A Cryogenic K-Band Ground Terminal for NASA'S Direct-Data-Distribution Space Experiment

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***Abstract*—A K-band receiver terminal has been designed for ≈77-K operation to support the NASA Glenn Research Center's direct-data-distribution (D^3) space experiment. The D^3 experiment involves a 256-element phased-array antenna, aboard the space shuttle, transmitting dual 622-Mb/s beams to the ground terminal. The beams are left- and right-hand-side circularly polarized for isolation. The terminal consists of a Cassegrain reflector antenna with a corrugated feed horn, a six-pole $YBa_2Cu_3O_{7-\delta}$ microstrip bandpass filter, a three-stage InP high electron-mobility transistor monolithic-microwave integrated-circuit amplifier, and a 1-W at 80-K Stirling cycle cryocooler.**

***Index Terms*—Cryogenic electronics, receiving antennas, superconducting filters, MMIC amplifiers.**

I. Introduction

The NASA Glenn Research Center (at Lewis Field), Cleveland, OH, is developing the space-based phased-array and ground segment technologies to demonstrate a K-band 622-Mb/s direct-data-distribution (D^3) system from spacecraft in low Earth orbit (LEO) to strategically placed tracking ground terminals [1]. Operational systems based on this approach may help alleviate problems associated with relaying information from remote sensing and other scientific spacecraft over geostationary links. An immediate advantage occurs because of the 30 dB or so savings in power from reduced path loss, and propagation delay is almost negligible by comparison. However, for such a scenario to be competitive, the downlink data rate must be commensurately higher because of the brief contact times, and the data usage must be latency tolerant. The ground antenna must track the spacecraft from ≈45° off the horizon, and pointing may be accomplished in an open-loop mode using spacecraft ephemeris data. The angular tracking rate is about 1°/s for a 285-km orbit. Given the required G/T of 20.6 dB/K, a 1.8-m reflector would be required to support the link using a conventional receiver. The corresponding antenna beamwidth is 0.6°. In order to simplify tracking, a cryogenic ground terminal is under development. By using a cryogenically cooled low-noise receiver and carefully designed Cassegrain reflector system, the same G/T can be maintained while allowing the antenna diameter to shrink from 1.8 to 0.9 m. The beamwidth of the 0.9-m antenna is about 1.1°. A drawing of the cryo-terminal is shown in Fig. 1. A system noise temperature of about 167 K is predicted at the 45° elevation angle.

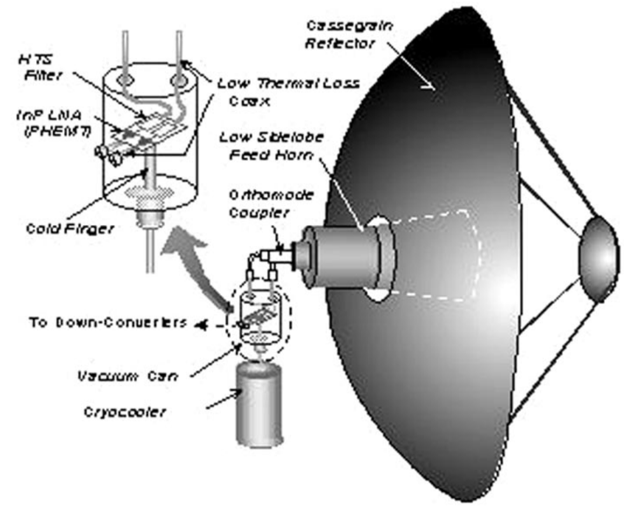

Fig. 1. 18.8–19.3-GHz cryogenic receiver terminal. The Cassegrain antenna is 0.9 m in diameter.

II. Low-Noise Amplifier

The radio astronomy community is very familiar with liquid-helium-cooled maser amplifiers, superconducting mixers, cooled bolometric detectors, etc. However, the commercial satellite imaging and communications industry has been less receptive to cryogenically cooled electronics because of perceived inconvenience or marginal benefits and high cost. Nevertheless, some specialized highly integrated microwave receivers have been developed (e.g., see [2]–[4]). The D^3 receiver uses a three-stage InP high electron-mobility transistor (HEMT) monolithic-microwave integrated-circuit (MMIC) low-noise amplifier (LNA) at the front-end [5]. The advantages of an InP HEMT over GaAs include higher gain, lower power consumption, and lower noise figure, especially at cryogenic temperatures.

