Block IIA Traveling-Wave Maser

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Two 8.4-GHz low-noise traveling-wave masers (TWMs) with effective input noise temperatures of 3.6 to 3.9 K and bandwidth in excess of 100 MHz have been supplied to the Deep Space Network. These TWMs are used on the 64-meter antennas at Deep Space Stations 14 and 43 to meet the requirements of the Voyager Uranus encounter. The TWMs have improved isolator assemblies and new interstage matching configurations to reduce gain/bandwidth ripple. They are equipped with followup Field Effect Transistor Amplifiers as part of the design to meet the 100-MHz bandwidth requirements of very long baseline interferometry.

I. Introduction

Two new 8.4-GHz low-noise traveling-wave masers (TWMs) have been installed on the 64-meter antennas at Deep Space Stations 14 and 43 as part of the Mark IVA DSCC Antenna Microwave Subsystem upgrade. The TWMs were built to meet the sensitivity requirements of the Voyager Uranus encounter and support very long baseline interferometry (VLBI) bandwidth requirements.

A previous version of the maser, designated Block II TWM (Ref. 1), met the noise requirements for the Voyager Saturn encounter but failed to meet the new 100-MHz bandwidth requirements. A new prototype TWM was designed and built that would meet requirements of both the Voyager Uranus encounter and VLBI. This new 8.4-GHz TWM is identified as the Block IIA Low-Noise TWM and is shown in Figs. 1, 2, and 3. This maser provides 45-dB net gain (measured between the input of the TWM and the input to the receiver mixer), with a -3-dB bandwidth greater than 100 MHz (see Table 1) and an effective input noise temperature of 3.6 to 3.9 K.

II. Design Goals

The following performance design goals were established for the Block IIA Low-Noise TWM:

(1) Gain 44.5 ± 1.5 dB, to be adjusted on the particular Front End Area (FEA) of the antenna for net gain of combined TWM, Field Effect Transistor (FET) Amplifier, and hybrid loss in front of the receiver mixer.

(2) 100-MHz minimum -3-dB bandwidth covering 8400 to 8500 MHz.

(3) Equivalent input noise temperature of 4 ± 1 K within the specified bandwidth.

(4) Gain slope within the specified bandwidth ±0.2 dB/MHz.

(5) Improved pump source assembly reliability and ability to meet Radio Frequency and Microwave Subsystems Section (Section 333) stress analysis standards.

(6) Closed-cycle refrigeration (CCR) stage temperature monitoring capability.

(7) Interchangeability with existing Block II TWMs (Ref. 1) and previous Block I TWMs (Ref. 2).

Table 1 lists additional design requirements for the Block IIA TWM.

III. Maser Description

The Block IIA Low-Noise TWM external package is identical to the Block II TWM (Ref. 1) with the exception of the FET amplifier assembly, mounted near the output waveguide port of the TWM. Internal cryogenic temperature sensors are mounted on the three temperature stages of the CCR (70 K, 15 K, and 4.5 K). This allows the stage temperature to be monitored during cool-down and when the unit is cold. Monitoring of these sensors is useful in troubleshooting the CCR system during cool-downs and while the unit is cold. A new magnet field monitor sensor results in more accurate and repeatable magnetic field monitoring.

The major performance design changes are within the maser structure assembly. The previous DSN Block II 8.4-GHz TWMs had marginal gain bandwidth product. Most of the six units built could not meet the minimum gain requirement of 45-dB gain with 100-MHz bandwidth. The gain was adjusted for 45-dB gain and the resulting bandwidth was less than 100 MHz on most units (actual bandwidth realized varied from 65 MHz to 108 MHz on the six Block II TWMs). The cause of low gain/bandwidth product was inadequate inversion ratio and excessive ripple in the gain/bandwidth response.

