A 2.3-GHz Low-Noise Cryo-FET Amplifier

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A cryogenically cooled, low-noise Field Effect Transistor (FET) amplifier assembly for use at 2.2 to 2.3 GHz has been developed for the DSN to meet the requirements of a Very Long Baseline Interferometry (VLBI) upgrade. An amplifier assembly was developed at JPL that uses a commercial closed-cycle helium refrigerator (CCR) to cool a FET amplifier to an operating temperature of 15 K. A cooled probe waveguide-to-coaxial transition similar to that used in the R&D Ultra-Low-Noise S-band Traveling Wave Maser (TWM) is used to minimize input line losses. Typical performance includes an input flange equivalent noise contribution of 14.5 K, a gain slope of less than 0.05 dB/MHz across a bandwidth of 2.2 to 2.3 GHz, an input VSWR of 1.5:1 at 2.25 GHz, and an insertion gain of 45 ± 1 dB across the bandwidth of 2.2 to 2.3 GHz. Three 2.3-GHz FET/CCR assemblies were delivered to the DSN in the spring of 1987.

I. Introduction

A requirement for a broadband low-noise amplifier for 2.2 to 2.3 GHz was established as part of the VLBI upgrade. The VLBI requirements did not demand the ultra-low-noise performance of a Traveling Wave Maser (TWM), and as reliability and bandwidth were priorities, the Radio Frequency and Microwave Subsystems Section (Section 333) proposed a design using a cryogenically cooled FET with a helium refrigerator (CCR) operating at 15 K. Using this refrigerator rather than the 4.5-K refrigerators used by the TWMs increased reliability, and using the FET guaranteed that the required operational bandwidth was obtainable.

The design requirements agreed upon between Section 333 and the VLBI project were an input flange equivalent noise contribution of 20 K maximum, a 1-dB bandwidth of 2.2 to 2.3 GHz, and an insertion gain of 45 dB. Although no specification was given for phase delay versus frequency, it was to be measured for each amplifier assembly.

II. Design

A. Refrigerator (CCR)

The overriding concern in the selection of the helium refrigerator was to improve the reliability of the FET/CCR over the existing maser helium refrigerators. The main detractor in the reliability of the maser refrigerators is the need for a Joule–Thomson (J–T) expansion valve and the attendant helium gas heat exchangers to obtain the necessary 4.5-K operating temperature. These refrigerators suffer occasional loss of capacity due to contamination in the helium, which solidifies in the heat exchangers or in the J–T valve. There is also a reduction in refrigerator reserve capacity for 4-K operation, compared to 15-K operation, due to the heat load of these components. Therefore, a significant increase in reliability is achieved simply by being able to select a refrigerator operating temperature of 15 K instead of 4.5 K. The heat capacity of the 15-K CCR is 5 watts at 15 K; the calculated reserve heat capacity of the final design with the RF input and output lines, the amplifier, and all internal components would be no less than 3 watts, compared to a typical reserve capacity of 400 to 700 milliwatts for a maser refrigerator with all the maser components installed. The CCR vacuum housing and the internal configuration were based on the design used for the successful L-Band Venus Balloon Experiment FET/CCR. The CTI, Inc., Model 350 helium refrigerator and compressor were incorporated into the design of the VLBI 2.3-GHz FET/CCR.

There are several available helium refrigerators that are smaller than the CTI 350. However, even though a more compact design could be implemented, it was felt that reliability was enhanced with the greater heat capacity. In addition, the expansion engine portion of the CTI 350 is essentially interchangeable with the expansion engine used by the maser CCRs and is supportable by the existing spares and maintenance capability in the DSN. Figure 1 shows the CTI 350 CCR.

