Jet Propulsion Laboratory/NASA Lewis Research Center Space Qualified Hybrid High Temperature Superconducting/Semiconducting 7.4 GHz Low-Noise Downconverter for NRL HTSSE-II Program

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(Invited Paper)

Abstract—**A deep space satellite downconverter receiver was proposed by Jet Propulsion Laboratory (JPL) and NASA Lewis Research Center (LeRC) for the Naval Research Laboratory's (NRL) high temperature superconductivity space experiment, phase-II (HTSSE-II) program. Space qualified low-noise cryogenic downconverter receivers utilizing thin-film high temperature superconducting (HTS) passive circuitry and semiconductor active devices were developed and delivered to NRL. The downconverter consists of an HTS preselect filter, a cryogenic low-noise amplifier, a cryogenic mixer, and a cryogenic oscillator with an HTS resonator. HTS components were inserted as the front-end filter and the local oscillator resonator for their superior 77 K performance over the conventional components. The semiconducting low noise amplifier also benefited from cooling to 77 K. The mixer was designed specifically for cryogenic applications and provided low conversion loss and low power consumption. In addition to an engineering model, two space qualified units (qualification, flight) were built and delivered to NRL. Manufacturing, integration and test of the space qualified downconverters adhered to the requirements of JPL class-D space instruments and partially to MIL-STD-883D specifications. The qualification unit has ~50 K system noise temperature which is a factor of three better than a conventional downconverter at room temperature. Commercial applications such as intersatellite links and V-SATS are envisioned to benefit by >3 dB link margin, or a factor of 2 in antenna size, from a future hybrid HTS/semiconducting cryogenic receiver employing new InP based HEMT LNA. In a spread spectrum communication network, the number of users per beam would more than double.**

I. Introduction

The DISCOVERY of the high temperature superconductor $YBa_2Cu_3O_{7-d}$ in 1987 followed by other ceramic superconductors brought in a rush to employ their exotic low microwave loss and finite penetration depth characteristics in the fabrication of new and radical breeds of microwave components. NRL's call for participation in the HTSSE-I program was the first serious attempt to develop HTS components for space applications. JPL participated in the NRL HTSSE-I program by delivering low pass filters. HTS passive components (such as filters, resonators, delay lines, ...) are superior to the conventional planar circuits in their performance and are also miniaturized. Active HTS devices are a promising future technology which requires further development. Semiconducting active devices, on the other hand, are mature with excellent performance in the areas of low noise amplifiers, and low conversion loss mixer elements. For a cryogenic application, the marriage between HTS passive components and semiconducting active devices provides the best solution.

The purpose of the HTSEE-II program was to demonstrate the functionality of HTS advanced devices and communication subsystems in space [1]. JPL and NASA LeRC joint participation in the NRL HTSSE-II program was made in an environment of cooperation governed by the issuance of a memorandum of understanding between NASA and NRL. The JPL/NASA LeRC team submitted a proposal to build a hybrid HTS/semiconducting low noise cryogenic receiver downconverter for NASA applications. A conventional deep space satellite receiver was bench marked for development. A frequency of 7.4 GHz was chosen based on the uplink frequency allocation of NASA's JPL Deep Space Network. The proposal was accepted for consideration by NRL. After successful delivery of a prototype unit to NRL (March 31, 1993), JPL/NASA LeRC were cleared for continued design, fabrication, integration, test, and delivery of two space qualified units. The qualification unit was delivered January 6, 1994 followed by a flight unit on July 8, 1994. Results of HTSSE-II program will enable spacecraft designers to evaluate the benefits of using HTS components in space communication links.

The delivered cryogenic low noise downconverter receiver units were intended for integration into the Advanced Research and Global Observation Satellite scheduled for launch in 1996

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by Lockheed Corporation. The units were qualified by JPL as class-D space instruments and adhered to some specific JPL requirements. The JPL team which was responsible for the integration phase of the project, also adopted some of the requirements of MIL-STD-883D which applies to the integration and test of hybrid microelectronics.

In this paper, we present the design and performance of space-qualified hybrid semiconducting/HTS 7.4 GHz cryogenic low noise receiver downconverter units which were delivered to NRL. Performance comparisons between the delivered units and conventional state-of-art receivers will be made. Advances in the relevant technologies subsequent to the technology freeze date for this project, promise improved performance for a future hybrid semiconducting/HTS receiver. Possible applications and market impacts of a future advanced hybrid MMIC/HTS receiver will be identified. In addition, we will discuss the issues concerning the integration of these units in accordance with the requirements of JPL class-D space instruments and in partial adherence to MIL-STD-883D.

II. Receiver Downconverter Design Rationale

The hybrid HTS/semiconducting cryogenic receiver downconverters were designed with a single market in mind. NASA provides an infrastructure of ground stations to track, monitor, command, and communicate with the Earth-orbiting and deep-space satellites. Deep-space probes have specifications which set them apart from commercial satellites. These include low bit rate communication transceivers, very low threshold command receivers, and ultra stable frequency transponders. The hybrid HTS/semiconducting receiver promises to satisfy the specific NASA needs. The hybrid HTS receiver was conceptualized after considering a portion of a deep-space transponder where the impact of HTS insertion seemed the most beneficial. The antenna and its associated sky noise temperature, and the preselect filter in the RF signal path establish a lower bound for receiver system noise. An HTS component with its inherent low microwave loss is a natural candidate for the construction of front-end preselect filter. A local oscillator in a transponder design needs to satisfy stringent requirements such as high stability, low jitter, low phase noise. As these characteristics are governed by the quality factor (Q) of the resonator, application of planar HTS resonators for the stabilization of the local oscillator seems advantageous.

III. Description of the Downconverter

A block diagram of the HTS downconverter is shown in Fig. 1. It consists of an HTS preselect filter, a cryogenic low noise amplifier (LNA) using High Electron Mobility Transistors (HEMT), a cryogenic diode mixer, and a cryogenic Field Effect Transistor (FET) oscillator with an HTS resonator. The HTS film is $YBa_{1.95}La_{0.05}Cu_3O_{7-d}$ (YBLCO) deposited only on one side of lanthanum aluminate ($LaAlO_3$) substrates.