Low inversion ratio results when an insufficient number of maser spins make the energy level transition upon application of pump energy. Attempts to analyze the pump frequency RF fields in the TWM structure have met with little success due to the complexity of the dielectric loading, presence of the half-wave comb slow-wave structure, and overmoding of the pump energy within the structure. Measured variations in inversion ratio have resulted from changes in comb resonant strip material thickness, comb resonant material (pure copper vs. thin-film copper over chrome), and dielectric material shape. Hand-assembled combs using pure copper resonator strips consistently produced better inversion ratios than those obtained with thin electro deposit film strips. Also, attempts to increase the gain bandwidth product of the structure by changing the ruby geometry (a bevel at the edge of the ruby opposite the resonant fingers increases the slowing factor) resulted in lower inversion ratios. Therefore, maximum inversion ratio in this Block IIA TWM was achieved by using hand-fabricated copper combs with minimum ruby shaping. The geometry of the dielectric-loaded pump coupling waveguide was also modified to improve the inversion ratio.

Figure 4 shows a Block II TWM gain bandwidth curve, selected to show a worst-case sample of gain ripple. This ripple is caused by a combination of insufficient isolator reverse loss and interchannel voltage standing wave ratio (VSWR). Reflected signal due to marginal VSWR and insufficient isolator reverse loss results in in-phase and out-of-phase signal voltage additions, causing peaks and nulls in the maser bandpass. The electrical length of the forward and return path of each structure determines the frequency difference in MHz between adjacent peaks and nulls. This condition was improved in this block IIA design by improving the impedance match at the input and output connector of each channel, and by increasing reverse loss of the distributed resonance isolator in each channel. The Block II TWM isolator had nominally 30-dB reverse loss per channel, or 120-dB total reverse loss per TWM consisting of four channels. The new Block IIA isolator assemblies have a reverse loss of 40 dB per channel (160 dB per TWM). The increase in reverse loss is achieved by increasing the quantity of yttrium iron garnet isolator material (YIG) in the area where the RF signal magnetic field is circularly polarized. Increasing the YIG in this area also results in increased forward loss, which is undesirable. The resulting increase in noise temperature contribution from this loss is, however, offset by the reduction in noise temperature due to the use of a followup FET amplifier (discussed later).

The geometry of the Block IIA TWM input, output, and interstage RF coupling probes was redesigned to improve the long-term mechanical stability of these components. This results in a more repeatable VSWR from cool-down to cool-down and after disassembly and reassembly.

The improvements in isolator performance and VSWR stability have resulted in the gain bandwidth curve for the Block IIA TWM shown in Fig. 5. The performance of a second unit is shown in Fig. 6.

An FET amplifier and variable attenuator are used on the Block IIA TWM, shown in Fig. 7, to offset the high-noise contribution which would otherwise result from the followup receiver. The gain of the TWM/FET/attenuator system is set at 52 dB, on the particular 64-meter FEA, by adjusting the variable attenuator. With the 7-dB insertion loss resulting from power dividers and waveguide loss, a net gain of 45 dB results from TWM input to receiver mixer input.

The receiver mixer is specified at 11 dB maximum noise figure and the insertion loss between TWM and receiver is 7 dB maximum, making the total noise figure for the receiver 18 dB.

The followup receiver noise temperature contribution to system noise temperature is given by the expression:

$$T_f = \frac{T \text{ receiver}}{G \text{ maser}}$$

Therefore, the receiver followup contribution (T_f) to total system temperature (T_{op}) in the previous Block II TWM configuration with a gain of 45 dB is 0.57 K. The T_f contribution to T_{op} with the Block IIA TWM plus FET (total gain = 52 dB) is equal to 0.11 K. This is an improvement in T_{op} of 0.46 K.

A redesign of the pump source assembly was made in accordance with Section 333 stress analysis standards. A stress analysis of all components used in the pump system was included with this design effort.

IV. Performance

The performance of the Block IIA TWM meets all the design goals and specified requirements shown in Table 1.

The gain/bandwidth curves of the two production Block IIA TWMs are shown in Fig. 5. The gain bandwidth curves are smooth with no evidence of the signal addition ripple that is characteristic of Block II TWMs. The net gain of both Block IIA TWMs can be adjusted to 44.5-dB gain at the input to the receiver mixer with bandwidths exceeding 100 MHz. Figure 8 shows the bandwidth curve of the Block IIA TWM with the gain varied in 3-dB steps (±6 dB total) with no bandwidth shape change as the result of the gain variation.

The equivalent input noise temperature at the room temperature input waveguide flange is shown in Fig. 9 for both Block IIA TWMs. The noise temperature was measured by attaching a high-quality feedhorn to the waveguide input flange and alternately viewing the "cold" sky and an ambient termination microwave absorber.

