandwidth), a second set of trim coils is used. The gain adjustment coils change the magnetic field across a total of one-half the amplifying length of the maser. This field change shifts the resonance frequency and results in a stagger tuning of the resonance line. Figure 12 shows how one step in the magnetic field provides five separate sections of amplification, alternately operating at two separate frequencies. As the current through the gain adjustment coil is increased, the separation between F_1 and F_2 is increased, the bandwidth increases, and the overall net gain is reduced. Stagger tuning of the resonance line has been discussed in detail by Siegman (Ref. 7). The results of stagger tuning are shown in Figs. 13 through 15.

The basic difference between the new TWM's and the masers previously used at the Goldstone Deep Space Stations is tunability. The new slow-wave comb structure has been designed and loaded to give a tuning range that covers both 2295 and 2388 MHz. When the

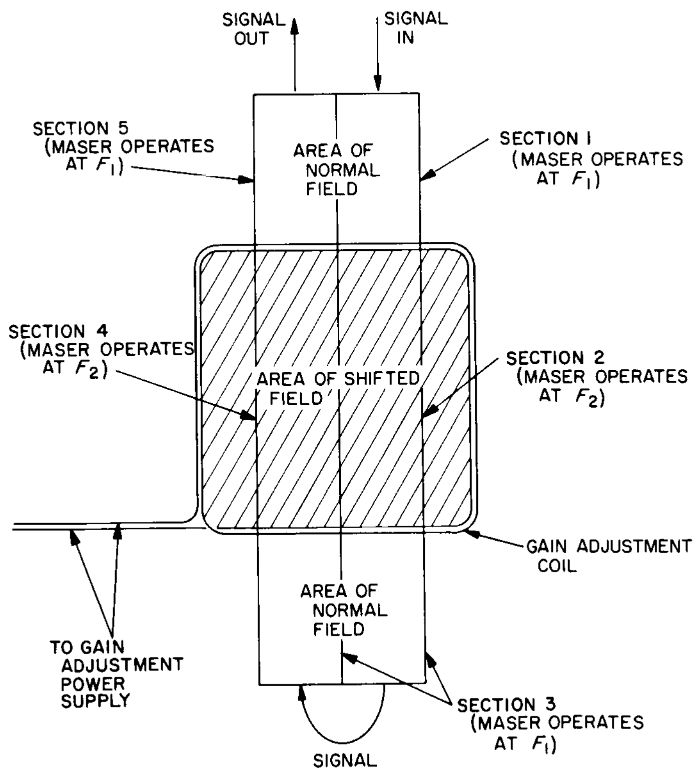

Fig. 12. Gain adjustment coil

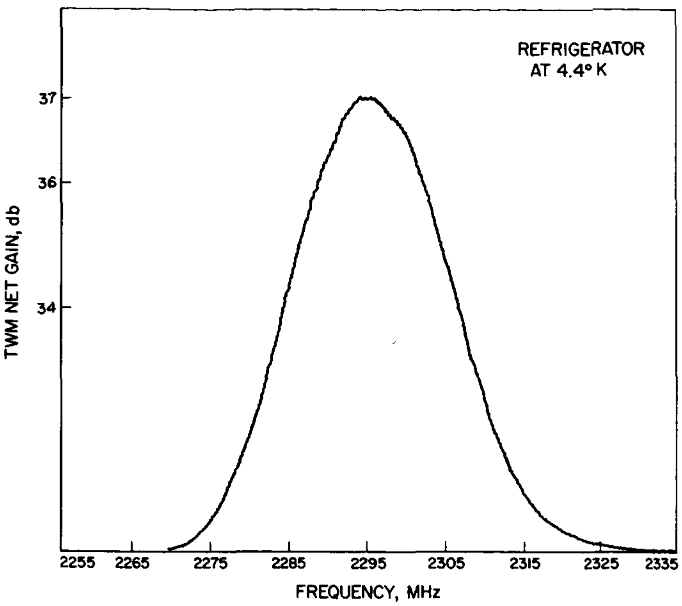

Fig. 13. Stagger-tuned maser at 2295 MHz

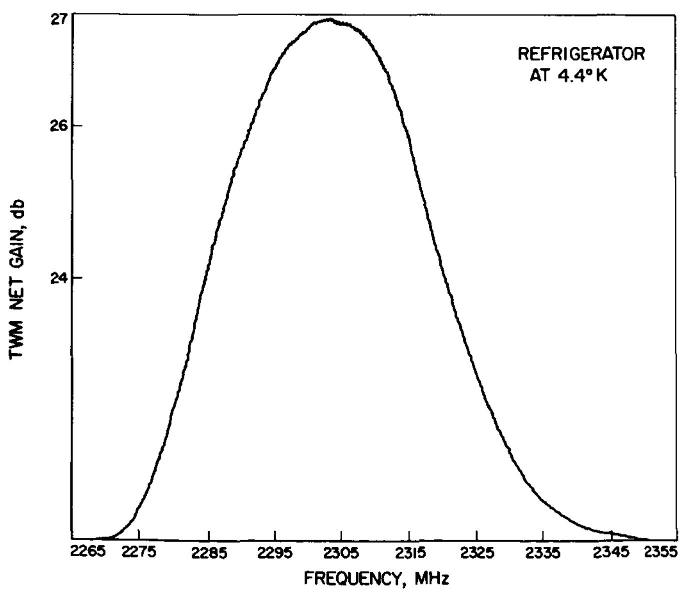

Fig. 14. Stagger-tuned maser at 2305 MHz

signal frequency is changed, the pump klystron frequency must also be changed. An external overcoupled cavity is used with the pump klystron to extend its electronic tuning range. No mechanical adjustments at the maser package are necessary when the signal frequency is tuned to either 2295 or 2388 MHz. This frequency change may be accomplished entirely from the maser instrumentation rack.

