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High Temperature Superconducting Thin Film Microwave Circuits: Fabrication, Characterization, and Applications

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HIGH TEMPERATURE SUPERCONDUCTING THIN FILM MICROWAVE CIRCUITS:

FABRICATION, CHARACTERIZATION, AND APPLICATIONS

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SUMMARY

Epitaxial $YBa_2Cu_3O_7$ films have been grown on several microwave substrates. Surface resistance and penetration depth measurements have been performed to determine the quality of these films. In this paper, the properties of these films on key microwave substrates are described. The fabrication and characterization of a microwave ring resonator circuit to determine transmission line losses is presented. Lower losses than those observed in gold resonator circuits were observed at temperatures lower than critical transition temperature.

Based on these results, potential applications of microwave superconducting circuits such as filters, resonators, oscillators, phase shifters, and antenna elements in space communication systems are identified.

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INTRODUCTION

The discovery of superconductivity in ceramic oxides such as Y-Ba-Cu-O, Bi-Sr-Ca-Cu-O and Tl-Ca-Ba-Cu-O with transition temperatures T_C around 100 K has inspired many researchers around the world to manipulate and to alter these ceramic oxides to form beneficial products for various applications. One important application where high T_C superconductors have begun to show promise is in the area of microwave communication and radar systems. The use of high T_C superconductors in a microwave system requires development of thin films on microwave substrates which then can be patterned into desired microwave circuits such as filters, phase shifters, ring resonators, and delay lines. The superconducting thin films for microwave circuits need to be deposited on low dielectric constant and low loss substrates, have smooth morphology, high critical temperature T_C, high critical current density J_C and low surface resistance R_S. Furthermore, films on the substrates must be evaluated as microstrip or ring resonator circuit to determine the quality factor "Q", and various losses prior to developing microwave circuit applications.

In this paper, we describe the characteristics of high quality Y-Ba-Cu-O thin films on microwave substrates and evaluation of their microwave properties. We discuss the fabrication, characterization, and performance of ring resonator circuits. In conclusion, we present some examples of applications of superconducting microwave circuits.

FABRICATION OF THIN FILMS ON MICROWAVE SUBSTRATES

To obtain high quality $YBa_2Cu_3O_7$ films on suitable substrates the substrate lattice constants must be matched to those of the films and there must not be a detrimental chemical reaction between the substrates and the film. In addition, the film composition must be as close to the correct composition as possible. To date, to obtain the highest quality films several physical and chemical deposition techniques have been used. Many of these require post-annealing at high temperatures. This high temperature anneal causes chemical interactions at the film-substrate interface, making the substrate/film interface unsuitable for microwave applications (ref. 1). See table I for the properties of sequential evaporated films on microwave substrates. To circumvent this problem, an in situ annealing procedure which allows lower growth temperatures have been used to grow epitaxial films using a laser ablation technique (ref. 2).

The details of the geometry of the laser ablation are shown in figure 1(a). The substrates were mounted onto a stainless steel plate with a diameter of 63 mm. The plate was heated from the backside using a resistive heater. The sample chamber was evacuated to 3×10^{-7} torr, or lower, using a liquid nitrogen cold trapped diffusion pump before the sample was warmed up to 700 °C. During deposition the chamber pressure was 170 mtorr; the laser wavelength was 248 nm; the energy density was 1.5 (J/cm^2)/pulse; the pulse rate was two pulses per second; and the distance between the target and the sample was 8 cm. The laser beam was rastered up and down 1 cm over the target using an external lens on a translator. After deposition the oxygen pressure was raised to 1 atm, and the temperature was lowered to 450 °C at a rate of 2 °C/min. The temperature was held at 450 °C and held for 2 hr, then cooled to room temperature.

The best film had a T_c of 89.8 K immediately after deposition as determined by a standard four point resistance measurement. Its resistance versus temperature behavior is shown in figure 1(b). From x-ray diffraction data the film was determined to be c-axis aligned. Critical current density J_c versus temperature is shown in figure 1(c). As can be seen, the value of J_c was greater than 10^6 Å$/cm^2$ at 77 K. The surface morphology of the HTS on $LaAlO_3$ is shown in figure 1(d). The surface is very smooth with some small structure of about 0.25 μ in size. This size of structure has been confirmed by Scanning Tunneling Microscopy. We do not observe large numbers of HTS particulates due to the laser ablation process. In table I, we list the performance of $YBa_2Cu_3O_7$ thin films on various microwave substrates along with properties of these substrates.