B. Amplifier

At the time this project started, Section 333 was in the process of evaluating various commercially available coolable FET amplifiers and had demonstrated excellent noise performance and reliability with amplifiers made by Berkshire Incorporated. The Berkshire commercial coolable FET amplifier used a Teflon circuit board substrate that has been very successful for cryogenic use, and has eliminated failures due to microstrip conductor separation and substrate breakage during thermal cycling. In addition, Section 333 was evaluating High Electron Mobility Transistor (HEMT) devices being manufactured by General Electric and had successfully installed several of these HEMT devices into the first stage of amplifiers with a similar design. This ensured the possibility of later upgrading to a HEMT first-stage device if these could be proven reliable for this project. For these reasons, it was decided to incorporate the Berkshire FET amplifier into the design of the assembly. Figure 2 shows the Berkshire amplifier mounted on the 15-K stage of the FET/CCR assembly (the vacuum jacket and radiation heat shields have been removed). Although the three amplifier assemblies were completed as FETs, the success of a 2.3-GHz HEMT/CCR installation at DSS-13 [1] demonstrates that these assemblies can be upgraded when desired to incorporate HEMT devices in the first stage. As the gain of the cryogenically cooled FET amplifier is 34 to 37 dB, a room-temperature postamplifier and a variable attenuator were incorporated into the design to provide a nominal insertion gain of 45 dB. The amplifier is protected from interfering signals above 3.3 GHz by a low-pass filter. Figure 3 shows an RF schematic of the FET/CCR assembly.

C. Waveguide-to-Coaxial Transition

To take advantage of the noise performance of the FET device and to eliminate the need for an input isolator, a broadband low-loss input line with good VSWR was required for the implementation of the VLBI 2.3-GHz FET/CCR. In order to provide a substantial CCR heat capacity reserve, a design was required that also minimized heat transfer from the ambient temperature portion of the input line to the 15-K portion of the refrigerator. A cryogenically cooled coaxial probe transmission line was first designed and implemented in 1973 for the 4.5-K, 2.3-GHz TWM/CCR [2]. This input line was recently redesigned for 1.668 GHz and implemented in the DSN in a FET/CCR assembly used for the Venus Balloon Experiment [3]. At an RF probe temperature of 4.5 K, the original input line contributed less than 0.1 K of the equivalent excess noise of the TWM noise temperature. In the Venus Balloon FET/CCR, the input line contributed approximately 0.5 K equivalent noise temperature due to the increased RF probe physical temperature of 12 to 15 K. The noise temperature contribution of the present 2.3-GHz cold probe input assembly is also estimated to be 0.5 K. Figure 4 shows the final design of the 15-K, 2.3-GHz probe. Figure 5 shows the assembled probe and waveguide transition.

III. Performance

All performance goals were met with the 2.3-GHz FET/CCR: the nominal cool-down time of the FET/CCR is 4 hours; the final stage operating temperature is 12 K; and the measured refrigerator reserve capacity exceeds 3 watts on all three FET/CCR assemblies. Measurements of VSWR, gain, and phase delay were made on the prototype and deliverable FET/CCR assemblies with the Hewlett-Packard HP 8510 network analyzer. Figure 6 shows plots of input VSWR, insertion gain, and phase versus frequency for a typical 2.3-GHz FET/CCR. Noise temperature data were measured using a calibrated 2.3-GHz microwave horn at the zenith position and a section of microwave-absorbing material to obtain Y-factor power measurements between the "cold" sky and an ambient temperature load [4], [5]. The absorber was placed over the horn aperture to provide the ambient temperature load. The noise temperature instrumentation consisted of a 2.3-GHz horn connected to the input waveguide and the output of the FET/CCR assembly connected to a 2.3-GHz transistor amplifier with 23-dB gain, an isolator, a tunable 2.3-GHz filter with a bandpass of 10 MHz, a Hewlett-Packard 8484A power sensor, and an HP 436A digital power meter. Figure 7 shows the schematic of the noise temperature measurement setup. The equivalent input noise temperature of the FET/CCR assembly and the test amplifier may be calculated from the relationship:

$$T_r = \frac{T_a - YT_h}{Y - 1}$$

where T_r is the equivalent input noise temperature of the FET/CCR system at the room-temperature input waveguide flange, in K; T_a is the physical temperature of the ambient load, in K; T_h is the theoretical value of the sky background noise plus the noise contributed by the calibrated 2.3-GHz horn; and Y is the actual numerical ratio of the power ratio established by the measurement. Table 1 shows the measured values of equivalent input noise temperature for the three delivered FET/CCRs. The values have been corrected for the follow-on contribution of the measurement amplifier setup.