Fig. 2 is a picture of the delivered qualification receiver. The white substrates are Al_2O_3 and are used in the conventional modules. The transparent substrates are typical of HTS circuits. The receiver components are integrated into a package machined from Kovar. The package is hermetically

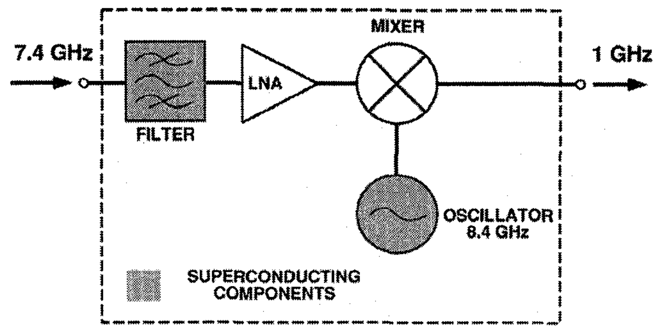

Fig. 1. The block diagram of the hybrid High Temperature Superconducting/semiconducting 7.4 GHz low-noise downconverter.

sealed for protection against hostile prelaunch and dock time environment. Cavity modes were considered for the design of the individual module compartments. A septum separates the two stages of LNA to minimize RF interference. The individual circuits are mounted on Kovar carriers which are attached to the housing using 0–80 screws and 0.001 inch thick indium foil shim for thermal sinking. Thermal analysis indicated that the temperature rise of HTS circuit in the vicinity of the oscillator device will not exceed more than 1 degree.

The description of the individual downconverter components follows.

IV. HTS Preselect Filter

The superconducting preselect filter is a microstrip circuit on a 15.0×7×0.51 mm $LaAlO_3$ substrate. The patterned microstrip conductor on the top surface is a thin film (~6000 Å typ.) of YBLCO ($T_c \sim$ 89–92 K, $J_c \sim 3 \times 10^6$ A/cm^2 @ 77 K). Our work has utilized ablation targets of nominal composition $YBa_{1.95}La_{0.05}Cu_3O_{7-d}$, because a small amount of La doping is reported to produce higher YBCO transition temperature [2]. We have found that the combination of working at relatively short target-to-substrate distances and using the La-doped YBCO target has resulted in better YBCO film quality and reproducibility with typical transition temperatures ranging from 89 to 91.5 K. Thin film of YBLCO was deposited by laser ablation at ~800°C and 100 mTorr of O_2 with a growth rate of ~3 Å/sec at 10 Hz laser repetition rate. An in-situ layer of gold was sputtered on cooled HTS film (<100°C) prior to air vent at 10 mTorr of Argon. Electrical contact pads were defined and ~4000 Å gold was evaporated by e-beam. The filter pattern was milled by 500 eV Ar ion while the substrate was on a water cooled stage. The in-situ layer of gold on YBLCO HTS thin film guarantees low contact resistance between the gold contact pads and HTS film. Additional gold at the contact pads improves bonding strength. Test bonding sites were placed along the edges of the substrate. Backside of the substrate consists of Nb (125 Å)/Cu (1 μ)/Au (300 Å) with copper providing the RF ground plane. Nb is a good adhesion layer and gold passivates the copper layer.

The filter is a four-pole parallel-coupled-line microstrip design with half-wavelength resonators. In this structure, the narrowness of the passband and the number of poles is constrained by size of the filter area. Six HTS filters, and a copper filter counterpart were fabricated and tested. One HTS

