Low-Noise Hybrid Superconductor/Semiconductor 7.4 GHz Receiver Downconverter for NASA Space Applications

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ABSTRACT

A low-noise microwave receiver downconverter utilizing thin-film high-critical-temperature superconducting (HTS) passive circuitry and semiconductor active devices has been developed for use in space. It consists of an HTS pre-select filter, a cryogenic. low-noise amplifier, a cryogenic mixer, and a cryogenic oscillator with an HTS resonator. The downconverter converts a 200 MHz wide band centered around 7.35 GHz to a band centered around 1.0 GHz. When cooled LO 77 K, the downconverter plus cables inside a cryogenic refrigerator produced a noise temperature measured at the refrigerator port of approximately 50 K with conversion gain of 18 dB.

1. INTRODUCTION

Low-loss thin-film passive microwave circuits are among the. first practical applications for high-critical-temperature (high-T_c) superconductors, utilizing the high quality HTS (high-T_c superconductor) films which can be grown as epitaxial films on suitable substrates. Active FITS devices are a promising future technology which require further development. In contrast, active semiconductor devices wiLh impressive performance (which can improve with cooling) are readily available commercially. Hybrid circuits which take advantage of the low 1os.ws and high quality factors ("Q'*) of HTS films in critical places and the advanced functionality and performance of modern semiconductor devices are a natural step in the quest for high-performance microwave circuits.

This work is a joint project conducted by two NASA centers, the Jet Propulsion Laboratory and the NASA Lewis Research Center. to develop a low-noise microwave receiver downconverter for the High Temperature Superconductivity Space Experiment, phase 11 (HTSSE-II) conducted by the Naval Research Laboratory (NIll,). The objective of HTSSE-II is to demonstrate the functionality of HTS advanced devices and subsystems in space. [1] Results of the HTSSE program will enable spacecraft designers to evaluate the benefits of using HTS components. The HTSSE-II package is to be integrated into the Advanced Research & Global Observation Satellite (ARGOS) scheduled for launch in September 1995. Much of the effort in developing the downconvertcr described here was in implementing fabrication and construction Techniques which can survive space qualification.

2. DESCRIPTION OF THE DOWNCONVERTER

The HTS downconverter is shown in Fig. 1; the block diagram is shown in Fig. 2. It consists of an HTS pre-select filter, a cryogenic low-noise amplifier (LNA) using HEMTs (High Electron Mobility Transistors), a cryogenic diode mixer, and a cryogenic FET oscillator with an I-ITS resonator. The local oscillator (LO) is 8.4 GHz and mixes with the input signal to produce the intermediate frequency (IF) output around 1 GHz. The. input frequency band is 7.25 to 7.45 GHz, which is near certain NASA uplink frequencies used for deep space communications. The 8.4 GHz oscillator frequency corresponds to a downlink transmission frequency and is typical of the LO in a deep space transponder. Although a spacecraft transponder is considerably more complex than this downconverter subsystem, the components to be integrated and the necessary integration techniques are representative of spacecraft requirements and would form a basis for introducing HTS material into other portions of a transponder subsystem.

Introduction of HTS material into the pm-select filter reduces losses in front of the LNA to improve the noise figure significantly compared to a filter of normal metal film. An HTS resonator provides a higher "Q for the oscillator, producing a more stable frequency output and lower phase noise than a lower "Q" normal metal film resonator could,

The layout of the downconverter is shown in Fig. 1. The HTS film is $YBa_{1.95}La_{0.05}Cu_3O_{7-\delta}$ (YBLCO) deposited on lanthanum aluminate ($LaAlO_3$) substrates. In Fig. 1 the YBLCO is black with some gold pads: the transparent lanthanum aluminate substrates appear darker than the white alumina substrates in the photograph because of the ground plane metallization on their bottom surfaces. The LNA and mixer circuits use gold film on alumina substrates. The receiver components arc integrated into a single hermetic package designed for space qualification and minimal intra-cavity RF interference. The package is machined from Kovar (ASTM F] 5 alloy) and nickel- and gold-plated. Descriptions of the individual downconverter components follow.

2.1. Superconducting pre-select filter

The superconducting pre-select filter is a microstrip circuit on a 15.0 x 7 x 0.51 mm lanthanum aluminate substrate. The patterned microstrip conductor on the top surface is a thin film of superconducting YBLCO. Low-resistance gold contact bonding pads arc deposited over the YBLCO (using an in-situ process) at the input and output, and at test bonding sites along the edges of the substrate. The ground plane on the bottom surface of the substrate is Nb-Cu-Au metal film.