IV. Conclusions

All performance requirements for the 2.3-GHz FET/CCR system have been met, and the MTBF is expected to be 1 year. The completed 2.3-GHz FET/CCR assembly is shown in Fig. 8. Future plans include the incorporation of a HEMT device in the first stage of the Berkshire amplifier.

Acknowledgments

Thanks to Dean Norris for his work in matching the WR 430 waveguide and coaxial probe prototype, and for his assistance in the assembly of the FET/CCRs delivered to the DSN. Thanks to both Dean Norris and Leroy Tanida for assistance in the network analyzer measurements and in the noise temperature measurements.

References

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[2] R. Clauss and E. Wiebe, JPL Technical Report 32-1526, vol. XIX, February 15, 1974.

[3] D. Norris, "Low Noise Cryogenic Transmission Line," *TDA Progress Report 42-91*, July–September 1987, Jet Propulsion Laboratory, Pasadena, California, pp. 89–93, November 15, 1987.

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[5] C. T. Stelzried, *The Deep Space Network Noise Temperature Concepts, Measurements, and Performance*, JPL Publication 82-33, Jet Propulsion Laboratory, Pasadena, California, pp. 12-1–12-8, September 1982.

Table 1. Equivalent input noise contribution

FET/CCR	Noise contribution, K		
	2.2 GHz	2.25 GHz	2.3 GHz
No. 1	14.0	14.4	16.3
No. 2	17.6	16.9	17.5
No. 3	10.7	12.1	11.0