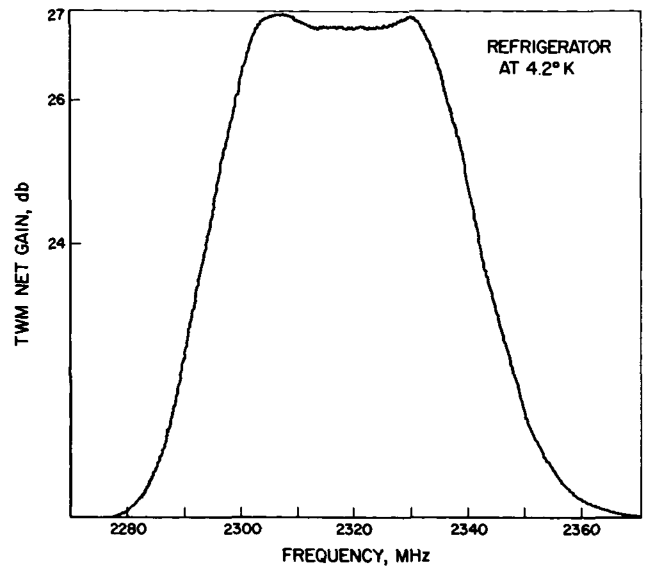

Fig. 15. Stagger-tuned maser at 2320 MHz

For several years, VA 246E and VA 246R klystrons have been used to pump S-band masers. This field experience has shown that these klystrons have adequate power, good stability, and reliability; however, they do not have sufficient tuning range to cover maser operation at both 2295 and 2388 MHz. A brief survey of available klystrons has not yielded a tube suitable for the required tuning range. A change to other pump sources (such as a backward-wave oscillator) might present new stability, reliability, or compatibility problems and has not been considered at this time.

Laboratory tests of a VA 246R klystron with an external overcoupled cavity have resulted in a split mode of operation at 12.72 and 12.88 GHz (normal electronic tuning range is 60 MHz). The external cavity is formed by the use of irises and a ½-wavelength section of guide through the klystron heat sink. Figure 16 shows

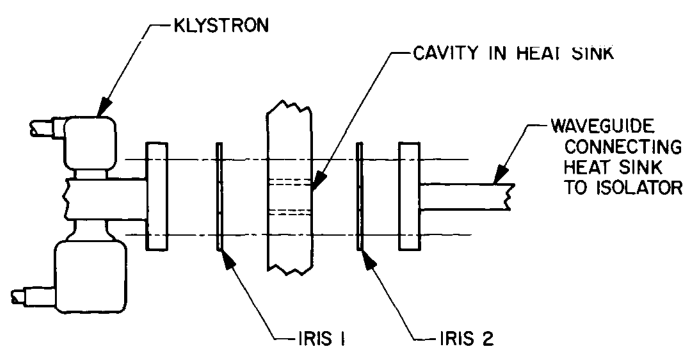

Fig. 16. Klystron and external cavity

the assembly sequence for the klystron and the external cavity. Capacitive tuning is accomplished with a tuning screw in the heat sink. Klystron tuning range is determined by the coupling and Q of the external cavity. The iris sizes determine the loaded Q and the coupling between the klystron and the external cavity.