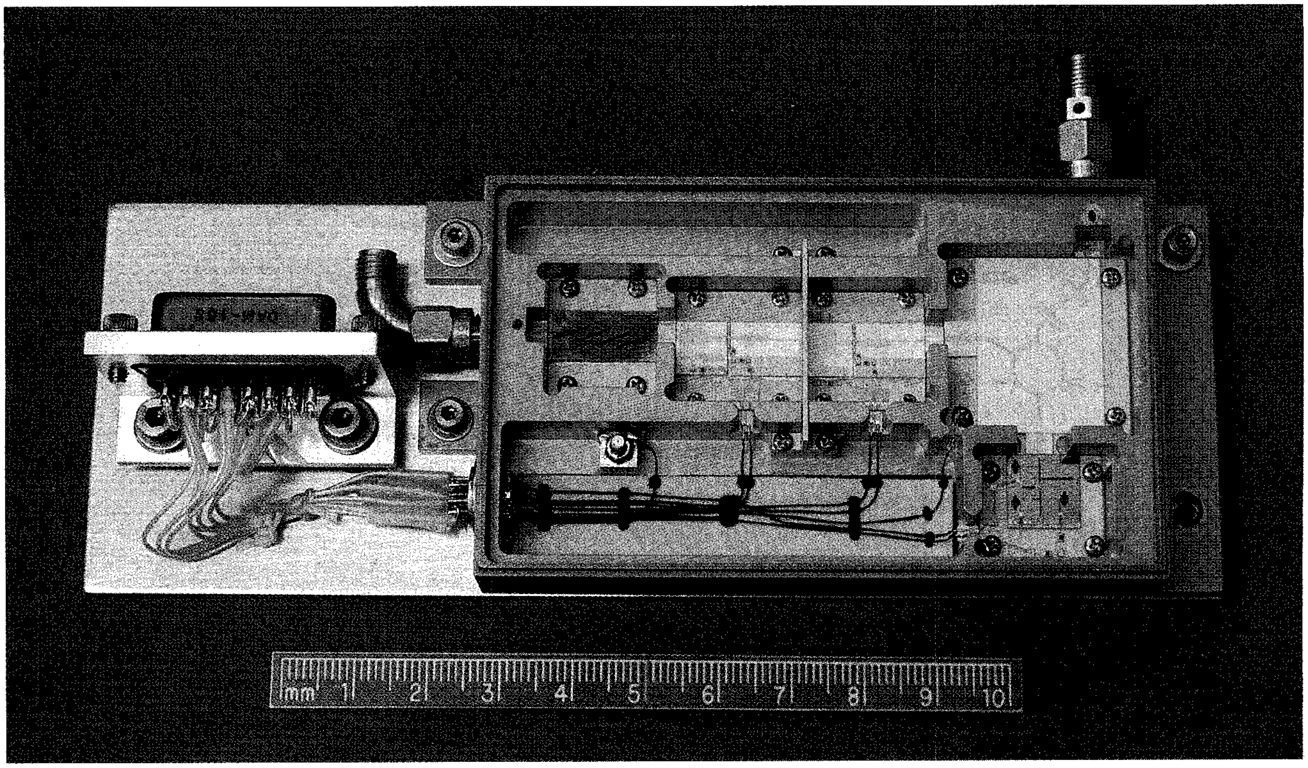

Fig. 2. A picture of the space-qualified qualification receiver prior to hermetic sealing. The white substrates are Al_2O_3 and the dark (actually transparent) substrates are $LaAlO_3$ which are used for HTS circuits.

filter provided poor results due to problems in making proper mechanical connections. All the remaining 5 HTS filters had a better performance than the Cu filter at 77 K (85 K) by 0.5–0.6 dB (0.4–0.6 dB). At 89 K, only one HTS filter performed worse than copper (this HTS filter was inferior to the rest of the HTS filters even at 77 K). Fig. 3 shows a typical response of the HTS 7.35 GHz filter, together with the performance of the counterpart copper filter, and the transmission of a gold microstrip calibration line on alumina all at 77 K. The estimated insertion loss for the HTS filter alone is 0.2–0.3 dB at 77 K, an improvement of over 0.5 dB compared to a copper film version of the filter at the same temperature. The simulation data (using EEsof Touchstone) is adjusted in Fig. 3 for better comparison. This adjustment was accomplished by use of 23.6 instead of 24 for the permittivity of the $LaAlO_3$ substrate, without correcting for thermal contraction.

V. Low Noise Amplifier

The LNA consists of two stages. Each stage of the flight/qualification (prototype) LNA units uses a GaAs-based Fujitsu FHX15X (Mitsubishi 4414C) HEMT chip device. The first stage is designed for optimum noise figure at cryogenic temperatures. The second stage is designed for gain and to flatten the response of the two stages together. It was found necessary in the case of flight units to use a septum to isolate the two LNA stages for higher stability and to eliminate cross-stage talk. The layout of the LNA is shown in Fig. 4. Each LNA uses microstrip circuitry with TiW-Au metallization on split alumina substrates assembled with Ablebond 84-1 LMI [3] on a Kovar carrier. A shim is placed in the gap separating the two substrates, grounded with the 84-1 silver epoxy, as the HEMT chip pedestal. The HEMT chip is also silver epoxied to the pedestal and baked at 150°C for an hour. HEMT chips were bonded to the bias microstriplines via 0.0005 inch gold wires.

Matching is performed for both stages by use of quarter-wave transformers. Bias is supplied at the gate by tying a high impedance 1/4-wave line to the transformer. Drain voltage is connected by 0.0005 inch gold wire bonds from the stabilizing resistor to the output matching section. A coupled-line section is placed at the output of each stage for blocking of dc voltages. The filter acts as a dc block for the amplifier input. Tuning pads were placed adjacent to transmission lines and wire bonds were tied from the transmission lines to appropriate pads to improve response.

The amplifier modules were tested at 77 K physical temperature prior to integration with other submodules. The flight LNA noise temperature measured at the refrigerator port, which includes the effect of refrigerator input coaxial cables and test fixture losses, was less than 44 K in the downconverter passband. Each connection included APC-7 hermetic feed-through (~0.3 dB loss), 0.141 inch semirigid stainless steel jacket coaxial cable (~0.16 dB loss), dc block (~0.11 dB loss) and an Eisenhart transition (~0.16 dB loss). The gain was 28 dB, with an estimated noise temperature of 21 K for the LNA alone.

VI. HTS Resonator Stabilized Oscillator

The local oscillator is a GaAs MESFET-based, reflection mode circuit implemented as a hybrid microwave integrated

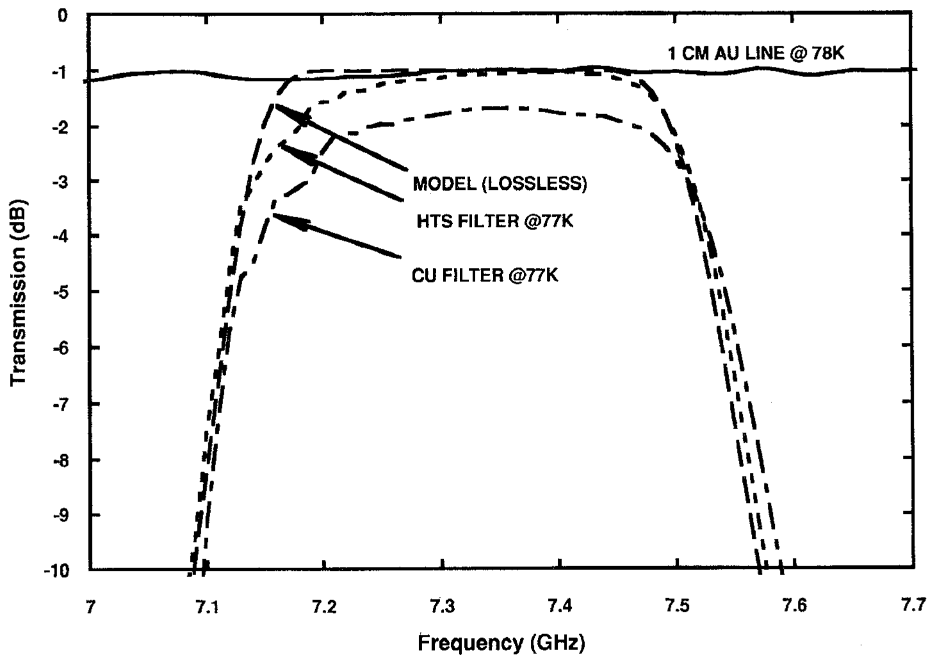

Fig. 3. A typical response of an HTS filter at 77 K together with the performance of a similar copper filter on $LaAlO_3$. The dashed line is the result of simulation of the filter performance by adjusting the dielectric constant to 23.6. The solid line is the transmission of the test fixture with a 50 Ohm gold line replacing the filters for reference.