The filter is a 4-pole parallel-coupled-line microstrip design with half-wavelength resonators (Fig. 3). The center frequency is 7.3S GHz with a -3-dB bandwidth of 400 MHz. In this structure, the narrowness of the passband and the number of poles is constrained by the desired area of the filter, The estimated insertion loss for the HTS filter alone is 0.2 to 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.

2.2. Low-noise amplifier (LNA)

The LNA consists of two stages, each using a GaAs-based Fujitsu FHX15X HEMT (High Electron Mobility Transistor) 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. The design of the LNA is shown in Fig. 4. It uses microstrip circuitry with TiW-Au metallization on alumina substrates.

Matching is performed for both stages by usc of quarter-wave transformers. Bias is supplied at the gate by tying a high impedance l/4-wave line to the transformer. Drain voltage is connected by wire bond 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 sub-modules. The noise temperature measured at the refrigerator port, which includes the effect of refrigerator input coaxial cables and test fixture 1os.scs, was less than 44 K in the downconverter passband. The gain was 28 dB.

2.3. Superconducting Oscillator

The local oscillator is a GaAs MESFET-based, reflection mode circuit implemented as a hybrid microwave integrated 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 an HTS film deposited on the top surface. The conductor layers are as described for the pre-select filter. The GaAs MESFET (Avantek ATF-13100-GP1 chip), which is the active element of the circuit, is attached to the substrate using a conductive epoxy. Gold bond wires connect the MESFET and the superconducting lines; gold contact pacts sputtered on the superconducting lines provide low resistance contact. Chip capacitors and resistors mounted next to the substrate are used to filter and de-couple 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 row), providing enough RF power to drive the mixer (O to 3 dBm), and minimizing phase noise. Although an oscillator using a resonator in the transmission mode (a 2-port resonator) should be less sensitive to load pulling, and bias drift and ripple, a design using a resonator in the reflection mode (a l-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 operating conditions for the oscillator when incorporated into the downconverter provide O to +3 dBm of output power with <50 mW of DC power dissipation. Because of variations in the I.aAlO3 substrates, the HTS etching, and the I-ITS 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 oft 20 MHz from 8.4 GHz and are bias and temperature dependent. Phase noise performance of the oscillator is expected to be good, based on the high "Q" values of the superconducting resonator. Measured "Q" values for resonators of similarly prepared films over a gold ground plane lie in the range of 4000.

2.4. Mixer

The mixer (Fig. 6) is a hybrid microstrip circuit of gold metallization on an alumina substrate. Low-barrier Si Schottky diodes with beam-leads (M/A COM MA40132) arc used. The circuit is a balanced mixer design using a hybrid ring. The diodes arc biased for cryogenic operation with a low LO (local oscillator) requirement.

In order to minimize the downconvertcr power dissipation load on the spacecraft cold buss, the mixer was designed to operate under "starved" LO conditions. Low-barrier silicon diodes arc used since the barrier potential is significantly lower than that obtainable with GaAs diodes. (The higher the barrier potential, the greater the LO power require. d,) Diodes were evaluated to temperatures as low as 50 K and no degradation in performance was observed. DC bias is required to compensate for the shift in the diode I-V characteristic as the diode is cryogenically cooled. Power consumed by the mixer is only about 1 mW.

A single-brrlanccd mixer design was chosen to minimize size. A single-ended design would usc only one diode and hence half the LO power, but the requisite filtering almost doubled the size relative to an equivalent single-balanced mixer. The single-balanced mixer also provides inherent rejection of AM noise as well as even-order spurious responses. A double-balanced mixer would require twice the LO power, have higher conversion loss, and occupy more substrate area The superior bandwidth of the double-balanced approach was not required.

Integral quarter-wave coupled lines are used to block DC from the oscillator and amplifier. The hybrid ring circumference is centered at the LO frequency to minimize LO feedthrough to the RF port. DC bias provides some tuning capability since VSWR (a measure of reflection) is a function of diode port impedance, not hybrid coupler topology.