Mechanical tuning adjustments are required after assembly of the dual-frequency klystron package prior to installation on the maser package. A block diagram of the klystron package is shown in Fig. 17. During normal operation with the maser, the klystron is in a CW mode. The klystron frequency is determined by the reflector voltage. In Fig. 18 (a graph of frequency versus reflector voltage), it is interesting to note that a double-valued region exists. In this region (shaded on Fig. 18) the klystron frequency is dependent upon the direction of reflector voltage change. For example, if a setting of 325 v is approached from 350 v, the klystron will oscillate at 12.872 GHz. If the setting of 325 v is approached from 300 v, the klystron will oscillate at 12.724 GHz. Even in this double-valued region, stability has been excellent, during both laboratory testing and field operation. The TWM requires approximately 100 mw of pump power. Figure 19 shows pump power output versus frequency. The data were taken during preparation of a dual-frequency klystron package that is in use on the 210-ft antenna.

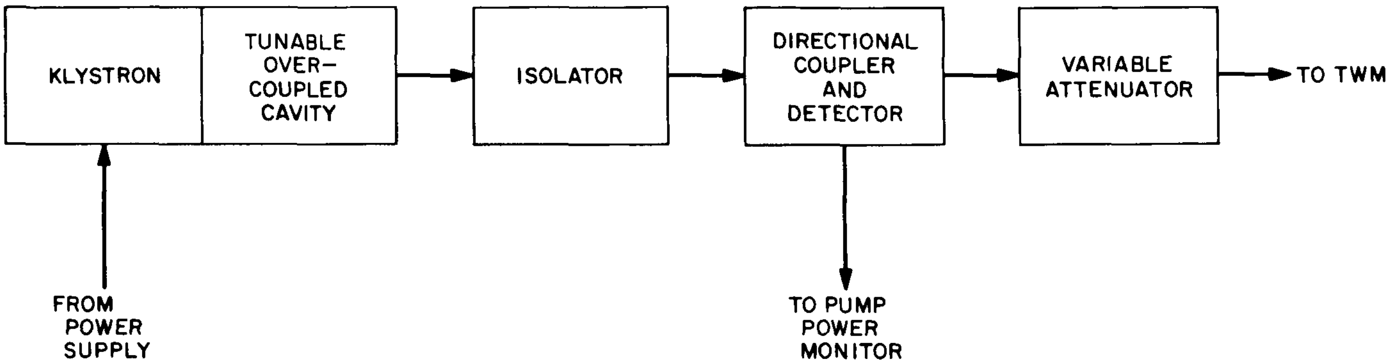

Fig. 17. Dual-frequency klystron package block diagram

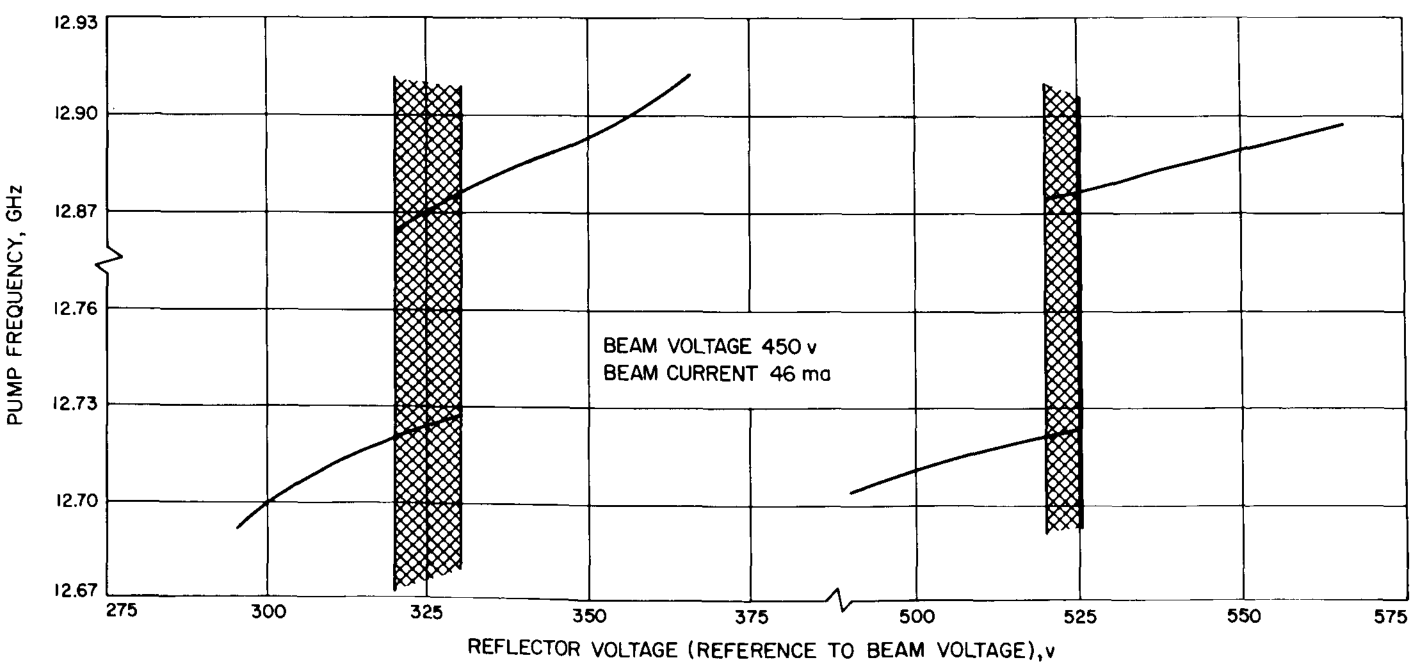