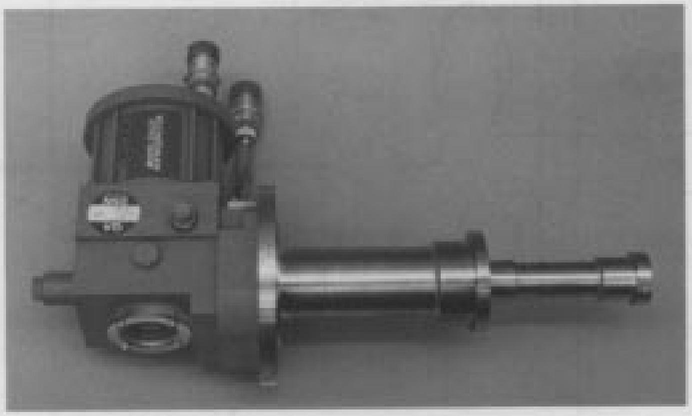

Fig. 1. CTI 350 refrigerator

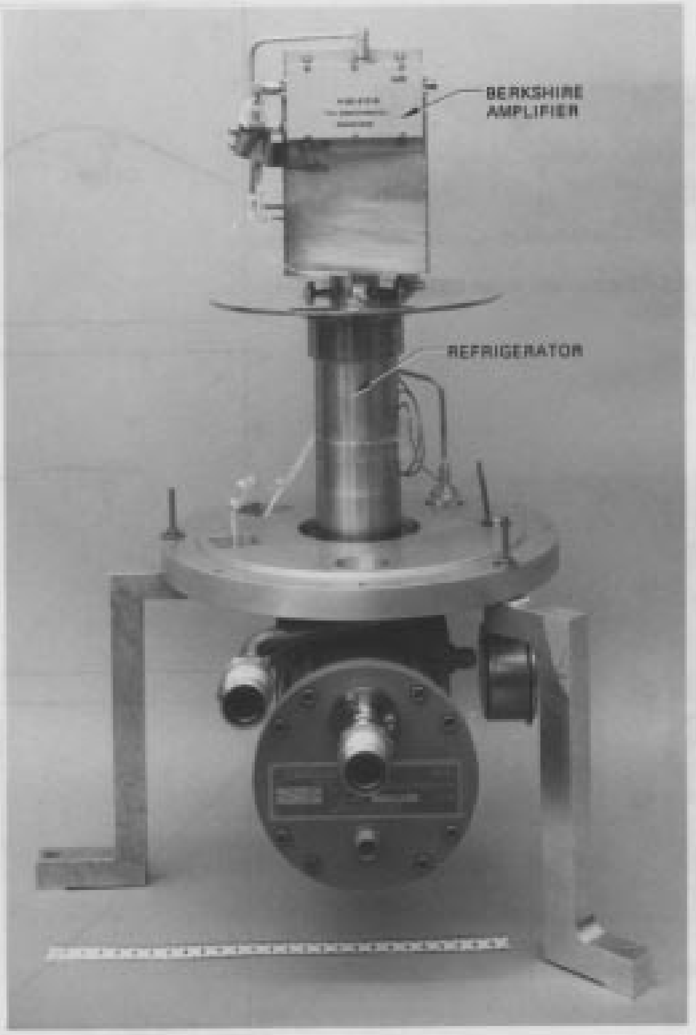

Fig. 2. Berkshire amplifier mounted on the 15-K station of the FET/CCR assembly (vacuum jacket and radiation heat shields removed)