3. FABRICATION ANI) INTEGRATION

The superconducting circuits, both the filter and the oscillator, are microstrip circuits on individual lanthanum aluminate ($LaAlO_3$) substrates. The patterned microstrip conductor on the top surface is a thin film of superconducting YBLCO. Low-resistance gold contact bonding pads arc deposited *in situ* on the superconducting YBLCO. The ground plane on the bottom surface of the substrate consists of a niobium/copper/gold trilayer film.

The YBLCO film was deposited by laser ablation onto polished $LaAlO_3$ substrates at -800 C and 200-500 milliTorr of oxygen. The average YBLCO film thickness was 0.6 pm. After the. film was allowed to cool and prior to air exposure, the YBLCO film was coated with 1000 A of gold by sputter deposition in 10 milliTorr of argon. The gold layer protected the YBLCO film from subsequent photolithographic processing and formed low-resistance bonding contacts to the YBLCO film. No post-deposition annealing of the YBLCO films or gold contacts was performed,

AC susceptibility transition measurements were performed to select suitable films for circuit fabrication. The apparatus consisted of a mutual inductance cell with astaticly wound coils. For these circuits, the following criteria were established to select the films. (1) The real component of the inductance must go completely to zero, i.e., fully screening one coil from the other. (2) The transition onset must be greater than 91 K. (3) The width of the transition must be less than 1 K wide, determined by the full width of the peak in the imaginary part of the mutual inductance. It was empirically determined that films which met these criteria performed well in microwave circuits while those that did not meet these criteria did not perform as well in circuits.

The YBLCO circuits were patterned with a photoresist mask and argon-ion milling. Additional processing was performed to increase the final gold contact thickness to 4000 A and to remove unwanted gold outside the contact areas. The normal-metal ground planes were deposited by sputtering in 10 milliTorr of argon. The thickness of the niobium, copper, and gold films *were* 125 A, 1 μm and 300 A, respectively.

Smaller "sister chips, " which were fabricated in parallel with each circuit chip, 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 adhesive tape is applied to the film surface, then peeled off. Successful adhesion was established as no removal of the metal film. In addition, loops of gold wire or ribbon *were* bonded to the gold on the YBLCO and pulled to test the breaking strength of the bonds.

The circuits were constructed as sub-modules attached to flat Ni-Au-plated Kovar carriers using silver-tilled epoxy. The filter and each LNA stage were attached to individual carriers. The oscillator and mixer were attached to a single common carrier together. Alumina with TiW-Au metallization was used for Lhe LNA and mixer substrates and RF interconnects between sub-modules. Alumina with Cr-Cu-Au metallization was used for DC interconnects to allow both soldering and thermosonic gold-ribbon bonding. Some procured substrates were screened with annealing to 350°F by the manufacturer.

The sub-modules arc integrated in a Ni-Au-plated Kovar housing which will be hermetically scaled to make the downconverter follow requirements of MIL-STD-883D for hybrid microelectronics. Kovar used for the downconverter housing and carriers were screened against γ to α transformation above 67 K (according to MIL-I-23011C). This transformation results in local deformation which could cause loss of hermeticity if it occurs in the vicinity of onc of the soldered-in feedthroughs. The Kovar carriers and housing were gold- plated according to MIL-G-45204C Grade C Type II over 0.00002 to 0.00004 in. nickel flash (per QQ-N-290A) and annealed to 350°F.

"K connectors™" (Wiltron Company) were used for the RF input and IF output of the downconverter housing. Hermetic K-connector glass bead feedthroughs and a hermetic DC connector were soldered in and the housing was leak-checked after three thermal cycles between room temperature and 77 K.

Substrates were attached to carriers, and FET chips and bias elements (chip capacitors and resistors) were mounted cm the substrates 01 Lhe carriers, using Ablebond® 84-1 LMI (Ablestik Laboratories) silver-filled cpox y and cured at 150°C for 1 hour. This adhesive satisfies NASA requirements for outgassing with Total Mass Loss (TML) of 0.26% and Collected Volatile Condensable Materials (CVCM) of 0.01%, and satisfies MIL-STD-883D method 5011.2.

The devices and and bias chips were connected by gold wire or ribbon bonding. 0.7 mil and 1 mil diameter gold wire and 0.5 x 3 r-nil 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 connection 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 HEMTs 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 g for 0.7 mil diameter gold wire, 3.0 g for 1 mil gold wire, and 4.5 g for 0.5 x 3 mil 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 FETs.