SURFACE RESISTANCE

Surface resistance characterization of superconducting film offers valuable information on the film quality for microwave circuit applications. Currently, surface resistance values are obtained by cavity (refs. 3 and 4) and stripline measurements (ref. 5). Correlation between material properties (i.e., dc conductivity above T_c, penetration depth, and T_c) and surface resistance are still not well understood for new high T_c superconducting films. Theoretically, surface resistance of metal conductor is given by

$$R_N = \left(\frac{\omega\mu}{2\sigma}\right)^{1/2} = \frac{1}{\sigma_N\ \delta_N} \tag{1}$$

where

$$\delta = \left(\frac{2}{\mu\sigma\omega}\right)^{1/2} \quad \text{is the skin depth.}$$

σ_N is the normal conductivity, μ_o is the magnetic permeability, and ω is the angular frequency. For superconducting films, conductivity is a complex quantity $\sigma = \sigma_1 + j\sigma_2$. For $\sigma_2 >> \sigma_1$ one can obtain the surface resistance of superconducting film

$$R_s = \frac{0.5\sigma_1\omega\mu}{\sigma_2^{3/2}} \tag{2}$$

where σ_2 is related to the penetration depth λ by

$$\sigma_2 = \frac{1}{\omega\mu\lambda^2} \tag{3}$$

From equations (1) and (2)

$$\frac{R_s}{R_N} = \frac{2\sigma_1}{\sigma_N}\left(\frac{\lambda}{\delta_c}\right)^3 \tag{4}$$

Clearly, from this expression to obtain surface resistance for superconducting film lower than for a normal metal, the lowest values of σ_1 and λ are desired. Miranda et al. (ref. 6) have measured microwave transmission in a waveguide for superconducting films as shown in figure 2. From the transmission data, using the two fluid models, σ_1 and λ have been obtained. A summary of results for Y-Ba-Cu-O films on various substrates is shown in table II. The penetration depth value was small for laser ablated film on lanthanum aluminate substrates. Using these values in equation (4), a surface resistance for films on $LaAlO_3$ is calculated. In figure 3, which is adopted from reference 7, we show how the quadratic variation f^2 of the surface resistance varies with frequency for laser ablated Y-Ba-Cu-O films on microwave substrates. The surface resistance is several orders of magnitude lower than that of copper. Clearly surface resistance, penetration depth, and microwave conductivity measurements provide valuable information on the quality of these films for microwave circuits.

BASIC MICROWAVE CIRCUIT - RING RESONATOR

Measurements of surface resistance by the cavity technique fail to model microstrip losses completely because it neglects substrate losses and fails to adequately probe the film-substrate interface. Microstrip resonators patterned from thin films on microwave substrates allow direct measurement of microstrip losses. We have fabricated microstrip ring resonators operating at 35 GHz from laser ablated YBCO thin films deposited on lanthanum aluminate substrate (ref. 11). Also, several groups have studied resonator circuits at lower frequencies (refs. 5 and 8 to 10). The resonator circuits we fabricated were patterned by standard photolithography using negative photoresist and a 'wet' chemical etchant. This etchant was either a 3-percent solution of bromine in ethanol or dilute phosphoric acid in water. A metal ground plane was deposited by first evaporating 100 Å of Ti for adhesion followed by 1 μ of gold. In addition to the resonator, each chip also had a test bar for directly determining T_c of the patterned film. Identical resonators were fabricated entirely from gold (both strip and ground plane) using evaporation and lift-off to define the strip.

The resonators were measured using a Hewlett-Packard 8510 Automatic Network Analyzer, operating in WR-28 waveguide. The microstrip circuit mounted in a tapered ridge waveguide to microstrip test fixture is shown in figure 4. The design of a cosine tapered ridge used inside the waveguide to couple the incoming signal to microwave circuit is shown in figure 5. The plot of the reflected power from the resonator (which is a measure of the loaded 'Q') is shown in figure 6 for several frequencies. Two features are apparent; (1) the coupling changes with temperature (the coupling coefficient increases with decreasing temperature) and (2) the resonant frequency shifts with temperature. The change in the resonant frequency versus temperature for a superconducting resonator is plotted in figure 7. This change is a consequence of the dependence of the internal impedance of the strip on the changing normal superconducting electron densities. The internal inductance of a superconducting strip over a ground plane is given by (ref. 8):

$$L_{int} = \mu_o \lambda \coth\left(\frac{t}{\lambda}\right)$$

Assuming the Gorter-Casimir temperature dependence of λ:

$$\lambda(T) = \frac{\lambda_o}{\left[1 - \left(\frac{T}{T_c}\right)^4\right]^{1/2}}$$

the form of the resonant frequency variation based on the changing line inductance matches the experimental observations (fig. 7).