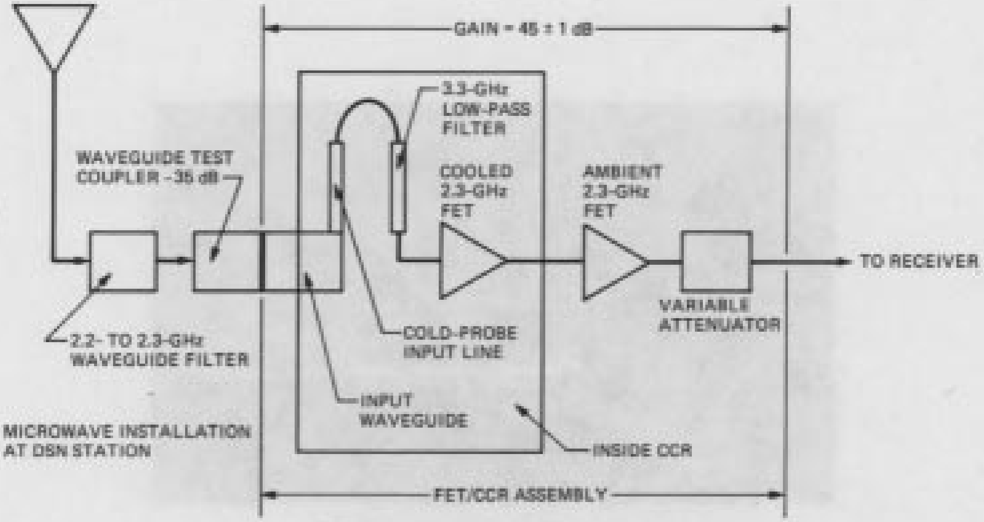

Fig. 3. RF schematic of the FET/CCR assembly

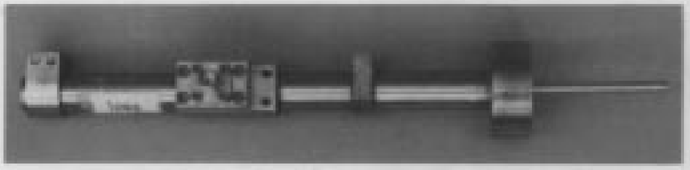

Fig. 4. Cryogenically cooled 2.3-GHz coaxial input line for use at 15 K

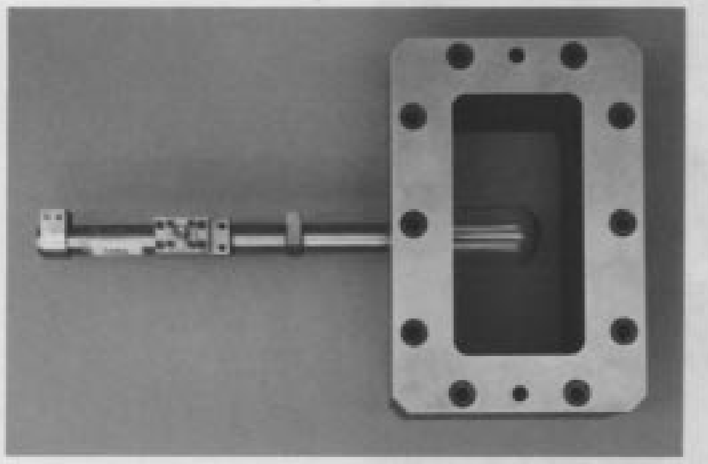

Fig. 5. Waveguide with coaxial probe installed

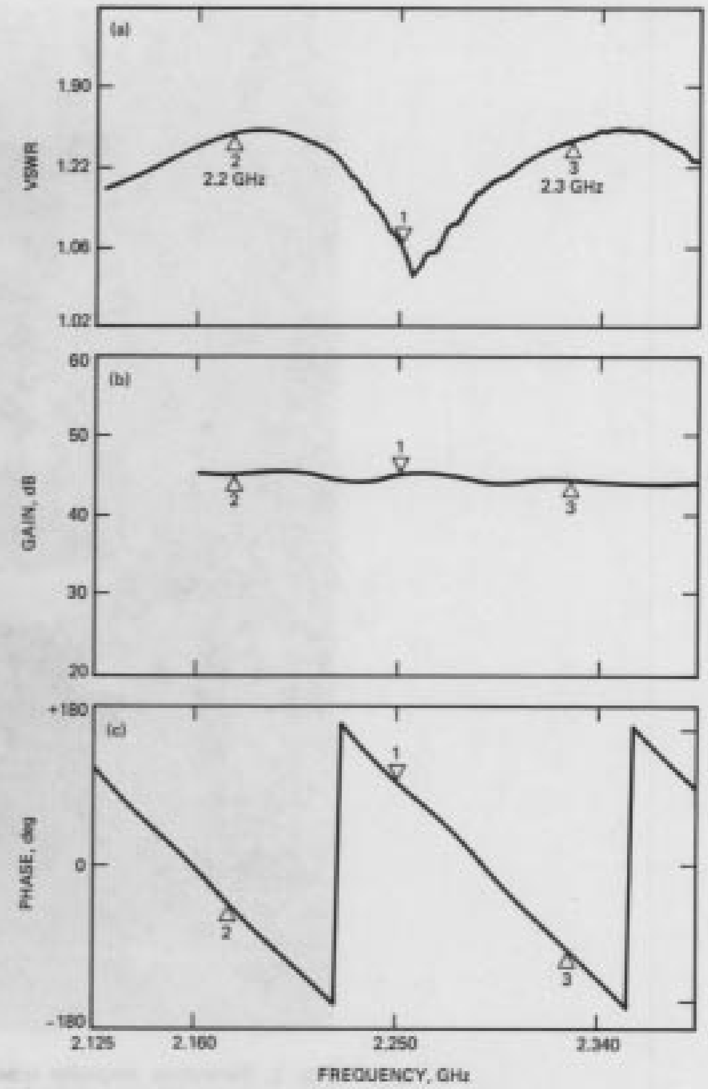

Fig. 6. Input VSWR, insertion gain, and phase versus frequency for a typical 2.3-GHz FET/CCR

