HYBRID SEMICONDUCTIVE/HIGH TEMPERATURE SUPERCONDUCTIVE Ku-BAND OSCILLATOR and AMPLIFIER MICs

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ABSTRACT

The design, fabrication and testing of hybrid semiconductive/high temperature superconductive (HTSC) Ku-band Microwave Integrated Circuits (MICs) operating at cryogenic temperatures is described. The first cooled feedback oscillator using GaAs FET Monolithic Microwave Integrated Circuit (MMIC) low-noise amplifiers for gain and a high Q TlBaCaCuO linear resonator for stabilization is presented together with a low-noise HEMT amplifier using TlBaCaCuO distributed stubs for matching. Both demonstrate that HTSC and semiconductive elements can be successfully integrated.

INTRODUCTION

Semiconductive and high temperature superconductive technologies presently excel in active and passive microwave circuits, respectively. By combining them in hybrid semiconductive/superconductive microwave circuits, higher performance components may be realized.[1]

Oscillator and amplifier MICs are two candidate circuits which may benefit by combining the two technologies. Performance superior to dielectric resonator oscillators may be possible by using high Q superconductive planar structures combined with cooled low-noise semiconductive devices. Such a circuit would be especially useful in MMICs where bulky dielectric resonators are difficult to integrate. HTSC technology also offers the possibility of reducing the losses of receiver antennas and low-noise amplifier input matching networks. In addition, by combining a narrow band channel filter with the input matching network it may be possible to integrate both functions in the same component. Lowering the temperature also improves the noise figure of semiconductive devices. In this paper, the design, fabrication and testing of feedback oscillator and low-noise amplifier MICs, operating in the Ku satellite band, are described.

Previous S-parameter measurements of three-terminal active semiconductive devices showed significant performance improvement for both GaAs FETs and HEMTs at 77K.[2] Passive HTSC resonators, using double-sided TlBaCaCuO thin-films fabricated at Superconductor Technologies Incorporated, were found to have Ku-band unloaded Qs over twenty times higher than gold at 77K. These components are employed in the MICs.

SUPERCONDUCTIVELY-STABILIZED MMIC FEEDBACK OSCILLATOR

The feedback architecture shown in Figure 1 was chosen to fully exploit the high Q of HTSC resonators for frequency stabilization. It allows the resonator to be lightly loaded, resulting in the highest spectral purity. Only signals in the passband of the resonator circulate through the loop, being amplified to overcome the losses of the other components and transmission lines. For the signal to be reinforced at resonance, the sum of the phase delay through the loop must be $2n\pi$ radians where n is an integer. A rat-race power divider was used to couple the output signal from the circuit.

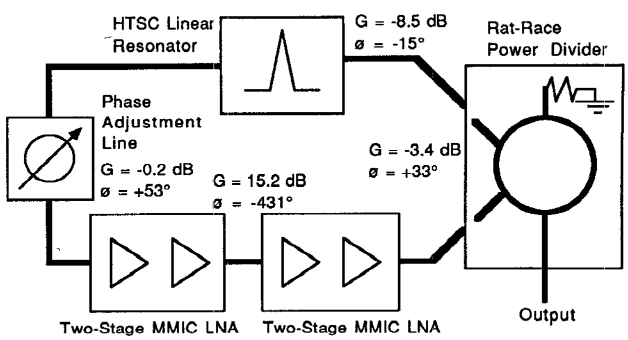

Figure 1. Block Diagram of Superconductively-Stabilized Feedback Oscillator

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The gains and phases of the components at 13 GHz are indicated on the block diagram. The amplifier and resonator values are measured results, while the coupler and phase adjustment line values are Supercompact simulations.

Sufficient gain to sustain oscillation is obtained by cascading two two-stage Ku-band quarter micron GaAs FET MMIC amplifiers, which were provided by Comsat Laboratories.[3] The die are silver epoxied to 0.006" high posts machined on a gold plated kovar carrier and are thermocompression bonded to the interconnecting 50Ω transmission lines and bias pads with 0.0007" diameter gold wires. Bias is decoupled with 100 pF chip capacitors and 2KΩ chip resistors are in series with the gates. These components are silver epoxied to a 0.010" thick alumina substrate and connected using ultrasonic bonded 0.0005" x 0.003" gold ribbons. The substrate is attached to the carrier with indium/lead solder to form the amplifier module.