The best resonators measured to date have shown unloaded 'Q's ranging from 2500 to 1000 at 20 and 77 K, respectively. This corresponds to a surface resistance value of, at most, 15 mΩ at 77 K at 35 GHz, a value two to three times better than copper at the same temperature and frequency.

POTENTIAL APPLICATIONS

High T_c superconducting thin films have shown lower surface resistance than copper. Low conductor losses for high T_c superconducting ring resonator circuit have been demonstrated. These characteristics are desirable in passive microwave circuits used in communication and radar systems since they reduce loss and size, increase bandwidth, and provide low noise. Complete system analysis of the impact of the advantages of high T_C superconducting microwave circuits is yet not available. From a block diagram of satellite transponder (fig. 8), we have considered the following examples of potential applications of HTS microwave circuits in satellite communications applications. One can easily project the application of superconducting passive circuits as low loss, high 'Q' filters (ref. 11), high 'Q' resonators, delay lines, power splitter combiners, and resonator stabilized oscillators. Based on results obtained to date on the performance of superconducting microstrip resonator circuits with high 'Q' values.

In addition to these applications, extremely low loss phase shifters using superconducting switches are also feasible. In figure 9, we show a phase shifter which utilizes superconducting-normal-superconducting switches in place of FET/diode switches. The switches are fabricated from high temperature thin films of YBCO. The switches operate in the bolometric mode with the film held near its transition temperature. Radiation from a light source raises the temperature and consequently causes the film to become resistive. If the switches in the reference path are illuminated, they will become resistive. The switches on the opposite side of the device are superconducting. Since each switch is positioned one quarter of a wavelength from the junction, the signal will be reflected from the delay path in phase. A similar phenomenon occurs at the output port. To achieve the desired phase shift, the opposite set of switches is illuminated. Figure 9 shows the predicted behavior for a 180° phase shifter, with exceptional narrow insertion loss envelope and excellent return loss.

In figure 10, we show an example of hybrid semiconductor/superconductor device. It is possible that by combining the excellent low noise properties of GaAs devices with the low loss and low noise properties of superconducting transmission lines one can achieve ultra low noise receivers for satellite communications applications. If these promising concepts of high T_C superconducting devices are actually brought to fruition, then one can conceive their use in low loss, low noise superconducting phased array antenna in space communications systems as shown in figure 11. HTS transmission lines can provide low loss feed network which is a major problem in antenna networks.

SUMMARY OF RESULTS

We have demonstrated that rare-Earth oxide thin superconducting films can be deposited on various microwave substrates with critical temperature T_C above 77 K, critical current densities J_C above 10^6 Å/cm^2, and low surface resistance. Films can be easily etched into microwave transmission line circuits. The basic microwave circuit ring resonator fabricated on a $YBa_2Cu_3O_7$ superconducting film on $LaAlO_3$ substrate showed higher 'Q' than gold circuits at 77 K. Such circuits can provide propagation characteristics of microwave signals at the film-substrate interface. Several key HTS circuits such as filters, oscillators, phase shifters, and phased array antennas' feeds are feasible in the near future. For technology to improve further, reproducible, large area films have to be grown on low dielectric constant, low loss microwave substrates. Tradeoffs between superconducting microwave circuits with cryogenic systems and normal metal microwave circuits will have to be quantitatively established to determine their suitability for advanced communication and sensor systems.