Fig. 18. Klystron frequency vs reflector voltage

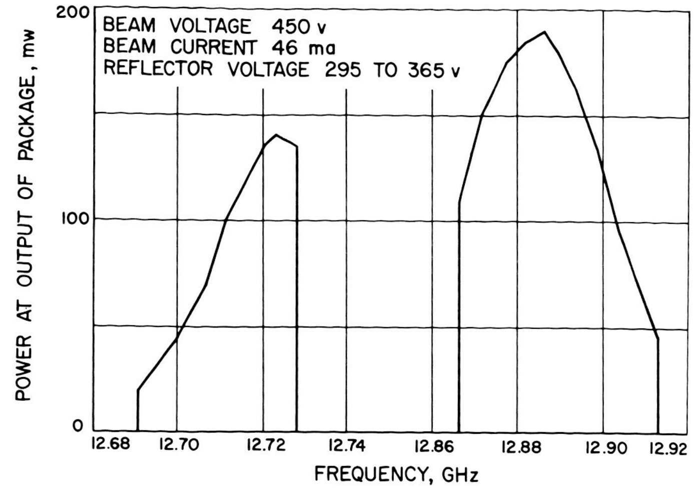

Fig. 19. Klystron power vs frequency

The phenomenon of "frequency pulling" due to a cavity external to the klystron is well known and is usually avoided. Here, it is used to extend the electronic tuning range of a klystron.

The most significant improvements affecting the operational use of masers have been made in the refrigerator development. The closed-cycle helium refrigerators (CCR) used with the 2295/2388-MHz TWM's are described in detail by Higa and Wiebe (Ref. 5). Rapid cool-down, adequate capacity, and long life are important features of these new refrigerators.

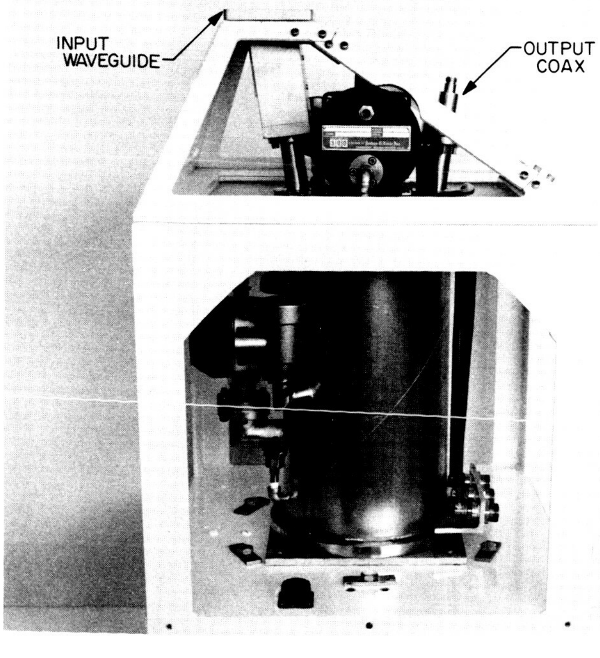

Fig. 20. Maser/refrigerator package

The assembled maser/refrigerator package is shown in Fig. 20. This assembly, ready for antenna installation, can operate in any position. The package weight is 400 lb and the overall dimensions are 20 × 22 × 38 in. The refrigerator and the maser structure are shown in Fig. 21 (vacuum jacket removed). Pump power is supplied to the maser through a stainless steel waveguide. Copper-plated stainless steel coaxial lines are used for the signal frequency input and output.