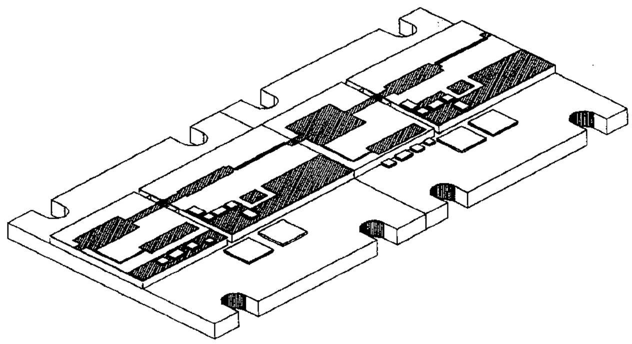

Fig. 4. Two stages of the 7.4 GHz low-noise amplifier with their circuit layouts. Each stage uses split alumina substrates with the HEMT device placed on a Kovar pedestal.

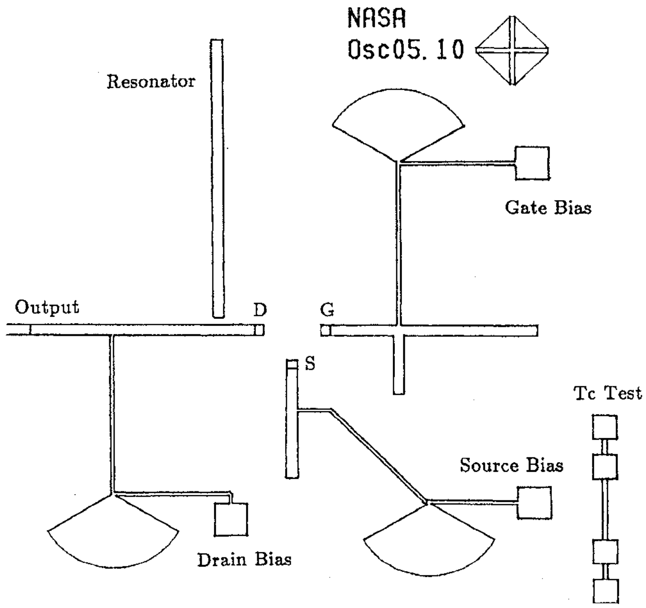

Fig. 5. A circuit layout for the 8.4 GHz HTS oscillator with a conventional MESFET.

circuit. The circuit (Fig. 5) consists of a single lanthanum aluminate substrate on which passive elements of the circuit (stabilizing resonator, reactive feedback elements, transmission lines, and dc bias lines) are realized as microstrip elements etched from a YBCO film deposited on the top surface. The HTS layers are as described previously for the preselect filter. The GaAs MESFET (Avantek ATF-13 100-GP1 chip), which is the active element of the circuit, is attached to the substrate using a conductive epoxy. One thousands of an inch gold bond wires connect the MESFET and the superconducting lines; gold contact pads sputtered in-situ on the superconducting lines provide low contact resistance. Chip capacitors and resistors mounted next to the substrate are used to filter and decouple the transistor bias.

The design of the oscillator represented a compromise between circuit performance and constraints for HTSSE-II. Design considerations for this oscillator included minimizing size for integration, minimizing power dissipation in the cryogenic package (to tens of mW), providing enough RF power to drive the mixer (0 to 3 dBm), and minimizing phase noise. Although an oscillator using a resonator in the transmission mode (a two-port resonator) should be less sensitive to load pulling, bias drift, and ripple, a design using a resonator in the reflection mode (a one-port resonator) was chosen to minimize complexity, size, and power dissipation. A linear resonator coupled to the output line was used.

The output of the oscillator is near 8.4 GHz with output power levels of up to +10 dBm (into a 50 Ω load). Typical

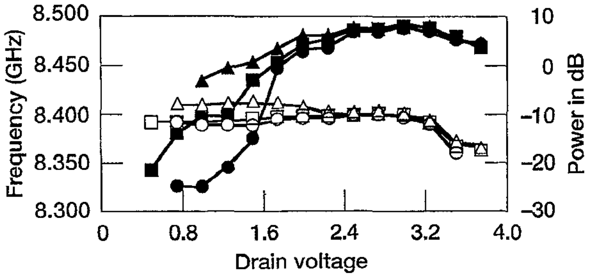

Fig. 6. Output power (filled signs) and frequency for the HTS local oscillator versus MESFET drain voltage as a function of the gate voltage (circles; −0.25 V, squares: −0.50 V, triangles: −0.75 V).

operating conditions for the oscillator when incorporated into the downconverter provide 0 to +3 dBm of output power with <50 mW of dc power dissipation. Because of variations in the $LaAlO_3$ substrates, the YBCO etching, and the YBCO material properties, the output characteristics of individual oscillators are not identical and the bias conditions for each oscillator must be individually tuned. Variations in the output frequency can be on the order of ±20 MHz from 8.4 GHz and are bias and temperature dependent. Bias dependence of output power and the oscillator frequency is plotted in Fig. 6. Phase noise performance of the oscillator is expected to be good, based on the high "Q" values of the superconducting resonator. Unloaded Q's approaching 6,000 have been obtained from the best resonators at this frequency.