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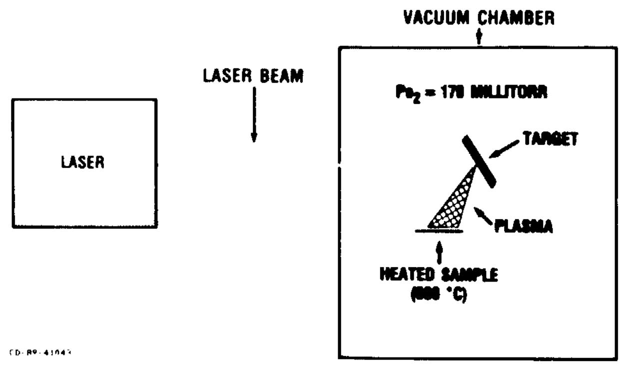
TABLE I. - KEY PROPERTIES OF MICROWAVE SUBSTRATE MATERIALS

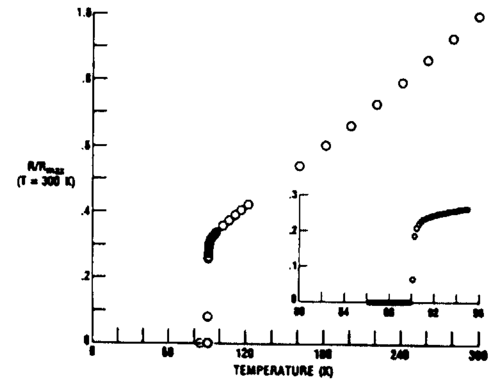
Material	T_c achieved		Dielectric constant	Loss tangent	Lattice size, Å
	Sequential evaporation, K	Laser ablation, K			
Magnesium oxide (MgO)	70	88	9.65	4×10^{-4}	4.178 (100)
Lanthanum aluminate ($LaAlO_3$)	82	90	22	5.8×10^{-4}	3.792 (110)
Lanthanum gallate ($LaGaO_3$)	--	88	27	2×10^{-3}	3.892 (110)
Sapphire (Al_2O_3)	71	60	9.4 11.6	1×10^{-6}	5.111 $(0\bar{1}\bar{1})$
Yttria stabilized zirconia (ZrO)	70	89	27	6×10^{-4}	3.8795 (100)
Silicon (Si)	--	--	12	10×10^{-4}	5.43 (100)
Gallium arsenide (GaAs)	--	--	13	6×10^{-4}	5.653 (100)

TABLE II. - MICROWAVE CONDUCTIVITIES (σ_n, $\sigma^* = \sigma_1 - i\sigma_2$) AND ZERO TEMPERATURE PENETRATION DEPTH (λ_0) at 33.3 GHz FOR LASER ABLATED $YBa_2Cu_3O_{7-\delta}$ SUPERCONDUCTING THIN FILMS

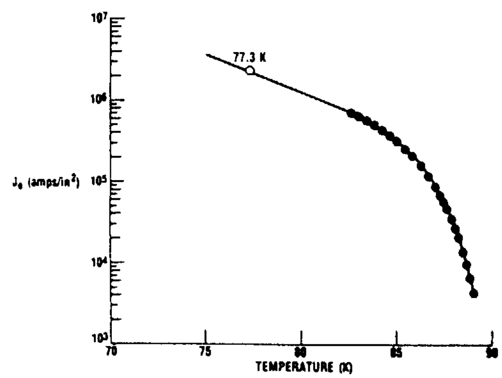
Parameter	YBCO on $LaAlO_3$			YBCO on MgO	YBCO on ZrO_2
	828 Å	1769 Å	5000 Å	3500 Å	1200 Å
σ_n (300 K)	3.0×10^5 S/m	2.2×10^5 S/m	1.5×10^5 S/m	1.4×10^5 S/m	2.8×10^5 S/m
σ_1 (77 K)	2.8×10^5 S/m	2.5×10^5 S/m	1.8×10^5 S/m	1.2×10^5 S/m	2.4×10^5 S/m
σ_2 (77 K)	5.4×10^6 S/m	1.1×10^7 S/m	4.6×10^5 S/m	3.0×10^6 S/m	8.4×10^6 S/m
λ_0	0.43 µm	0.36 µm	0.39 µm	0.53 µm	0.59 µm



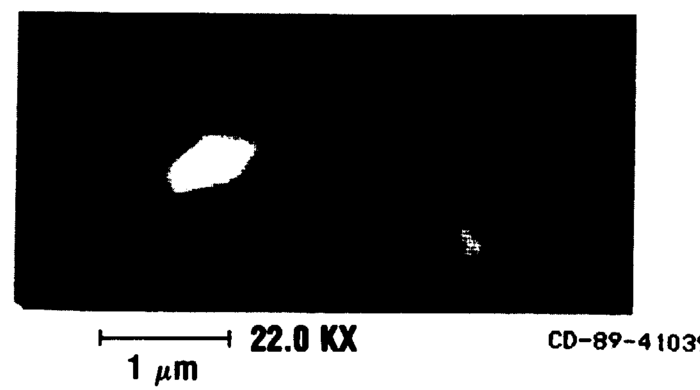
(a) LASER ABLATION TECHNIQUE.