Feedback is provided through a linear resonator operating at its second harmonic. A 0.040" wide microstrip line on a 0.020" thick lanthanum aluminate substrate forms the resonator. Its unloaded Q was 4,630 at 77K. Its width is large to reduce the effect of substrate voids, film pin-holes and degraded edges. The resonator is lightly capacitively coupled using 50Ω feed lines. Gold ohmic contacts at the ends of the feed lines allow ribbons to be ultrasonically bonded to the rest of the feedback circuit. Finally, gold deposition over the superconducting ground plane allows the substrate to be attached to a kovar carrier using low melting point indium/silver solder.

A rat-race coupler is used to split the power between the output port and the feedback loop. The rat race was designed to strongly attenuate frequencies at half the passband frequency since a second harmonic linear resonator is used in the feedback loop. A 13.8 dB notch in the feedback path at the fundamental frequency ensures that loop gain will only be sufficient to support oscillation at the second harmonic. This circuit was fabricated on a 0.010" alumina substrate which was indium/lead soldered to a kovar carrier. The unused port is terminated with a laser trimmed 50Ω chip resistor.

To obtain the correct phase delay around the loop at resonance, using the small-signal phase response as an approximation, the 50Ω phase adjustment line was sawn from a 0.010" alumina substrate to have a total length of 0.622". This was also soldered to a kovar carrier.

The four carriers are attached to a gold plated brass fixture to form the oscillator shown in Figure 2. The resonator is covered by a gold plated brass cover to minimize radiation loss. A K-connector sparkplug launcher is used for RF output while five DC feedthroughs, connected to phosphur-bronze wires, bias the MMIC amplifiers. Ceramic decoupling capacitors supplement the capacitance of all feedthroughs.

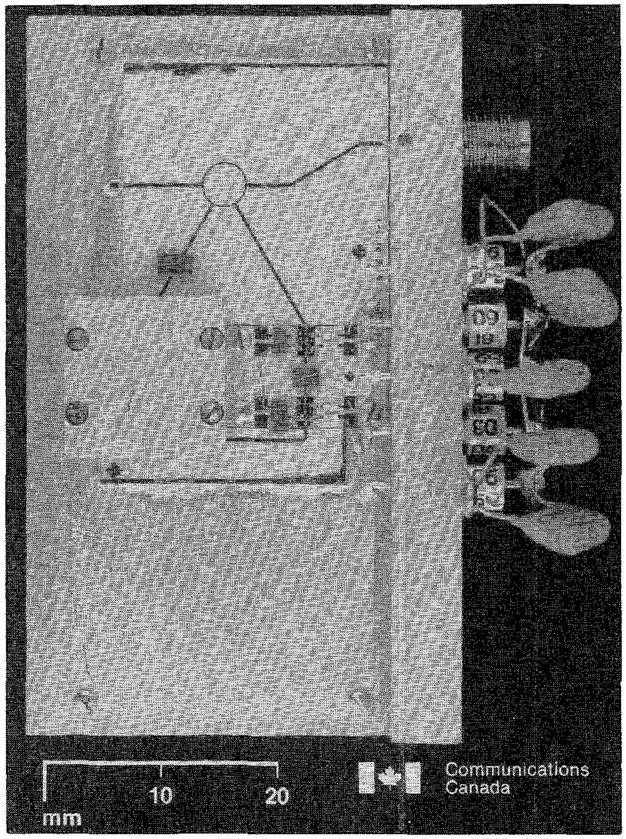

Figure 2. Superconductively-Stabilized Feedback Oscillator

The oscillator was attached to the second-stage cold station of a cryocooler.[4] The output was fed through a K-cable to an HP8569A spectrum analyser. A drain bias current of approximately 80 mA at 2.5V was found to produce the cleanest spectrum. As mentioned earlier, the center frequency is set to 13.0 GHz by the second harmonic of the linear resonator. Measurements were made at temperatures as low as 14K and the oscillator locked to the resonator at temperatures below 94K.

Noise power levels over a range of temperatures at 100 KHz and 1 MHz from the carrier are shown in Figure 3. At 100 kHz offset, a phase noise minimum occurs around 40K. Similar behavior does not occur at 1 MHz. The minimum may be due to the higher Q in the resonator being countered by increased 1/f FET noise due to dopants freezing out as the temperature is lowered. The best phase noise, occuring at 40K, was -95 dBc/Hz at 100 kHz from the carrier.