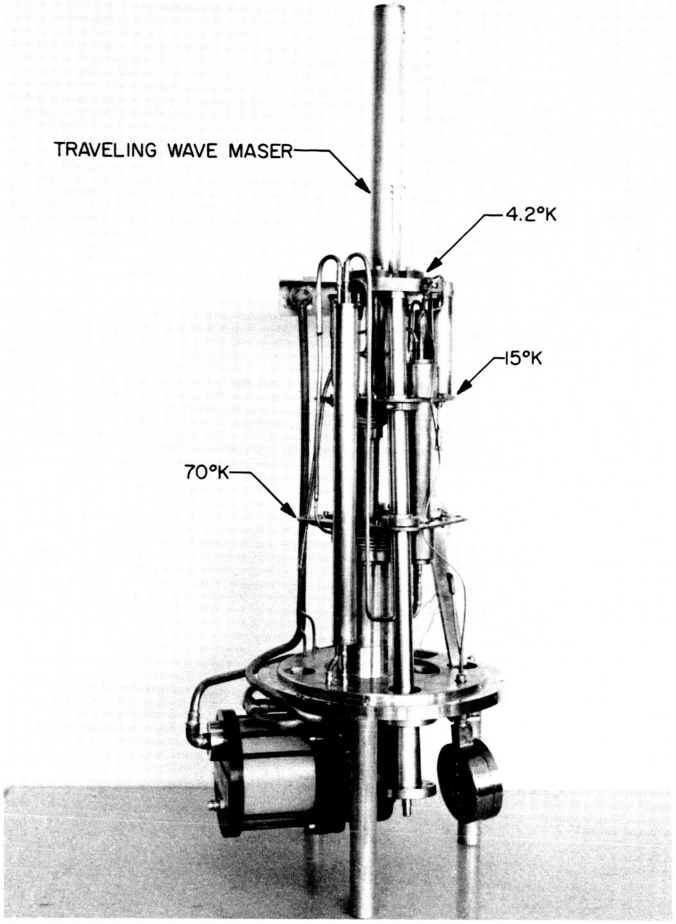

Fig. 21. Refrigerator with maser (vacuum jacket removed)

Noise added to the maser by the signal input transmission line has been reduced by cooling the center conductor. Figure 22 shows the manner in which heat is transferred from the ambient vacuum seal, through the center conductor into the refrigerator. Refrigeration at the first stage is used to cool the center conductor from ambient temperature to 80°K along a 4-in. length. Use of the in-line quarter-wave thermal short circuit (see