A 150-μm device cell was selected to best meet the requirements of K-band receiver applications, specifically the bandwidth, noise figure, matched conditions, and power-handling capability. We have obtained a device extrinsic transconductance (g_m) of 800 mS/mm and breakdown voltage of 7–8 V from 0.1-μm InP fully selective HEMT devices. These InP low-noise HEMT's have exhibited good reliability with median

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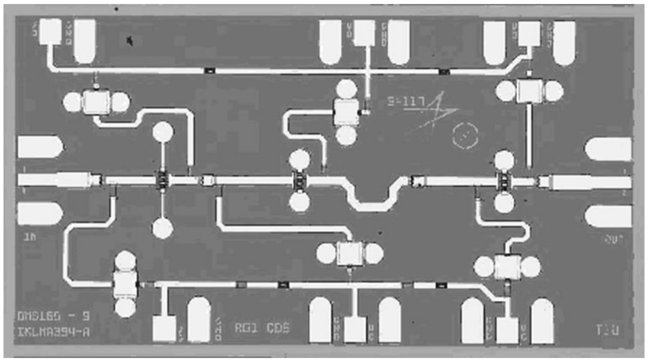

Fig. 2. K-band three-stage InP MMIC LNA. Chip size is 2.70 mm × 1.46 mm.

time to failure (MTTF) of 10^8 h at a channel temperature of 100 °C [6]. A three-stage InP MMIC LNA has been designed to provide the flexibility for a broad-band and high-gain amplifier. Source feedback has been used in the first-stage device to provide good noise match and input VSWR match simultaneously. The MMIC LNA is fully monolithic, with on-board bias decoupling elements, thus allowing complete on-wafer testing while simultaneously minimizing the required number of off-chip components. Extensive in-depth circuit stability analysis is performed on these MMIC circuit designs to ensure that they are unconditionally stable from low megahertz to 100 GHz. Proper coplanar-to-microstrip transitions were incorporated at both input and output ports to facilitate the on-wafer RF testing. A photograph of this MMIC amplifier is shown in Fig. 2. The chip size is 2.70 mm × 1.46 mm.

This MMIC LNA has a noise figure of 1.1 dB with 33-dB gain at 20 GHz at room temperature. Better than 10-dB input and output return losses can be achieved from this MMIC amplifier from 17 to 22 GHz. Under normal operation, it can handle input power up to +20 dBm without any degradation. The output 1-dB compression point is +6 dBm at 20 GHz.

The LNA's were characterized using an on-wafer cryogenic probe station. The cryogenic probe station consists of an on-wafer probing system, vacuum pumps, open-cycle cooling apparatus, and a microscope. The vacuum chamber contains the copper sample stage, refrigerator cooling head, temperature sensors, and microwave probes attached to precision manipulators through a metal bellows [7]. A helium cylinder is used to pressurize a liquid-nitrogen Dewar. The coolant is transferred via a flexible line to the sample stage and monitored with a flow meter at the outlet. A temperature of 82 K was attained in this manner, though temperatures near 30 K can be achieved using liquid helium as the coolant. The station is used in conjunction with a Hewlett-Packard 8510C automatic network analyzer and an ATN NP5 automated noise-figure system. A solid-state noise source and impedance tuner are placed as close as physically possible to the input port. Calibration is performed using on-wafer standards at the operating temperature. A photograph of the entire cryogenic probe system is shown in Fig. 3.

In addition to determining the performance of the LNA's, the purpose of evaluating the LNA's near the temperature of liquid nitrogen was to determine the optimum source termination (Γ_{opt}) and whether or not a single gate and drain bias could be used. Since the receiver is to be cooled with a 1-W miniature cooler, eliminating heat conduction paths is an important consideration. At 82 K, F_{min} was within the measurement uncertainty of the system, estimated at 0.2 dB. Table I summarizes the results, and Fig. 4 shows impedance data and Γ_{opt} at 82 K. The sweep range was from 18.5 to 19.5 GHz.

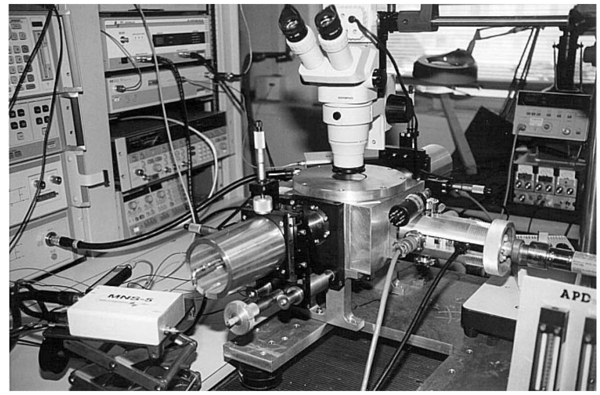

Fig. 3. Open-cycle cryogenic on-wafer probe station for measuring S-parameters and noise parameters through K-band to ≈30 K if helium is used instead of nitrogen.