Sub-modules were screwed down in their cavities inside the downconverter housing with 0.001 in. indium foil between the housing floor and each sub-module carrier for good thermal conduction. Space-qualified screws were torqued to 14 oz-inch.

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4. RESULTS AND CONTINUING WORK

The integrated 7.4 GHz receiver downconverter was tested successfully at 77 K and the noise temperature and gain were obtained. The noise temperature was approximately 50 K and the gain approximately 18 dB in a 200 MHz bandwidth around an IF center frequency of 1.02 GHz; this noise temperature and gain include the effects of losses in coaxial cables inside the refrigerator. The minimum noise temperature was 46 K. RF input of -40 dBm caused observable spurious responses at twice the IF and the difference frequency $f_{LO}-f_{IF}$. Fig. 1 depicts the receiver downconverter qualification unit for HTSSE-II with its sub- modules.

The integrated receiver downconverter will be vacuum baked for 24 hours at 100°C and then sealed by laser welding. The hermiticity will be tested according to MIL-STD-883D method 1014.9 (coarse and fine levels). The sealed package will then be vibrated according to the expected spacecraft vibration profile. Finally, the receiver will be integrated with a space-qualified power supply and delivered to NRL.

5. CONCLUSION

This work on a hybrid superconductor/scn~ iconductor receiver downconverter shows that HI'S passive microwave circuitry can be combined with semiconductor devices using processes which meet space qualification standards to produce subsystems with state-of-the-art perform.ante.

6. ACKNOWLEDGMENTS

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7, REFERENCES

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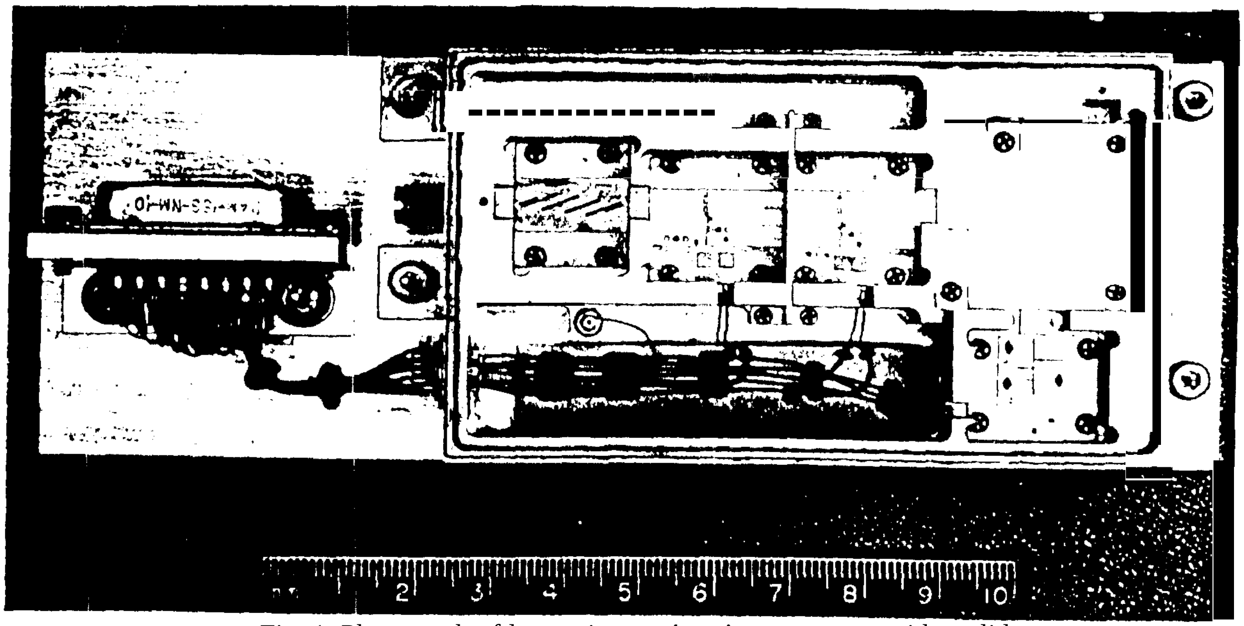

Fig. 1. Photograph of low-noise receiver downconverter without lid.