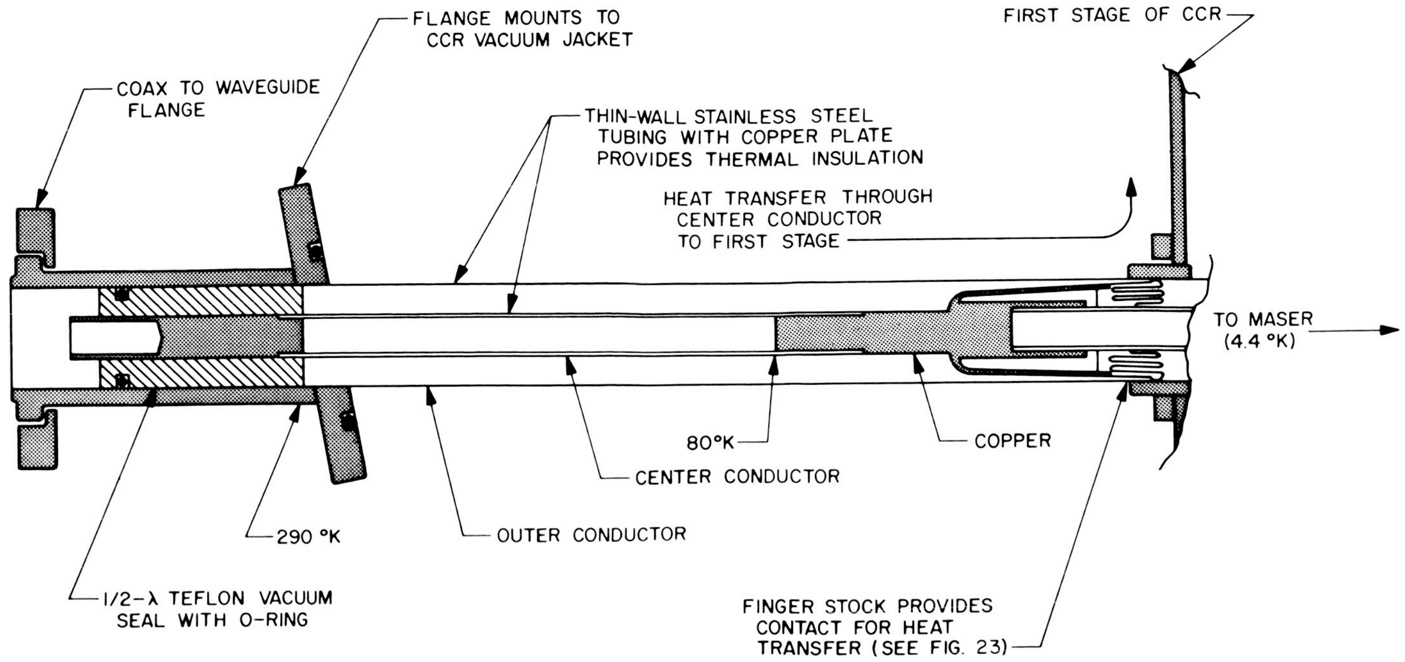

Fig. 22. Signal input coaxial line assembly

Fig. 23) has two important advantages: the noise contribution of the coaxial line is reduced, and the heat leak through the center conductor to the maser at 4.4°K is also reduced.

Work on the in-line quarter-wave thermal short circuit has been concentrated in three areas: (1) low loss at the signal frequency, (2) low VSWR in the signal frequency range, and (3) sufficient thermal conductivity to transfer approximately 400 milliwatts with a minimum temperature difference across the short. The use of 0.079-in.-diameter copper rods has provided the necessary thermal path. The insertion loss of the short is 0.011 db. When cooled to 80°K, this device contributes less than 0.1°K to the maser noise temperature. The measured VSWR from 2100 to 2800 MHz is shown in Fig. 24. Measurements of loss and VSWR were made by comparing the loss and match of a standard 6-in. length of rigid coaxial line to one with the thermal short circuit.

The total noise contribution of the input line components is 2.1°K. This includes noise generated by losses in the waveguide-to-coaxial-line transition, the vacuum seal, and the ⅞-in.-diameter coaxial line feeding the

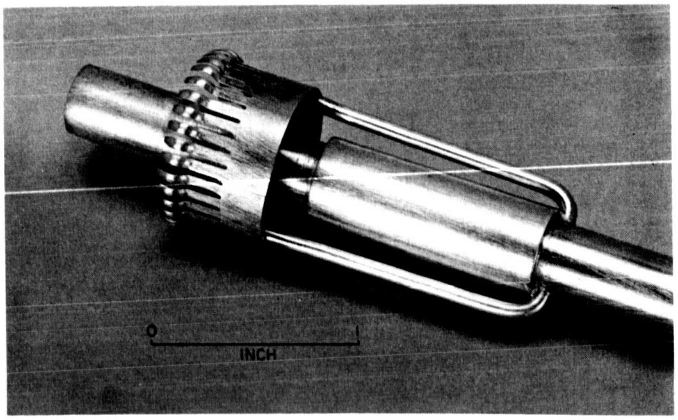

Fig. 23. In-line quarter-wave thermal short circuit

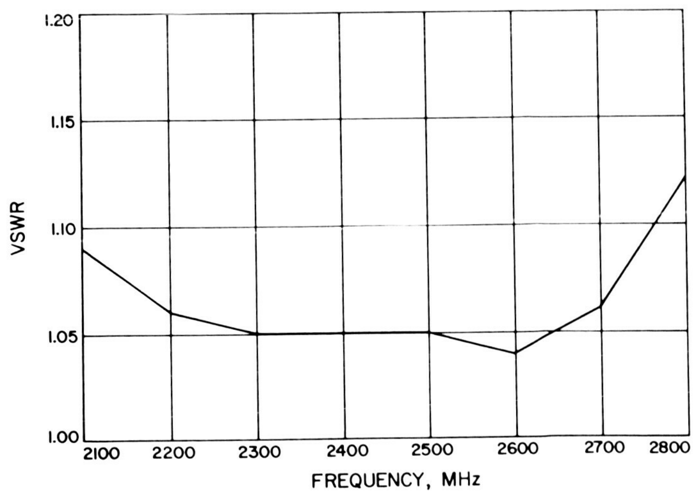

Fig. 24. VSWR vs frequency for thermal short circuit

maser. The equivalent input noise temperature of the TWM is predicted by adding the maser noise temperature (based on Table 1) and the noise contributed by the input line components. Figure 25 shows predicted and measured values for the Venus Site TWM. Errors at 2325 and 2350 MHz are caused by input mismatch.