V. Conclusions

The Block IIA 8.4-GHz TWMs have met or exceeded the performance goals established as part of the Mark IVA DSCC upgrade for the Voyager Uranus encounter and VLBI requirements.

Recently, two additional Block IIA TWMs were built by Eaton Corporation Airborne Instrument Laboratory (AIL) division for the European Space Agency with the assistance of JPL personnel as technical consultants. The successful fabrication of the Block IIA type TWM by a commercial company (AIL) demonstrates the repeatability of this TWM design and the success of the Block IIA TWM program at JPL.

References

1. Trowbridge, D. L., "X-Band, Low-Noise, Traveling-Wave Maser," *TDA Progress Report 42-60*, pp. 126-131, Jet Propulsion Laboratory, Pasadena, CA, Dec. 15, 1980.
2. Trowbridge, D. L., "X-Band Traveling Wave Maser Amplifier," *DSN Progress Report 42-28*, pp. 69-70, Jet Propulsion Laboratory, Pasadena, CA, Aug. 15, 1975.

Table 1. X-band Block IIA TWM and CCR assembly functional characteristics

Characteristics	Required value
Gain	45 ± 1.5 dB
Gain slope in specified bandwidth	±0.2 dB/MHz
Maser gain stability stationary, short-term	±0.03 dB/10 s, any position
Stationary, long-term	±0.5 dB/12 h, any position
Tilting	±0.5 dB/0.2 deg/s max rate, any position
Bandwidth	
Bandwidth	> 100 MHz (3 dB)
Center frequency	8450 MHz
Noise temperature	4.0 ± 1 K
Phase stability	
10 s	±1 deg max
12 h	±5 deg max
Moving antenna	±10 deg max
Group delay stability	
10 s	±0.1 ns max
12 h	±0.5 ns max
Moving antenna	±1.0 ns max
Group delay variations vs frequency	
Maximum in bandpass	10 ns peak to peak
Maximum slope	0.5 ns/MHz