VII. Mixer

The mixer (Fig. 7) is a hybrid microstrip circuit of TiW-Au metallization on an alumina substrate. The circuit is based on singly balanced hybrid ring design to minimize AM local oscillator noise and spurious signals and to conserve circuit area. The circuit area is 0.8 in^2, as opposed to 1.3 in^2 for a comparable single ended mixer design. Since the mixer is to be operated inside a cryostat, low mass is desirable to facilitate cooldown. A single-ended mixer design would use only one diode and hence half the local oscillator power, but the requisite filtering almost doubled the size relative to an equivalent single-balanced mixer. A double-balanced mixer would have higher conversion loss, but requires more power and its superior bandwidth was not required.

In order to minimize the downconverter power dissipation load on the spacecraft cold bus, the mixer was designed to operate under "starved" local oscillator (nominally 0 dBm). Low barrier beam-lead Si Schottky diodes (M/A Com MA40132) are used since the barrier potential is significantly lower than that obtainable with GaAs diodes. Diodes were evaluated to temperatures as low as ~ 50 K and no degradation in performance was observed. Integral quarter-wave coupled lines are used to block dc from the oscillator and LNA. A ceramic chip capacitor on the mixer's IF port blocks the passage of the bias voltage to the external connector. The hybrid ring circumference is centered at the LO frequency to minimize LO feedthrough to the RF port. Port to port isolation is good; ~ dB LO-to-RF, 43 dB LO-to-IF, and 37 dB RF-to-IF isolations. This prevents dynamic range reduction of the LNA. LO (sigma) port VSWR is 2.4:1. This poor return loss

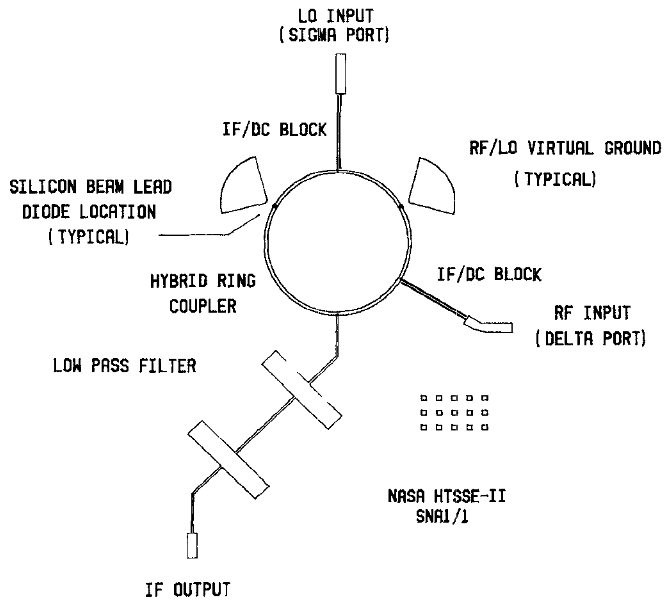

Fig. 7. A circuit layout for the cryogenic mixer. Integrated quarter-wave couplers are utilized in LO and RF inputs.

was corrected by a simple stub on the 50 ohm microstripline between the mixer and oscillator. (Diode impedance was estimated by pumping the mixer at the desired drive level and measuring the return loss at the alternate port with a network analyzer with the matching stub in place; the LO was well behaved).

Quarter-wave radial stubs were used to terminate the RF and LO signals. DC biases of the beam-lead diodes are adjusted for optimum ring diode port impedances to minimize conversion loss of the mixer. Reasonably good conversion loss (about 5.5 dB) was obtained.

VIII. Integration

Every module of the prototype HTS receiver was designed for the best performance at cryogenic temperatures. The issue of space qualification started with the development of the qualification and flight HTS receivers and power supplies. A preliminary review was held to discuss lessons learned in the development of the prototype receiver and to investigate the task plan for the development, integration, and test of the space-qualified units. Limited available time dictated minimum design changes. Nevertheless, a simpler HTS preselect filter design was chosen. HTS thin films fabricated at JPL Micro Devices Laboratory were to replace procured films from commercial HTS foundaries. The LNA development team adopted improved HEMT devices to decrease the system noise figure. A new housing material and design was chosen to provide hermeticity. Power supplies were added to the list of deliverables. The production of the HTS receiver modules and housings, the power supplies, and their integration and tests were now subject to JPL class-D space instruments [4] and MIL-STD-883D requirements (partial). The burden of adherance to the requirements were mostly in the integration and test phases of the flight units at the system level. We now describe the development of each individual module.

The individual circuits were mounted on Kovar carriers. The Kovar material procured was screened against γ to α transformation above 77 K (according to MIL-I-23 011C). The carriers were machined flat with $\pm$0.0005 in accuracy over their entire surfaces. They were gold plated (0.0001–0.0002 inch) according to MIL-G-45 204C Grade C Type II over 0.000 02–0.000 04 inch nickel flash, annealed to 350°F, and inspected for any sign of metal adhesion failure.

The HTS thin film of YBLCO was prepared as described before. In-situ deposition of a thin layer of gold guaranteed low contact resistance. The gold layer also protected the YBLCO film from subsequent photolithographic processing. No post-deposition annealing of the YBLCO films or gold contacts was performed. AC susceptibility transition measurements were performed to select suitable films for filter and oscillator circuit fabrications. The criteria for selection process were AC susceptibility onset transition temperature greater than 91 K and transition width less than 1 K. It was empirically determined that films which met these criteria performed well in microwave circuits.

Along with each $1\times1\,\text{cm}^2$ YBLCO film, a smaller "sister chip," was fabricated. The "sister chips," were tested for film adhesion. The normal-metal ground plane and gold contact layer on the YBLCO were subjected to a simple "tape test," in which an adhesive tape is applied to the film surface, then peeled off. If no metallization was removed by the tape, the HTS film was considered satisfactory.

In order to test the strength of wire bonding to the gold contact pads on the HTS films, gold wires or ribbons were bonded on the "sister chips," and pulled to break. Wire bond failures at its heels are indicative of improper settings for the bonding machine. Appropriate bonding machine settings were obtained after multiple trials and errors. Further failures occured at higher forces indicative of metallization adhesion strengths.