(b) RESISTANCE VERSUS TEMPERATURE OF $YBa_2Cu_3O_7$.



(c) CRITICAL CURRENT DENSITY OF $YBa_2Cu_3O_7$ ON $SrTiO_3$.



(d) SEM MICROGRAPHS OF $YBa_2Cu_3O_7$ FILM ON $LaAlO_3$.

FIGURE 1.

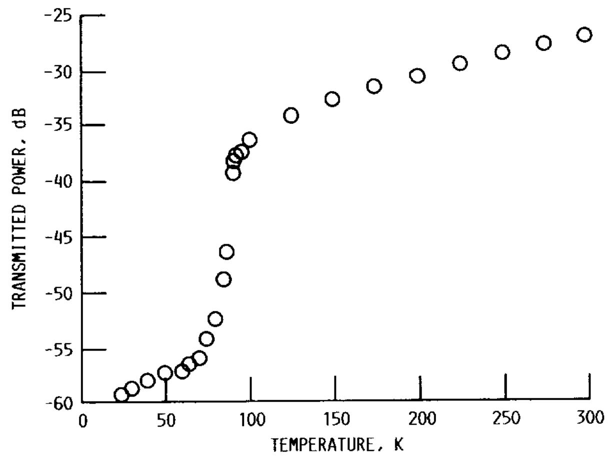


FIGURE 2. - TRANSMITTED POWER IN dB THROUGH A Y-Ba-Cu-O FILM ON $LaAlO_3$ SUBSTRATE AT 37 GHz.

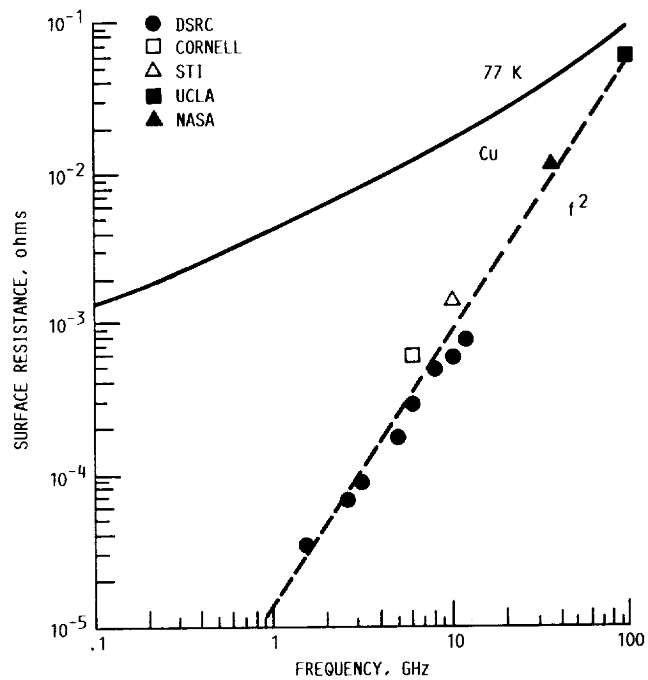


FIGURE 3. - SURFACE RESISTANCE OF LASER ABLATED Y-Ba-Cu-O FILMS ON $LaAlO_3$ SUBSTRATE VERSUS FREQUENCY. ADOPTED FROM APPLIED PHYSICAL LETTERS VOLUME 56, P.P. 1178-1180. NASA DATA OBTAINED BY MICROWAVE CONDUCTIVITY MEASUREMENTS.