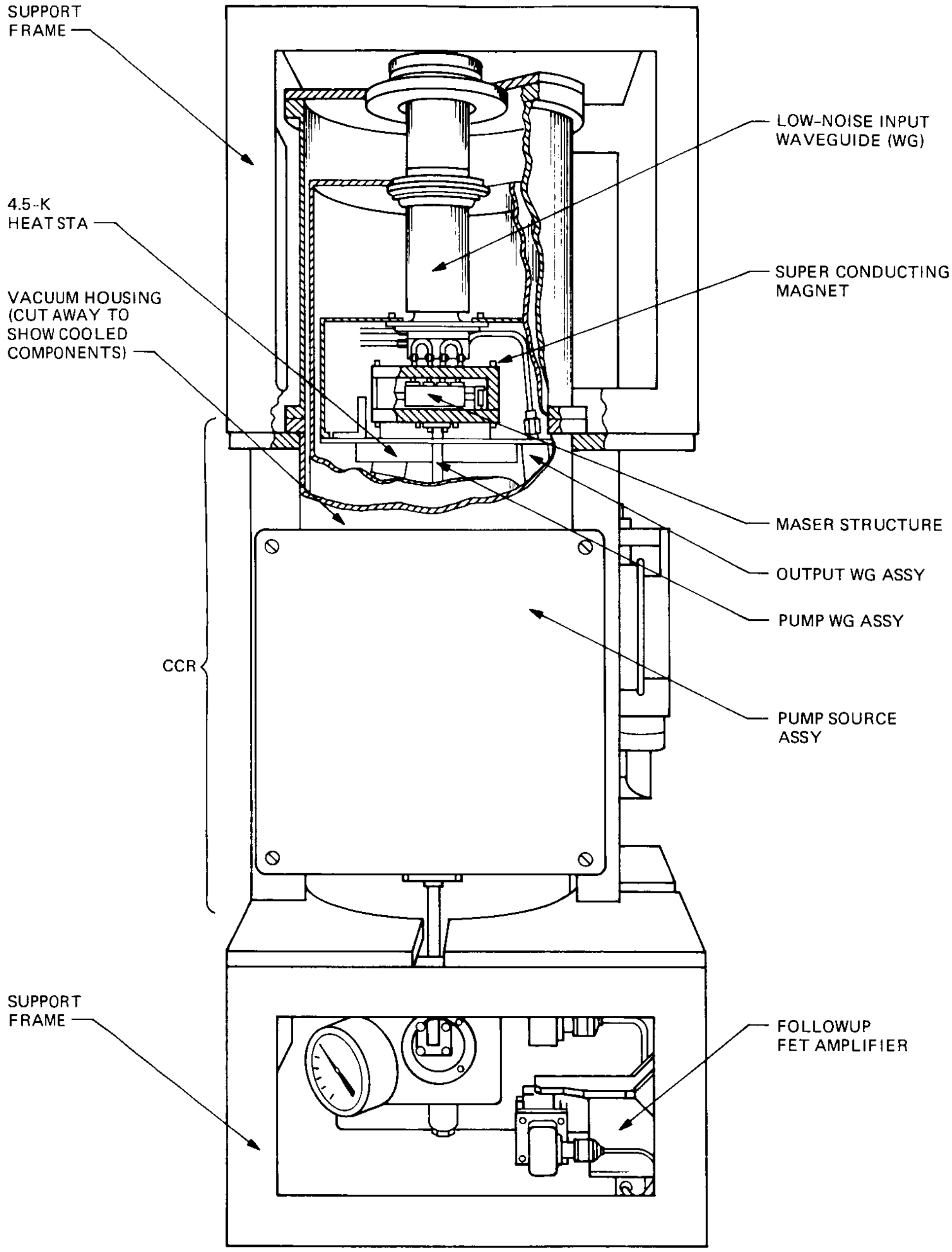

Fig. 1. Traveling-wave maser and closed-cycle refrigerator assembly, Block IIA

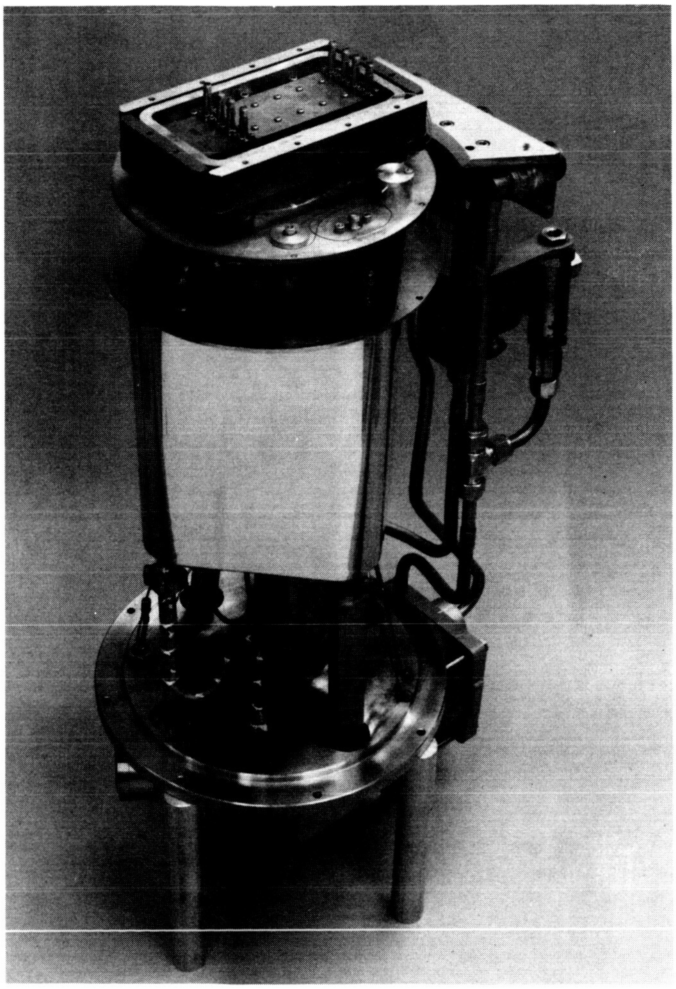

Fig. 2. Internal view of Block IIA 8.4-GHz TWM

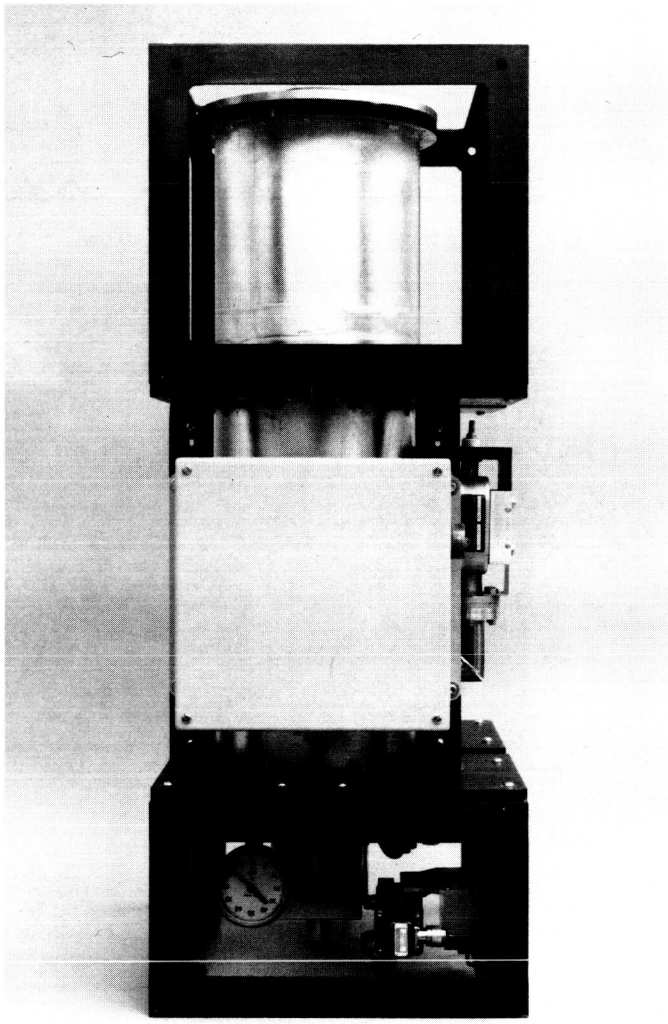

Fig. 3. External view of Block IIA 8.4-GHz TWM