The HTS films were attached to flat Ni-Au plated Kovar carriers using silver-filled epoxies (Ablebond 84-1 LMI). The preselect filter was attached to an individual carrier. The oscillator circuit was attached together with the mixer onto a single common carrier (a small alumina substrate with a 50 ohm TiW-Au matching microstripline separates the two circuits). The GaAs MESFET chips were attached on HTS oscillator circuits with Ablebond 84-1 LMI. The curing of Ablebond 84-1 LMI was done according to the schedule of 1 hour at 150°C. This is one of the recommended curing schedules by the manufacturer [3]. Ablebond 84-1 if cured according to this schedule in air results in 0.26% Total Mass Loss (TML), 0.01% Collected Volatile Condensable Material (CVCM), and 0.12% Water Vapor Retained (WVR) [5]. This silver epoxy therefore satisfies NASA standards for space-qualified epoxies [5] (TML $<$ 1% and CVCM $<$ 0.1%). In addition Ablebond 84-1 LMI adhesive meets the requirements of MIL-STD-883C, method 5011 as reported by the manufacturer [3] (MIL-STD-883D method 5011.2 provision 3.5.3 governs outgassed moisture to be less than 0.5% V/V, the nature of other gaseous species present in quantities over 0.01% V/V shall be reported). Corrosive contents of the outgassed materials are important in a hermetically sealed package.

Early in the project. We studied the effect of curing schedule on HTS thin films procured from an HTS commercial foundary. Metallic pads were fabricated on the superconducting lines by e-beam evaporation of silver and gold with subsequent annealing of the HTS film in oxygen at 425°C for 50 min. Effects of curing cycles on the transition temperature of the HTS film in combination with different etchants, annealing for 1 hour @ 150°C in air, and 24 hours @ 100°C in low vacuum was studied. The results indicated that for a HTS thin film of $T_c \sim 90$ K, the degradation was $\sim$0.5 K maximum. In one case, for a lower quality HTS film with initial $T_c \sim$ 88 K, T_c dropped by more than 8 K maximum. In our flight receivers, we used HTS films with in-situ gold layer which requires no annealing.

Alumina with TiW-Au metallization was used for the LNA substrates. Some procured substrates were screened with annealing to 350°F by manufacturer. They were inspected for any sign of metal adhesion failure. LNA circuits consist of two sections which were mounted on a Kovar carrier with Ablebond 84-1 LMI allowing a small gap in between. A piece of Kovar (0.015 $\times$ 0.003 inches) was cut and glued to the carrier in the gap with the same epoxy. This piece functions as a pedestal for the HEMT device. Additional chip capacitors and chip resistors were mounted to the carrier to provide bias voltages for the HEMT's. Ablebond 84-1 LMI was used for all LNA assemblies. The epoxy was cured in an oven according to a recommended manufacturer curing schedule. A Fujitsu FHX-15X was placed on top of the pedestal with 84-1 LMI epoxy and annealed for an additional curing schedule time. All HEMT's, resistors, capacitors, and TiW-Au circuit elements were bonded using 0.0007 inch gold wire. The wire bonds were pull tested destructively on additional test circuits. The pull tests satisfied 2.0 gram minimum failure strength as required by MIL-STD-883D method 2011.7.

LNA stages were tested at 77 K in a fixture similar to the final assembly housing. A dc block was used for the tests to prevent bias voltages connecting to the input port. Noise temperature and gain were measured in laboratory using a Berkshire Technologies [6] supply. Wire bonds were added to LNA $\lambda/4$ transformation stage to tune the circuit for the best noise figure. The gate voltages and drain currents of the two LNA stages were adjusted for the optimum performance. The LNA first stage provides front-end low noise figure while the second stage is tuned for maximum gain. When a satisfactory performance was achieved, a single LNA module was delivered for integration.

The GaAs MESFET transistor contacts to the oscillator HTS circuit were made with 0.001 inch gold wire. The oscillator circuit was later populated with chip capacitors and resistors as described above. The oscillator was tested alone at 77 K and its stability and phase jitter were investigated qualitatively [7]. Bias and temperature dependences were also measured [7]. The best unit was integrated with a mixer circuit and a 50 ohm transition microstripline on a single Kovar carrier. The overall performance of mixer/oscillator module was tested one more time. Due to high VSWR of mixer LO port, a stub microstripline was added to the 50 ohm transition line between the oscillator and mixer circuits. Wire bond jumpers protected the diodes during the assembly and bonding process. The best performance module was delivered for integration in the final space-qualified units. NASA LeRC performed vibration tests at the module level before its delivery.

All the modules were integarted in a Kovar housing. The Kovar material was additionally screened at JPL against γ to α transformation above 67 K (MIL-I-23011C). This transformation results in local deformation which could cause loss of hermeticity if it occurs in the vicinity of one of the soldered-in feedthroughs. The housing was gold plated in the same procedure as for the carriers. The weld seam lips on the housing and the lid were masked before this process to avoid gold plating which would have interfered with the hermetic sealing process.

A hermetic dc connector was soldered in with Sn-63 at 200°C. Space-qualified magnet wires were laid down and dressed over a 10 mil thick alumina substrate on the housing floor using Ablebond 84-3 nonconducting epoxy. This epoxy also satisfies NASA outgassing requirements as well as adhering to MIL-STD-883C method 5011 specifications.

"K connectors™" [8] were used for the RF input and IF output of the receiver housing. Hermetic K-connector glass bead feedthroughs were soldered in place with Sn-62 and the housing was leak-checked after three thermal cycles between room temperature and 77 K.

Fifty ohm TiW-Au microstriplines on alumina substrates were prepared as RF transition sections between modules. Additional CrCu-Au lines were used as dc standoffs. These were epoxied to the housing floors using silver epoxy Ablebond 84-1 LMI and cured according to a manufacturer recommended schedule. The bias magnet wires were soldered down to make appropriate connections.