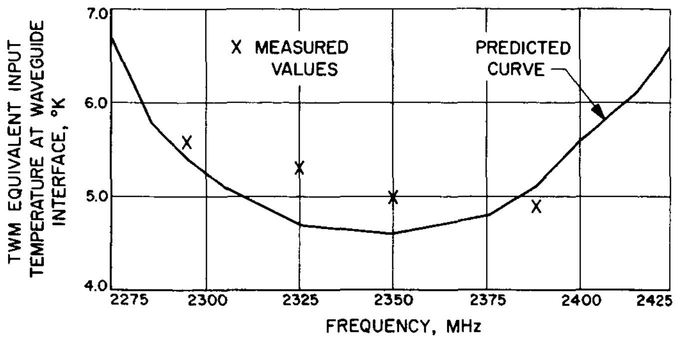

Fig. 25. TWM equivalent input temperature

Laboratory evaluation of the TWM has made use of a WR 430 waveguide termination at liquid-helium temperature (4.2°K). Figure 26 shows losses that result in a reference load temperature of 6.2°K at the ambient waveguide flange.[1]

[1]C. T. Stelzried, Jet Propulsion Laboratory, Pasadena, California, private communication.

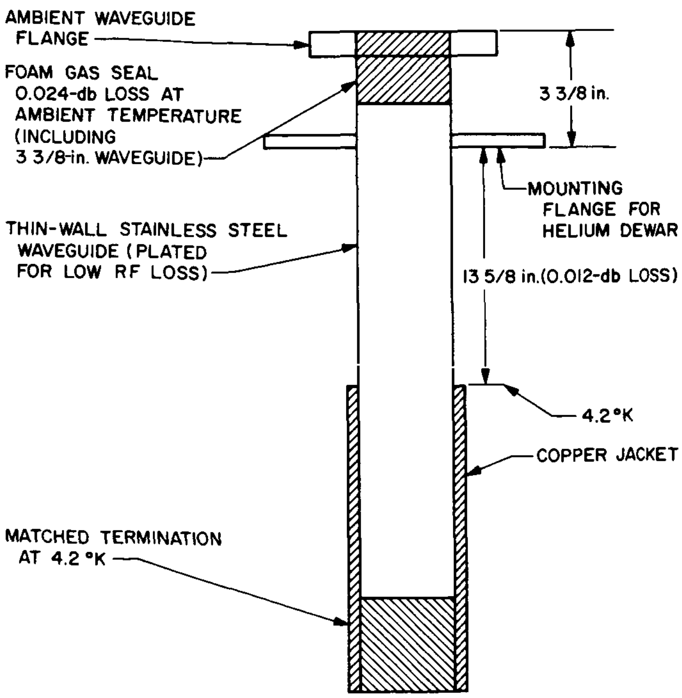

Fig. 26. Liquid-helium-cooled waveguide termination

A system block diagram for the temperature evaluation is shown in Fig. 27. Figure 28 is a recording of total