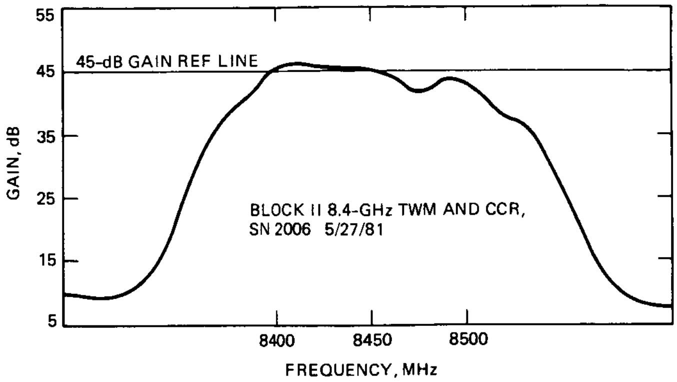

Fig. 4. Block II TWM gain bandwidth curve, SN 2006

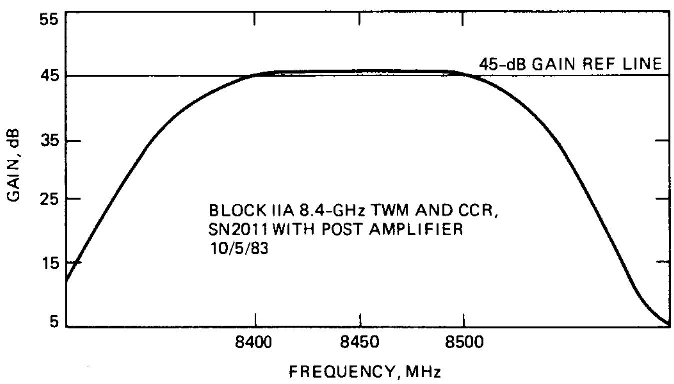

Fig. 5. Block IIA TWM gain bandwidth curve, SN 2011

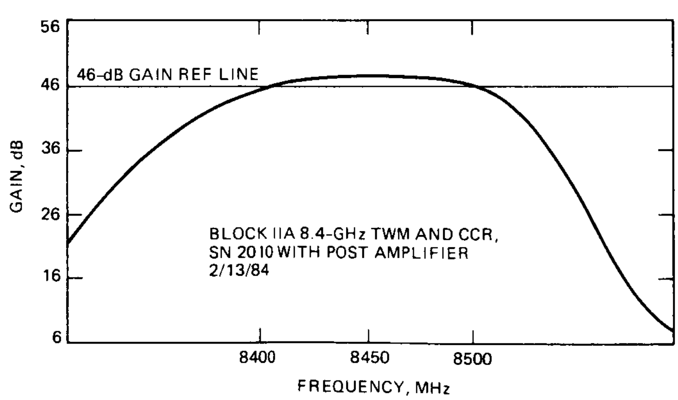

Fig. 6. Block IIA TWM gain bandwidth curve, SN 2010

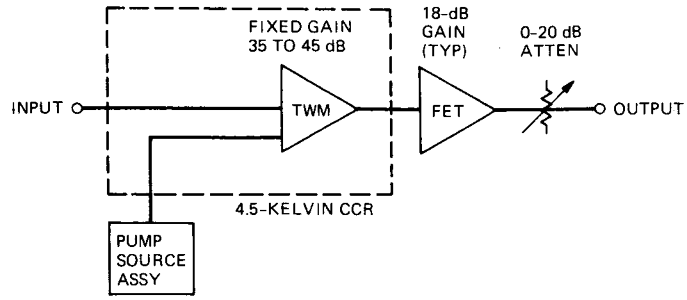