The modules were screwed down in their cavities inside the receiver housing with 0.001 inch indium foil shims between the housing floor and each module carrier for good thermal conduction. Space-qualified #0–80 screws were torqued to 14 inch-Oz.

One thousandth of an inch diameter gold wire and 0.0005 $\times$ 0.003 inch gold ribbon were used for RF and dc connections. Two wires or ribbons for each connection were made for dc connections and RF connections between substrates to avoid single point failures. A single ribbon was silver-epoxied between each of the "K connector™" feedthrough pins and a microstrip line at the RF input and the IF output. Samples of 10 bonds were tested for each type of bond and pulled destructively, except for the bonds to the HEMT's and FET where fewer than 10 samples were available. Bonds to the substrates passed pull tests (per MIL-STD-883D method 2011.7), of 2.0 gram for 0.0007 inch diameter gold wire, 2.5 gram for 0.001 inch diameter gold wire, and 4.5 gram for 0.0005 $\times$ 0.003 inch gold ribbon. Bonds made to gold bonding pads on YBLCO deposited using the in-situ process described above passed these bonding tests more readily than bonds to the commercial FET's.

At this stage, the integrated 7.4 GHz HTS receiver was tested at 77 K and optimized noise temperature and gain were obtained by tuning of the bias voltages and currents. The receiver was removed from the cryogenic set-up and all inside screws were retorqued and staked with epoxy 2216 [9]. Some of the long ribbons utilized for dc or RF connections were staked also with epoxy 2216 cured for 24 hours at room temperature to satisfy NASA outgassing requirements [5]. The use of this epoxy was minimized because it does not satisfy MIL-STD-883. The lid was placed after precap quality inspection of the housing. After the capped enclosure was vacuum baked at 100°C for 24 hours, the housing was laser sealed under mostly helium atmosphere according to a suggested modification to MIL-STD-883D method 1014.9 [10]. The deviation is as a result of filling the enclosure with helium gas instead of argon. Standard formulas which calculate the leak rate of a hermetic package after helium bomb are no longer valid. The HTS receiver was tested again after being sealed. Meanwhile, space-qualified power supplies were being built at JPL. The construction, integration, and tests of the power supplies adhered to the requirements of JPL class-D instruments [4]. The HTSSE-II power supply provides necessary voltages for five active devices inside the sealed downconverter. A total of seven voltages are needed including the drain and gate voltages for the LNA HEMT's, the oscillator MESFET, and the mixer diodes. In addition, the power supply has a voltage sequencing feature for the HEMT devices. The LNA gates were servo controlled to maintain the LNA drain currents. Devices were also current-limited. The best performances of the HTSSE-II downconverters were obtained through optimization of the bias voltages. The tests showed that variations in the bias voltages within $\pm 10\%$ of the optimum settings do not change the performances of our downconverter significantly. Nevertheless, the HTSSE-II power supply was designed such that the voltages delivered at the downconverter pins were independent of voltage drops across the wires between the power supply and the downconverter. This precaution was undertaken because we did not know the resistances *a priori*. The temperature profile and physical length of the wires running between the cold bus and the ambient platform was unknown. We have utilized sense wires on the voltages provided to the LNA drains, the oscillator drain, the mixer and common to guarantee the voltages delivered were exactly the optimized values. This led us to have a total of 12 wires connecting to the downconverter, and resulted in some concern about the heat load for the cold bus. The power supply and HTS receiver were integrated and tested together. Potentiometers in the power supply were replaced with fixed resistors. Both HTS receiver and power supply qualification and flight units were tested against NRL supplied environmental requirements (vibration and thermal vacuum cycling). Each unit was tested after each single change to guarantee early detection of failures.

Finally after 56 hours operation, 16 cycles to cryogenic temperatures, and 44 on-off switchings the flight receiver and power supply were delivered to NRL.

IX. HTS Receiver Performance

The best performance of the units was obtained for the qualification receiver. Noise temperature of 50 K and gain of 18 dB was obtained at external refrigerator ports as is

TABLE I
INTERMODULATION CHARACTERISTICS OF THE FLIGHT HTS RECEIVER *vs* RF INPUT POWER

	Frequency Intermodulation Response (dBm)													Frequency (GHz)
Input RF Power	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	7.4
Output IF Power	-70 8	-66.8	-61.17	-56.5	-51.33	-46.17	-41.17	-36 33	-31	-25 67	-21.17	-16 17	-11.33	1.016
2xIF										-70.5	-60.67	-51.33	-42.33	2.033
RF Leakage						-68 17	-66 87	-61.5	-57.17	-52.5	-47.33	-42.83	-37.83	7.399
LO Leakage	-26.67	-27.33	-26 67	-26.67	-26.67	-27	-26 67	-26.83	-26.67	-26.67	-26.5	-26.83	-26.5	8.416
LO+RF *											-58.87	-55.17	-50.17	15.816
LO+2xRF *												-57	-50.17	23.216
2xLO+RF *										-52.67	-47.83	-43.67	-38.33	24.233
3xLO *	-24.17	-25	-24.33	-24.5	-24.17	-24.33	-24 17	-24.17	-24 17	-24 17	-24 5	-24.33	-24.33	25.249
* Power not calibrated														

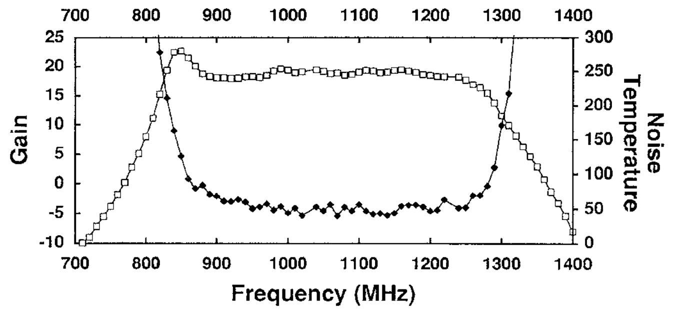

Fig. 8. Final electrical performance of the qualification HTS receiver as a function of RF input frequency as determined by its noise measurement.

illustrated in Fig. 8. For the flight unit, we obtained noise temperature of 76 ± 6 K and gain of 15.3 ± 1.5 dB in the IF frequency range of 950–1250 MHz. The nonlinearity of the flight receiver was tested against input power levels. At input power of −40 dBm, deviation from linear behavior starts with appearances of higher frequency harmonics. Table I represents the intermodulation characteristics of the flight receiver.

