A Coplanar Transmission Line High-T_c Superconductive Oscillator at 6.5 GHz on a Single Substrate

Ralf Klieber, Roland Ramisch, Alejandro A. Valenzuela, Robert Weigel, and Peter Russer

Abstract— **The design and construction of a planar, low-noise cryogenic oscillator operating at 6.5 GHz are presented. The oscillator has been built as a hybrid superconductive microwave integrated circuit (SMIC) on a single 10×10 mm $LaAlO_3$ substrate. Single-sided, coplanar line structures are used throughout the circuit with $YBa_2Cu_3O_{7-\delta}$ as conductor material. The oscillator was constructed around a GaAs-MESFET as the active device. The complete oscillator is cooled by immersion into liquid nitrogen. An output power of 4.9 dBm was obtained. Single-sided noise power at 10 kHz offset from carrier was –90 dBc/Hz.**

I. Introduction

THE potential of planar, low-loss, high-T_c superconductive transmission lines as resonant structures in low-noise oscillators has been investigated by several authors [1], [2]. High stability of frequency and low phase-noise have been predicted. Published oscillator designs using superconductive high-T_c materials have relied on cooled resonators separated from the rest of the circuit with the active device operated at room temperature [3]. The design of low-noise cryogenic microwave integrated systems of higher complexity will require complete oscillators operating in the same low temperature environment. Up to now, deposition of high-T_c superconductive (HTSC) films is usually done only on one side of a substrate. Therefore, the easiest way to implement cryogenic systems with hybrid superconductive microwave integrated circuits (SMIC's) is to use a single-sided, coplanar transmission line technology. With liquid nitrogen cooling, a majority-carrier device is best employed as the active element [4]–[6].

We have constructed a completely coplanar oscillator which incorporates a GaAs-MESFET as the active device, on a 10-mm by 10-mm sized substrate of $LaAlO_3$ using a superconductive film of epitaxially grown $YBa_2Cu_3O_{7-\delta}$.

II. Circuit Design

The oscillator circuit uses a center-coupled half-wave resonator that has been published previously [7]. Coupling to the resonator is accomplished by a 30 μm×200 μm gap. The characteristic impedance of this 6.5-mm long coplanar waveguide resonator with an 80-μm wide center-conductor and a 40-μm wide gap amounts to 35 Ω. From measurements of such resonators, maximum unloaded Q-values of 3850±180 were obtained. This value is 43 times larger than the Q-value obtained with a resonator out of copper on $LaAlO_3$ substrate having the same geometry but a considerably larger conductor thickness. The complete circuit diagram of the oscillator is shown in Fig. 1. Series-feedback at the source of type NE71000 GaAs-MESFET is established by a combination of open and shorted stubs. At 6.5 GHz it provides a slightly capacitive impedance required to fulfill the oscillation condition. Potential instabilities at multiples of 6.5 GHz are suppressed. All lines were placed symmetrically around the transistor to avoid unsymmetrical modes in coplanar lines. A three-dimensional layout of the oscillator is shown in Fig. 2.

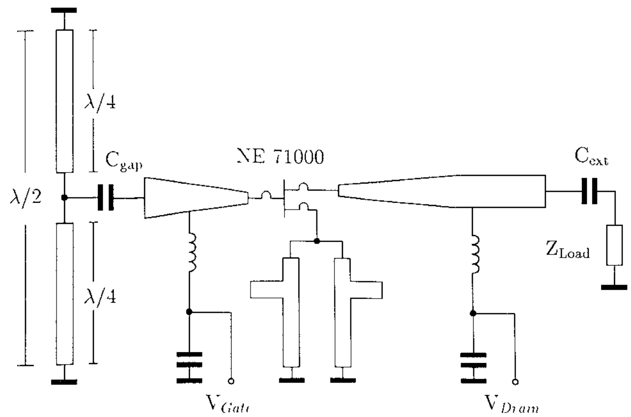

Fig. 1. Circuit diagram of SMIC oscillator. All lines are coplanar type, larger width indicates lower impedance.

To assess the influence of cooling on transistor two-port parameters, comparative scattering-parameter measurements of encapsulated NE71084 transistors at 77 K and at room temperature were undertaken. Table I shows the observed changes. Similar observations have also been made by others [6]. The changes were considered to be in a range accountable for by reserves in the design of the oscillator. Therefore, scattering parameters of the transistor chip measured at room temperature were used in circuit design. Some reserve in closed-loop gain has been provided to account for the transconductance decrease in the stationary oscillating state and for possible deviations in resonator Q and device tolerances.

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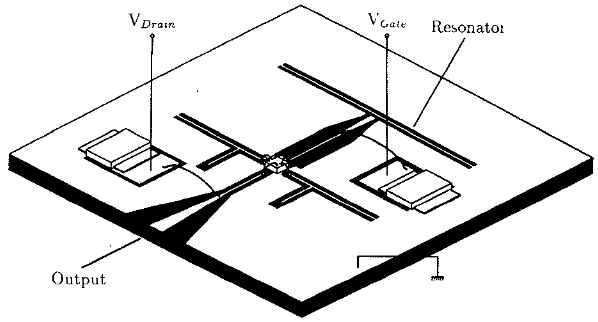

Fig. 2. Three-dimensional view of the SMIC oscillator. YBCO conductor layer is shown in white.