TABLE I
F_{min} RESULTS OF ON-WAFER MEASUREMENTS AT ROOM TEMPERATURE AND 82 K

T(K)	$V_{G1,2,3}$ (V)	V_{D1} (V)	V_{D2} (V)	V_{D3} (V)	I_{D1} (mA)	I_{D2} (mA)	I_{D3} (mA)	G_a (dB)	F_{min} (dB)
299	-0.2	2.42	1.82	1.80	14.8	15.8	15.1	27	1.1
82	-0.1	1.50	1.00	1.00	14.7	15.5	14.0	28	0.2

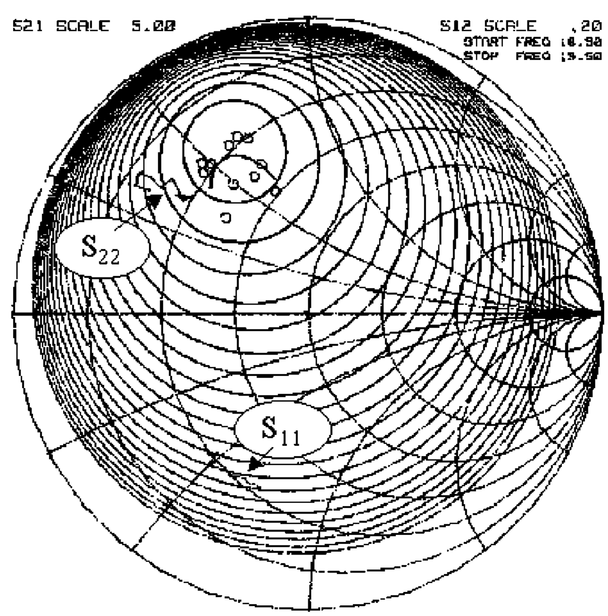

Fig. 4. Impedance data, optimal source termination, and constant noise-figure circles at 82 K. The frequency sweep is from 18.5 to 19.5 GHz.

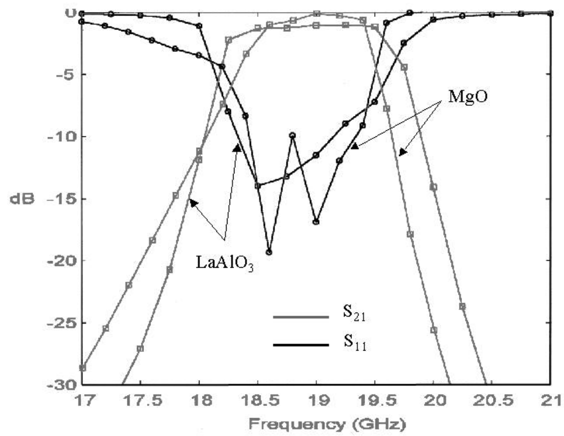

Fig. 5. Modeled insertion and return loss of the $YBa_2Cu_3O_{7-\delta}$ six-pole microstrip filter on 0.25-mm-thick $LaAlO_3$ and 0.3-mm-thick MgO.

III. Filter

Due to the high gain and wide bandwidth of the LNA, a high-temperature superconductor edge-coupled microstrip bandpass preselect filter is used ahead of the LNA. This prevents the LNA from being driven into saturation by powerful out-of-band sources and reduces interference. Filters, similar to the style presented in [4], were designed on 250-μm-thick $LaAlO_3$ and 300-μm-thick MgO. While film quality is generally superior on the former because of the close lattice match, for a given impedance, linewidths are wider and, hence, conductor loss is smaller for the latter. For each filter, a six-pole design was chosen as a compromise between insertion loss and rolloff. Fig. 5 shows theoretical results based on a full-wave electromagnetic simulation using Zeeland Software Inc., Fremont, CA, IE3D. The surface resistance of the $YBa_2Cu_3O_{7-\delta}$ film was assumed to be 1 mΩ at 75 K and 19 GHz in both cases. Also, both the strip and ground plane are superconducting. The in-band insertion loss of the filter on the $LaAlO_3$ and MgO substrates is 0.9 and 0.6 dB, respectively. An equivalent gold filter would have a loss of 2 dB. The $\approx$400-nm-thick superconducting films were grown by Neocera Inc., Beltsville, MD, using pulsed laser deposition. The best films had a critical temperature transition onset of 89.4 K and a transition width of about 0.5 K with a difference between front-side and backside films of less than 0.5 K. Initial tests showed a higher than predicted in-band ripple that is believed due to a higher than anticipated penetration depth. Modeling suggested that if the zero-temperature London penetration depth $(\lambda_L(0))$ was allowed to deteriorate to $\approx$300 nm, instead of 200 nm as expected, most of the measured characteristic was explained. The performance of passive microwave circuits can be strongly dependent on λ_L, and tests to confirm the foregoing hypothesis using microstrip resonators are underway [8].