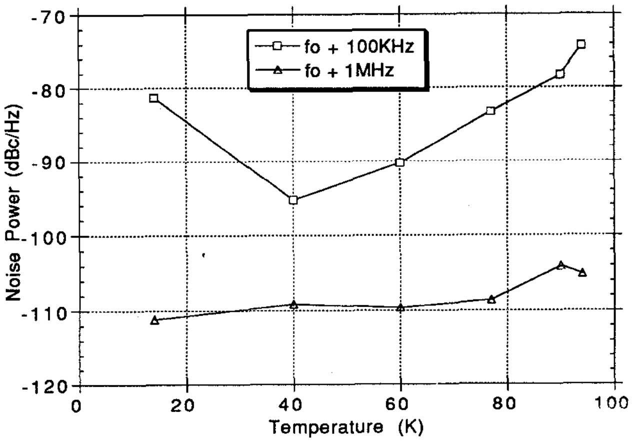

Figure 3. SSB Oscillator Phase Noise versus Temperature

Spurious oscillations were evident in the wide-band spectrum. By mixing with the fundamental signal, these secondary oscillations create additional phase noise, limiting spectral purity. These oscillations are caused by a reduction in amplifier stability as it is cooled. S-parameter measurements of the MMIC amplifier module at 77K reveal input reflection coefficients greater than unity from 5 to 11 GHz with up to 27 dB of associated gain. In an attempt to remove the secondary oscillations, Eccosorb MFS-117 blocks were placed on the microstrip lines to attenuate the reflections and gain of the amplifier. However, these oscillations could not be removed without quenching the fundamental. Phase adjustments were also difficult to make.

SUPERCONDUCTIVELY-MATCHED HEMT AMPLIFIER

As one of the first hybrid semiconductive /superconductive low-noise amplifiers to be attempted, the design was kept as simple as possible and proven components were used in its assembly. HTSC microstrip stubs were used to match the HEMT at 77K. Distributed matching structures were patterned TlBaCaCuO films grown on lanthanum aluminate substrates, while the Fujitsu FHR10X HEMT was chosen as the active device.

The HEMT was matched for gain using open-circuit stubs shunting the input and output 50Ω transmission lines. Touchstone was used for design simulation using S-parameters measured at 77K. Although complex multi-stub matching would more fully exploit the lower loss offered by HTSC films and allow a narrow band filter to be integrated, they were not used due to constraints on thin-film size and the basic design principle of simplicity. Following the same reasoning, DC blocking capacitors on the input and output were omitted. Photographs of the assembled amplifier are shown in Figure 4.

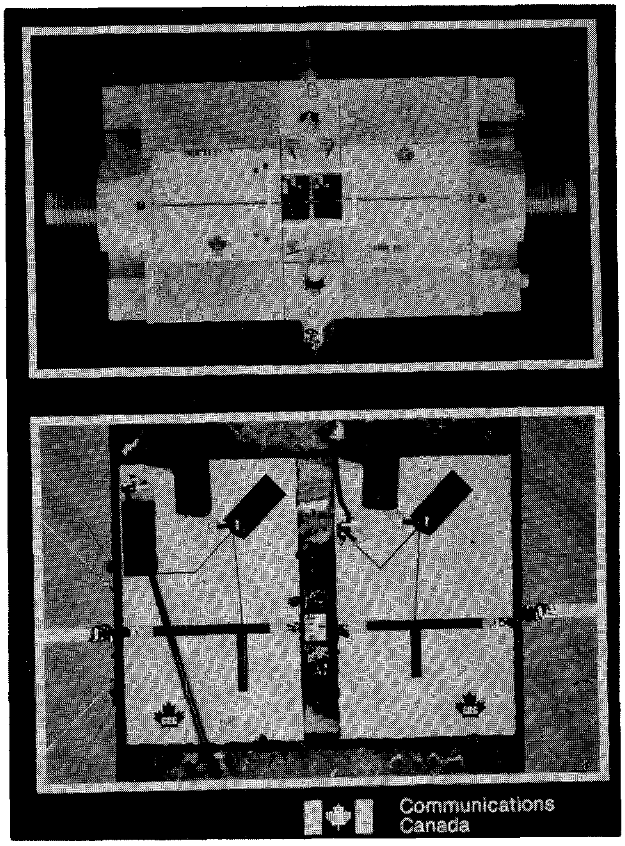

Figure 4. Low-Noise Amplifier Mounted in Test Fixture

Bias is fed through high impedance/low impedance quarterwave transmission line networks on the gate and drain. In addition, a 50Ω resistor in series with a 100 pF capacitor are added in the middle of each bias network to help stabilize the amplifier at low frequencies. On the gate, bias is passed through a 2KΩ resistor.