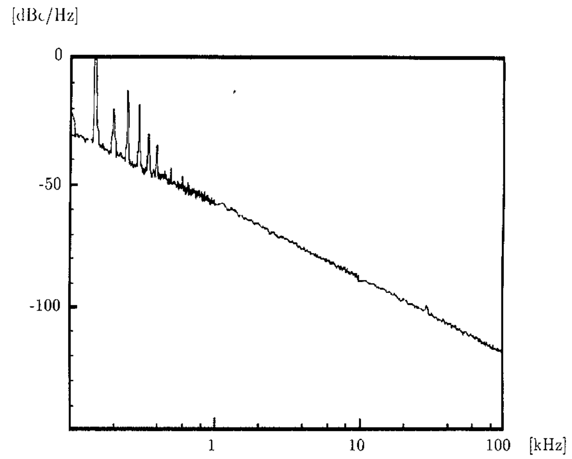

Fig. 3. Measured oscillator single-sideband phase noise performance.

TABLE I
DEVIATIONS OF SCATTERING PARAMETERS OF ENCAPSULATED NE71084 TRANSISTORS MEASURED AFTER COOLING FROM 293 K TO 77 K*

f[GHz]	$\|S_{11}\|$	$\angle S_{11}$	$\|S_{22}\|$	$\angle S_{22}$	$\|S_{21}\|$	$\angle S_{21}$	$\|S_{12}\|$	$\angle S_{12}$
6.4	12.4%	12.3%	22.7%	8.1%	2.4%	10.4%	20%	15.8%
6.5	12.5%	13.7%	22.9%	9.2%	2.3%	12.3%	24%	17.9%

*Measurements were taken with drain-source voltage and current kept constant.

The output line has been tapered to allow connection of a coaxial SMA-connector. Coplanar lines were simulated according to [8] and are based on ideal conductors. Assuming ideal conductors in the simulation of coplanar lines and calculating the losses by the power-loss method is possible because the depth of penetration of the field is small compared to the conductor spacing. The results of these calculations were verified with the results obtained from an accurate full wave calculation method [9] and found to be correct.

III. FABRICATION

The YBCO film has been deposited by *in situ* laser-ablation onto a 0.5-mm thick <100> orientated $LaAlO_3$ substrate. At 77 K, these films show high critical densities of $2 \cdots 5 \times 10^6$ A/cm^2 [11] and low surface resistance values of $7 \cdots 300$ $\mu\Omega$ at 6 GHz [12]. The 200–nm film had a critical temperature of 90.1 K and a transition temperature range of 1.6 K. Patterning was carried out by a standard wet etching technique using diluted phosphoric acid and was followed by a cleaning treatment in a plasma reactor.

Following standard hybrid technology, the transistor chip was attached to the substrate using an epoxy-type glue. In manufacturing hybrid MIC's, thermosonic bonding of thin gold-wires is usually used to contact the usually small, i.e., 40 μm$\times$40 μm sized contact areas on active devices. Direct bonding of gold wires to YBCO is not possible. Therefore, to allow bonding of transistor- and bias-connections, small (60$\times$ 175μm) pads of gold were formed in a separate deposition step and patterned by lift-off. Adhesion of these pads was increased to a value necessary for thermosonic bonding by a thin intermediate layer of (normally conducting) niobium.

Gold was also deposited on all areas where external connections are made to, namely the ground area near the outer rim of the substrate as well as on the output line and on bias contact pads. Bias voltages are fed to gate and drain lines via 17.5-μm diameter gold wires bonded from large pads that are decoupled by beam-lead MIS chip capacitors (cf. Fig. 2). These capacitors were fixed by bonding their leads directly onto the pads. On the output line, an external dc-blocking capacitor is used. The substrate was mounted removably inside a brass fixture with the outer rim of the substrate's top side in contact with the fixture. The circuit rests on a support of PTFE and is secured under spring pressure from its bottom side. Bias contacts were made with miniature precision spring loaded probes.

IV. RESULTS

All measurements were taken with the SMIC oscillator entirely immersed into liquid nitrogen. In a first measurement, liquid nitrogen was allowed to flow freely around the substrate through openings in the fixture. At a drain current of 7 mA, an oscillator power of 4.9 dBm with second and third harmonic down 10 and 30 dB, respectively, was obtained. It was however noted, that as a result of power dissipation in the SMIC, nitrogen-gas bubbles formed continuously and were released from the surface of the circuit. Because of a difference in ϵ_r between the liquid and gaseous state of nitrogen, this produced frequency jumps (<1 MHz) by propagation constant modulation of the coplanar waveguide. To overcome this phenomenon, all openings of the fixture were subsequently sealed hermetically and only thermal conduction cooling through the fixture was allowed in further experiments. This results in a somewhat elevated temperature of the SMIC, however significant thermal effects were only noted at drain currents above 8 mA, when parts of the SMIC seem to undergo a transition into the normal conducting state. The oscillator was however operated at lower currents. Measured single-sideband noise power of the oscillator at 10 kHz offset from carrier was –90 dBc/Hz (cf. Fig. 3).

Larger dc drain and gate voltages than expected had to be applied to the oscillator. The reason for this was found to be the presence of dc resistance in all YBCO-niobium-gold contact pads. Separate measurement of such a pad revealed a capacitively shunted, strongly nonlinear resistive characteristic. The oscillator was cycled many times from room temperature to 77 K, however no degradation of performance could be measured.

V. Conclusion

A miniaturized oscillator operating at 77 K and built in SMIC technology has been demonstrated. Two mask levels, one for patterning the YBCO layer and one for the definition of contact pads were required.

Measured noise power of this oscillator is comparable to the noise power values of published DRO's, e.g., in [13]. The noise behavior is expected to be improved if better bondable YBCO contacts can be made.

It should be possible to build superconducting oscillator circuits very reproducibly using SMIC and combine them with other SMIC components like miniaturized antennas and low-loss filters to obtain very compact RF systems. Such systems seem especially suited for application in space, where cooling is easily accomplished.

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