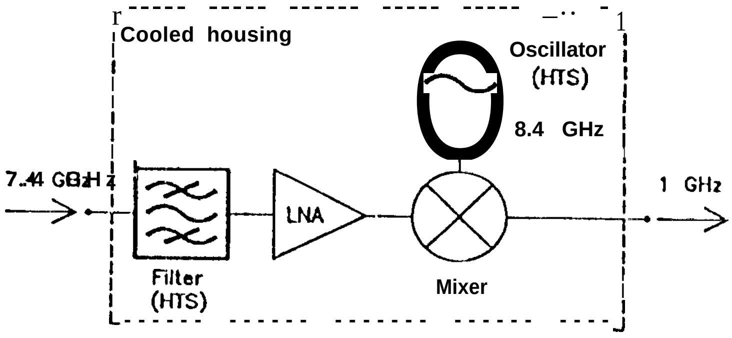

Fig. 2. Low-noise receiver downconverter block diagram.

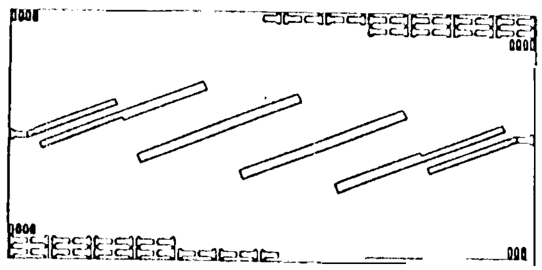

Fig. 3. Superconducting filter design for YBLCO on 15.0 x 7.5 x 0.51 mm lanthanum aluminate substrate.

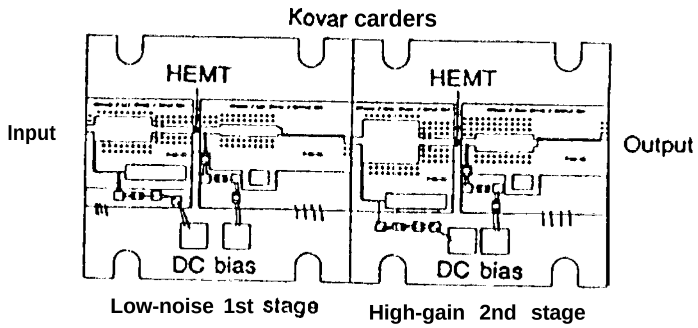

Fig. 4. *Cryogenic* low-noise amplifier design.

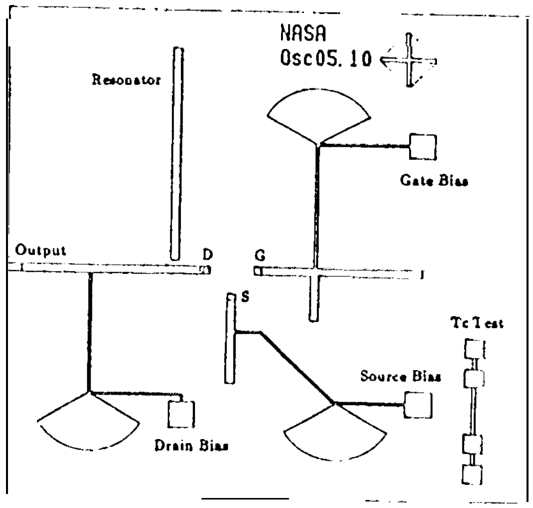

Fig. 5. Superconducting oscillator design for HTS on 10.0 x 10.0 x 0.51 mm lanthanum aluminate substrate.

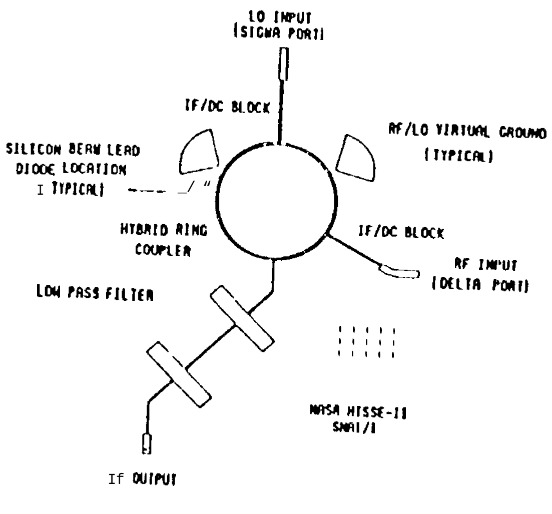

Fig. 6. Cryogenic mixer design.