The HTSC films are attached to a gold plated kovar carrier using low temperature indium/silver solder. 50Ω and 2KΩ laser trimmed chip resistors and 100 pF multilayer chip capacitors are attached to the substrate with low temperature Epo-Tek H20E silver epoxy. A 0.020" high ridge was machined on the carrier, allowing the HEMT to be mounted. The HEMT is thermocompression wire bonded into the circuit while ultrasonic bonded ribbons connect the other components, input/output transmission lines and DC bias lines to the two filtercons.

S-parameters of the amplifier were obtained using the enhanced cryogenic microwave measurement technique.[4] To obtain noise figure data, the cryocooler apparatus was modified. Instead of connecting to the network analyser, an HP346C noise source was connected to the input coaxial vacuum feedthrough on the cryocooler shroud, while the output feedthrough was connected to an HP8970B noise figure meter. A through line, formed by ribbon bonding the two halves of the test fixture together, was measured to calibrate out the losses of the input cables and mixer noise figure. The repeatability of reconnecting the through was ±0.1 dB in noise figure and ±0.02 dB in gain at Ku-band. A conventional short/open/load calibration was used to determine the absolute input loss.

Measured gain and noise figure of the amplifier at 77K, with the nominal drain current of 5 mA at 2.0V, are shown in Figure 5. The gain response peaks to a value of 15.9 dB at 13.5 GHz. Input and output return losses are also minimum at this frequency with values of 4 dB and 8 dB, respectively. A noise figure minimum of 0.4 dB occurs around 13.2 GHz. Compared with earlier work,[5] performance lies between that of conventional FET and HEMT MIC amplifiers operating at 13K.

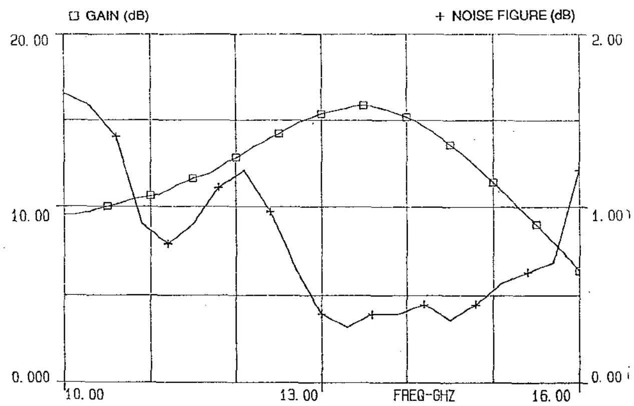

Figure 5. Amplifier Gain and Noise Figure Responses at 77K

CONCLUSION

Cryogenic semiconductor and HTSC technologies are successfully applied in the development of a superconductively-stabilized MMIC feedback oscillator and a superconductively-matched low-noise HEMT amplifier. The oscillator is the first reported which combines MMIC and HTSC components in a feedback configuration which is completely cooled. Secondary oscillations are presently limiting its phase noise performance. Cooling the entire oscillator hampered attempts to adjust the gain and phase through the loop, making it difficult to verify that it was configured for optimum performance. The low-noise amplifier is the first reported to integrate HEMT and HTSC elements. Gain is high for a single-stage design. Lower noise figure is anticipated by matching for noise rather than gain.

The successful realization of these hybrid semiconductive/superconductive MICs demonstrates that it is possible to integrate these technologies. Future experiments are needed to realize the potentially higher levels of performance which are promised by combining semiconductive and superconductive technologies.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Wayne Coyne, Mrs. Siegrid Bernhoff, Mr. Roy Cunningham, Mr. Charlie Szabo and Mr. Gary Shaver, all of the Communications Research Centre, for their technical assistance.

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