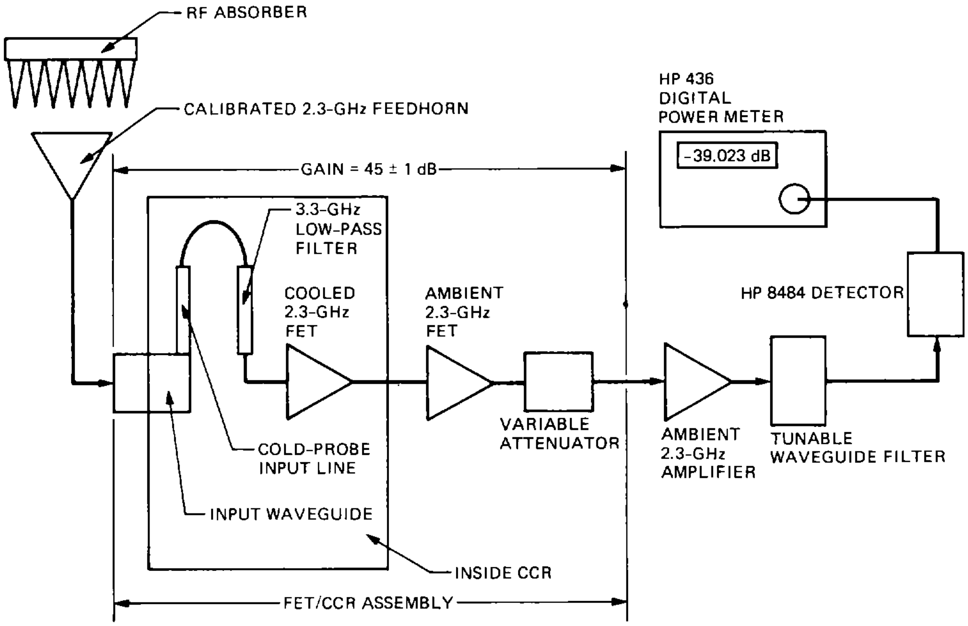

Fig. 7. Noise temperature setup

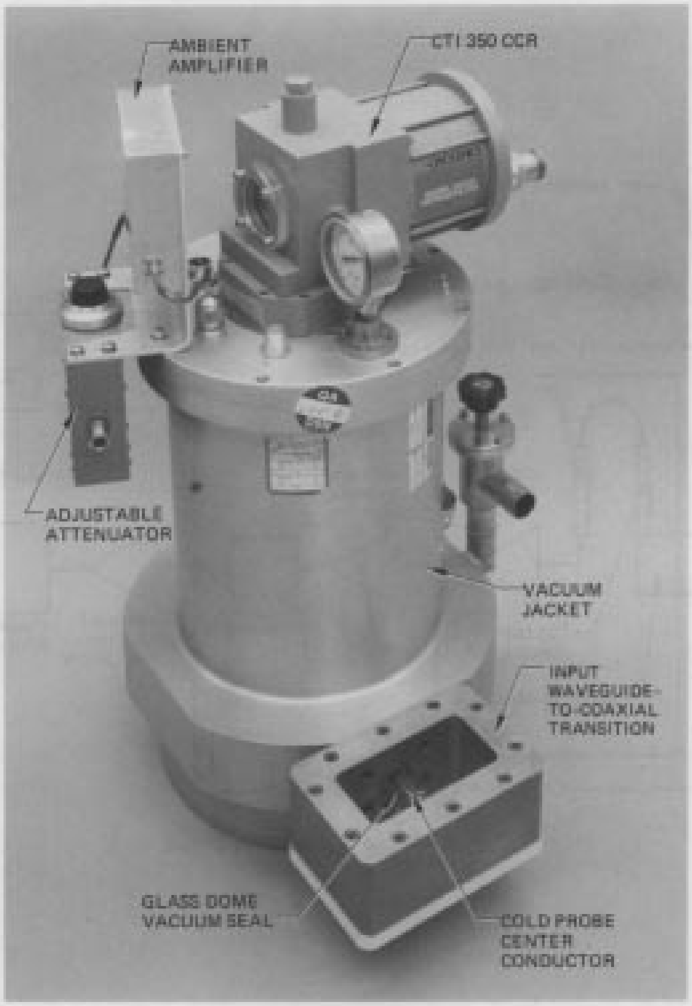

Fig. 8. The 2.3-GHz FET/CCR assembly