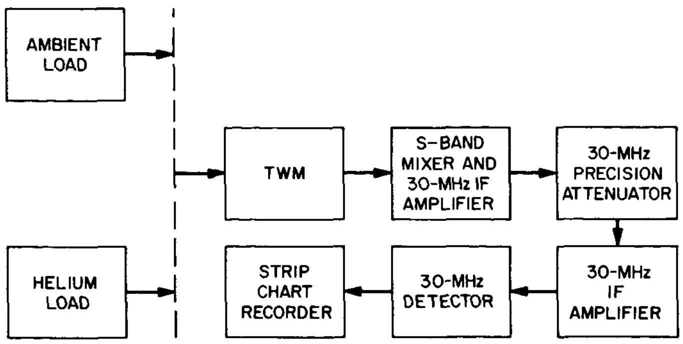

Fig. 27. Block diagram for system temperature evaluation

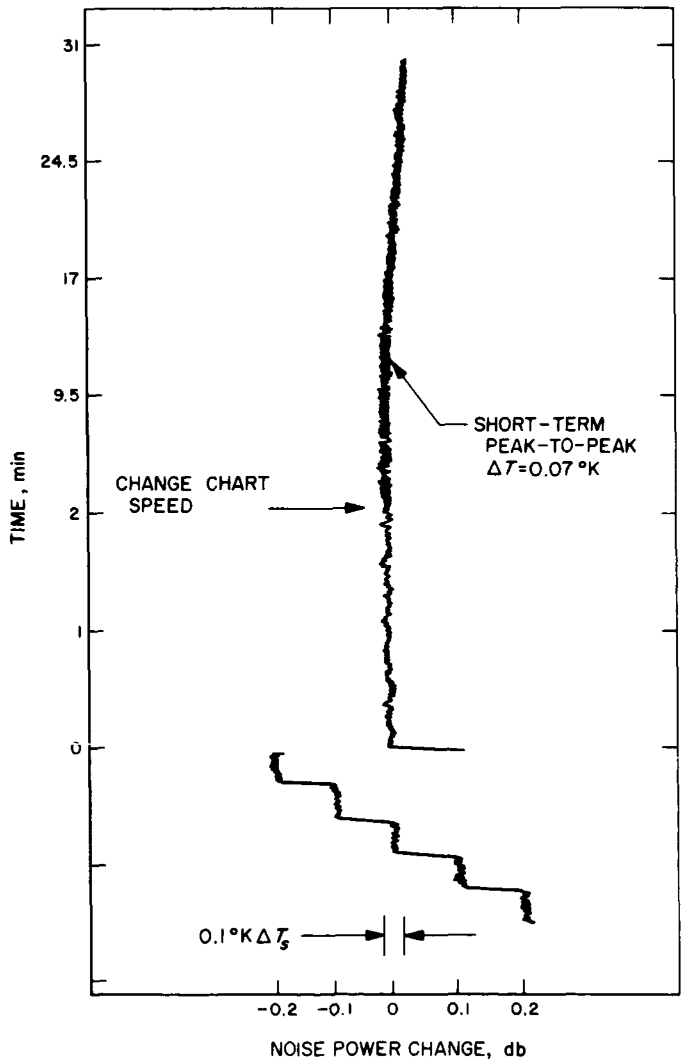

Fig. 28. Recording of total system noise power

system noise power which shows the resolution obtained by having a very low system temperature (T_s) and good short-term stability. A precision attenuator is used at the 30-MHz IF frequency to measure the change in system noise power when changing from an ambient load to the 6.2°K load. Table 2 shows contributions to the system temperature at 2388 MHz. The power change measured when switching loads was 14.08 db. This represents a total system noise temperature of 11.8°K.

Table 2. System temperature contributions

System	Temperature, °K
Liquid-helium-cooled termination	6.2
Waveguide connecting TWM to cooled termination	0.35
Receiver following TWM	0.35
TWM equivalent input temperature at waveguide interface	4.9
Total	11.8

IV. Conclusion

Today the traveling wave maser is used in the field to achieve receiving system noise temperatures lower than those that can be obtained with any other amplifier. The successful use of the TWM is dependent on a reliable cryogenic refrigerator. Operational field use of the maser/refrigerator systems described here has been highly successful. Knowledge and experience gained in the field, combined with new techniques developed in the laboratory, have resulted in the development of high-performance maser/refrigerator systems. Gain, noise temperature, and tunability have been improved, field maintenance has been simplified, and reliability has been increased.

References

1. Sato, T., and Stelzried, C. T., "An Operational 960 Mc Maser System for Deep-Space Tracking Missions," *IRE Transactions on Space Electronics and Telemetry*, June 1962, pp. 164–170.
2. Higa, W. H., "A Maser System for Radar Astronomy," *Low Noise Electronics*, Fifth AGARD Avionics Panel Conference, Oslo, Norway, July 31 to August 2, 1961, pp. 296–303.
3. Higa, W. H., *Maser Amplifiers in Radar and Radio Astronomy*, Technical Memorandum No. 33-125, Jet Propulsion Laboratory, Pasadena, California, March 15, 1963.
4. Bathker, D. A., and Clauss, R. C., "An Ultra Low Noise Receiving System for Deep Space Telemetry Reception," *1966 National Telemetering Conference Proceedings*, National Telemetering Conference, Boston, Mass., May 10–12, 1966, pp. 198–201.
5. Higa, W. H., and Wiebe, E., "A Simplified Approach to Cryogenic Refrigeration." To be published in *Cryogenic Technology*.
6. Okwit, S., and Smith, J. G., "Packaged Electronically Tunable S-Band Traveling-Wave Maser System," *Proceedings of the IRE*, Vol. 50, June 1962, p. 1470.
7. Siegman, A. E., *Microwave Solid State Masers*, McGraw-Hill Book Company, Inc., 1964, pp. 326–331.