The performance of the hybrid HTS/semiconducting 7.4 GHz downconverter can be compared with the state-of-art conventional receiver. A prototype deep space receiver uses a front-end filter with 0.73 dB insertion loss. This receiver offers a system noise temperature of 129 K and 27 dB gain at room temperature. The noise temperature of our qualification HTS receiver was 50 K when operating at 77 K ambient temperature. Total power consumption was only about 70 mW. Cooling of the state-of-art conventional receiver will most definitely improve its performance.

A future hybrid HTS receiver can benefit from the advantages of the new InP based HEMT devices. A low-noise amplifier based on InP technology can offer ~7 K noise and ~28 dB gain. The noise temperature of a future hybrid HTS receiver can reach 31 K. For comparison with the conventional receivers, we have considered two applications:

1) For a hypothetical communication between a Low-Earth-Orbit (LEO) and a Geostationary-Earth-Orbit (GEO), the noise temperature of a system with the HTS receiver is 31 K. This will improve the signal-to-noise ratio by 3 dB which directly translates to decreasing the size of the receiver antenna or the transmitter power by half.
2) In a Very Small Aperture Terminal (VSAT) application, the future hybrid HTS receiver can be used inside a cryostat. In the cryogenic settings and with losses of cryogenic coaxial cables used for interfacing the receiver to ambient temperature, total noise temperature of the receiver is 41 K. This will still improve the data rate by a factor of 2. If one deals with a Spread-Spectrum Multiple-Accessing communication scheme, due to the inherent nonlinear nature of the link, the number of users per beam can more than double as a result of use of the HTS receiver on VSAT's.

X. CONCLUSION

We have delivered two space qualified hybrid HTS/semiconducting 7.4 GHz low-noise downconverter receivers to NRL's HTSSE-II program. The qualification unit has a noise temperature of 50 K when operating at 77 K. This represents improvement over state-of-art conventional receivers. A future hybrid HTS receiver using InP based HEMT technology can offer substantial benefits to the commercial communication industry in applications such as intersatellite-link and VSAT's.

In continuation of this project, a TRW/NASA LeRC/JPL team has devised an experiment to validate a miniature, high performance receiver that blends three complementary technologies; mechanical refrigerators, HTS, and PHEMT Monolithic Microwave Integrated Circuits (MMIC). Specifically, a HTS band pass filter, InP MMIC amplifier, HTS-sapphire resonator stabilized local oscillator (LO), and a miniature pulse tube cooler will be integrated. The cooled 20 GHz downconverter will be integrated onto the Space Shuttle. A signal will be transmitted to the receiver via the Advanced Communication Technology Satellite. The bit error rate (BER) will be measured in situ. The receiver is also equipped with a radiometer mode so that experiment success is not totally contingent upon the BER measurement. In this mode, the receiver uses the Earth and deep space as a hot and cold calibration source, respectively. The experiment closely simulates an actual cross-link scenario. Since the receiver performance depends on channel conditions, its true characteristics would be masked in a terrestrial measurement by atmospheric absorption and background radiation. Furthermore, the receiver's performance depends on its physical temperature, which is a sensitive function of platform environment.

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REFERENCES

[1] M. Nisenoff, J. C. Ritter, G. Price, and S. A. Wolf, "The high temperature superconducting space experiment: HTSSE I-components and HTSSE II-subsystems and advanced devices," *IEEE Trans. Appl. Superconduct.*, vol. 3, no. 1, pp. 2885–2890, Mar. 1993.

[2] R. G. Buckley, D. M. Pooke, J. L. Tallon, M. R. Presland, N. E. Flower, M. P. Staines, H. L. Johnson, M. Meylan, G. V. M. Williams, and M. Bowden, "Ca and La-substitution in $YBa_2Cu_3O_{7-d}$ and $Y_2Ba_4Cu_7O_{15-d}$ and $YBa_2Cu_4O_8$," *Physica C*, vol. 174, pp. 383–393 1991.

[3] Ablestik Laboratory, Rancho Dominguez, CA 90221; Ablebond 84-1 LMI data sheets.

[4] JPL Publication D-8966; JPL Standard for Flight Instrument Classifications and Product Assurance Requirements.

[5] NASA Ref. Pub. 1124 Rev. 2, "Outgassing data for selecting spacecraft materials," NASA Goddard Space Flight Center, 1990.

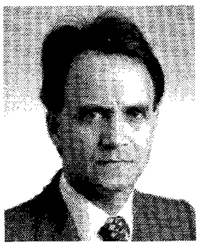
[6] Berkshire Technologies, Inc., Oakland, CA.

[7] F. A. Miranda, C. M. Chorey, R. R. Romanofsky, and K. B. Bhasin, "Space qualified hybrid superconductor/semiconductor planar oscillator circuit," *Symp. 187th Meet. Electrochemical Soc.*, Reno, NV, May 21–26, 1995.

[8] Wiltron Company, Morgan Hill, CA.

[9] 3M Adhesives, Coatings and Sealers Division, St. Paul, MN.

[10] A. DerMarderosian and V. Gionet, "Package integrity measurement technology and quality assurance," Raytheon Co. for Rome Lab., RL-TR-93-159, Aug. 1993.



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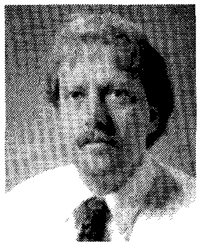

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Chris M. Chorey, photograph and biography not available at the time of publication.

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