IV. Antenna

The customized 0.9-m Cassegrain parabolic reflector was manufactured by the Millitech Corporation, Northampton, MA, and provides a gain of 43 dBi and half-power beamwidths of 1.11° and 1.14° in the E- and H-planes, respectively. The main reflector is constructed from graphite and the hyperbolic subreflector is machined aluminum. The edge taper produces sidelobes that are 18.7 and 20.2 dB down in the E- and H-planes, respectively. The measured E- and H-plane patterns are shown in Fig. 6. A waveguide polarizer and orthomode transducer (OMT) separate the two beams. The axial ratio of the polarizer is 0.6 dB and the maximum insertion loss through the OMT is 0.3 dB. The two orthogonal signals are connected to the receiver via waveguide-to-coax transitions. Gold-plated stainless-steel center conductor and thin ($\approx$10 μm) Au plated Cu jacketed coaxial cables are used for the two RF inputs. Stainless-steel cables are used for the two IF outputs of the receiver.

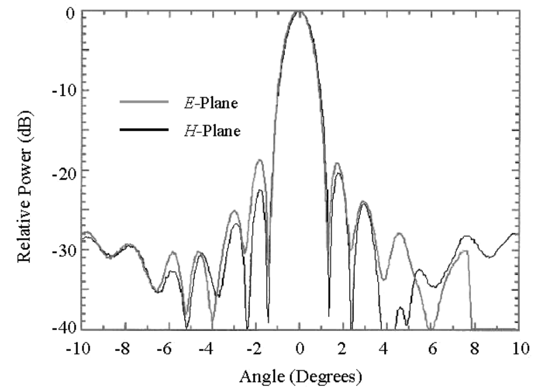

Fig. 6. Measured principal plane patterns of the 0.9-m Cassegrain reflector at 19 GHz.

TABLE II
CRYOGENIC RECEIVER THERMAL BUDGET

Coaxial Cables	412 mW
MMIC LNAs	104 mW
Radiation	57 mW
Bias Leads	27 mW
De-rating	120 mW
Margin	280 mW

TABLE III
ESTIMATED NOISE CONTRIBUTIONS TO SYSTEM PERFORMANCE

Antenna Temperature (@295 K)	53 (K)
OMT and Feed Loss (@295 K)	0.9 (dB)
Band Pass Filter Loss (@ 77 K)	0.6 (dB)
Low Noise Amplifier Gain (@ 77K)	28 (dB)
LNA Noise Temperature (@ 77K)	<20 (K)
Receiver Noise Temperature (@ 77K)	38 (K)
System Noise Temperature	167 (K)

V. Cooling

The cooler, which uses a dual-opposed piston design, provides 1 W of cooling capacity at 80 K with a 40 mW/K de-rating and was manufactured by Texas Instruments Incorporated, Dallas, TX. It weighs less than 4 lbs and consumes less than 55 W of power. Most of the heat load comes from the RF cables, although internal heat dissipation from the two MMIC chips and radiation are significant as well. Nine manganin bias leads are used to power the chips. The MMIC's and filters are housed in a polished oxygen-free high-conductivity copper package that has a thin Ni/Au finish. A vacuum can, machined with a diamond lathe, surrounds the package and attaches to the cooler flange using a neoprene O-ring. The can is evacuated to a pressure of about 10 mT. A thermal budget for the design is listed in Table II.

VI. Conclusions

The 0.9–m cryogenic ground terminal under development to support a dual 622-Mb/s link from a LEO spacecraft can provide a G/T of ≈20.6 dB/K at 19 GHz with a beamwidth of ≈1.1°. The total cost of the terminal without the pedestal was under \$30 000. Since the antenna elevation angle is at least 45°, the receiver noise performance dominates the overall system performance. By carefully engineering the terminal, the superior noise performance of the InP MMIC HEMT's can be exploited. A summary of the noise contributions is listed in Table III. The radio astronomy community is very familiar with cryogenic receiver technology, especially maser amplifiers and superconductor–insulator–superconductor (SIS) mixers. Also, NASA's deep-space network also employs maser and cooler pseudomorphic high electron-mobility transistor (pHEMT) devices. The receiver terminal developed here may find more widespread use in commercial satellite communications applications because of portability and low cost and complement alternative communications scenarios for future remote-sensing spacecraft.

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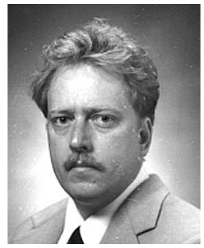

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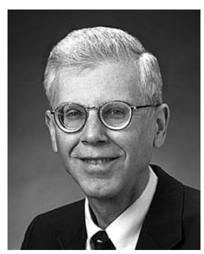

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