Fig. 7. Block diagram of Block IIA maser

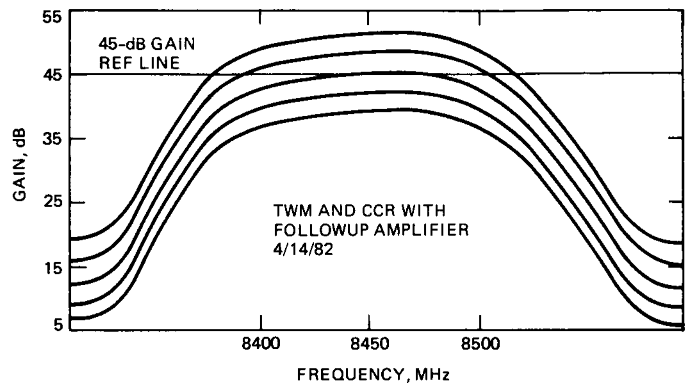

Fig. 8. Maser plus FET amplifier net gain as a function of system attenuator settings in 3-dB increments

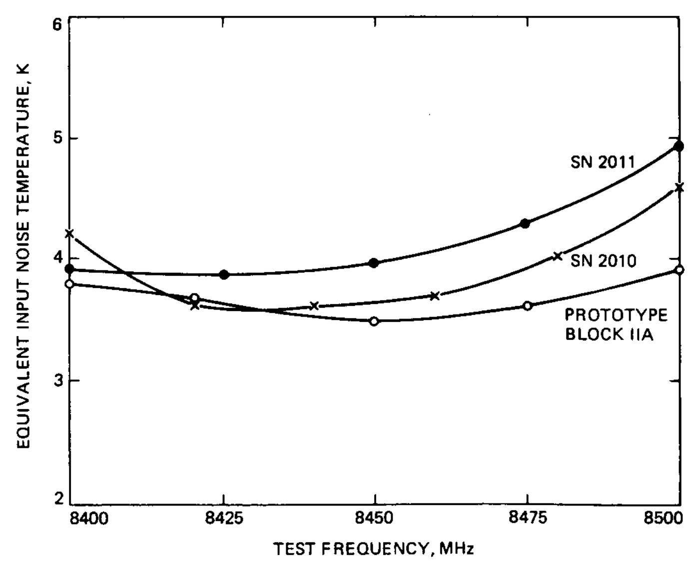

Fig. 9. Equivalent input noise temperature vs frequency, Block IIA TWMs