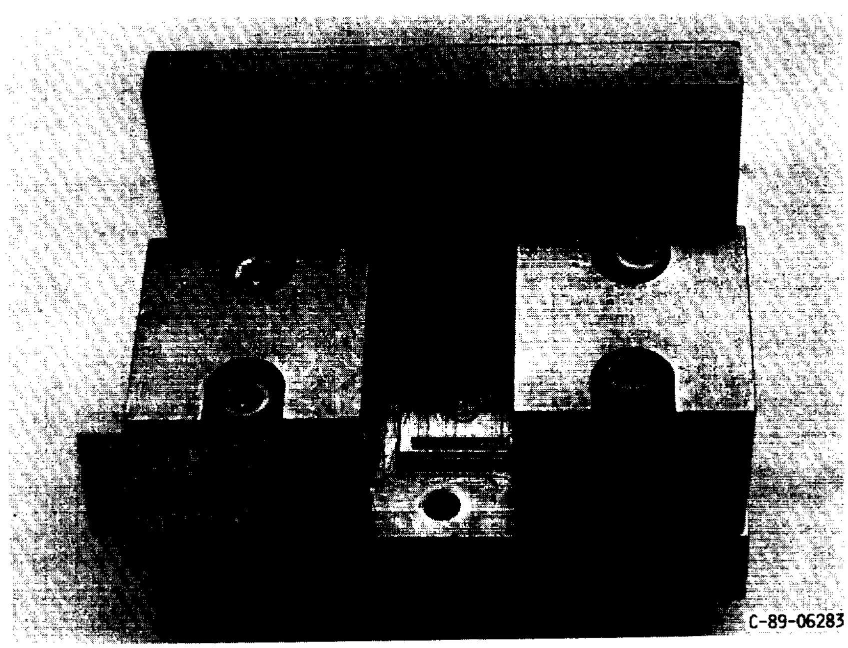


FIGURE 4. - WAVEGUIDE TEST FIXTURE USED FOR THE MEASUREMENT OF "Q" VALUES OF SUPERCONDUCTING RING RESONATORS.

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BLACK AND WHITE PHOTOGRAPH

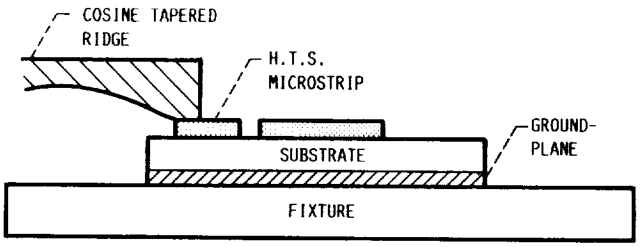


FIGURE 5. - DESIGN OF THE COSINE TAPER RIDGE INSIDE THE WAVEGUIDE USED FOR WAVEGUIDE TO MICROSTRIP TRANSITION.

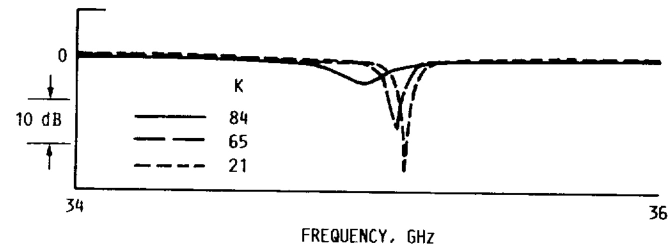


FIGURE 6. - RESONANCES OF Y-Ba-Cu-O RING RESONATOR AT THREE TEMPERATURES. NOTE THE FREQUENCY SHIFT WITH TEMPERATURE.

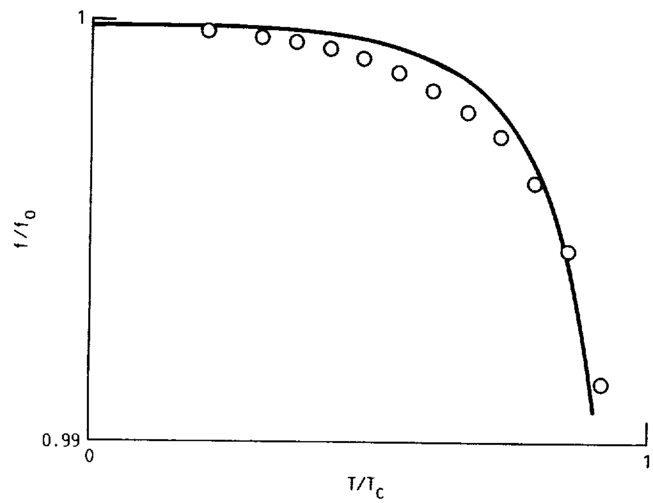


FIGURE 7. - RATIO OF THE OBSERVED RESONANT FREQUENCY (f) TO THE ZERO TEMPERATURE FREQUENCY (f_0) VERSUS THE T/T_c. O's REPRESENT EXPERIMENTAL VALUES. SOLID LINES REPRESENT CALCULATIONS BASED ON GORTER-CASIMIR MODEL.

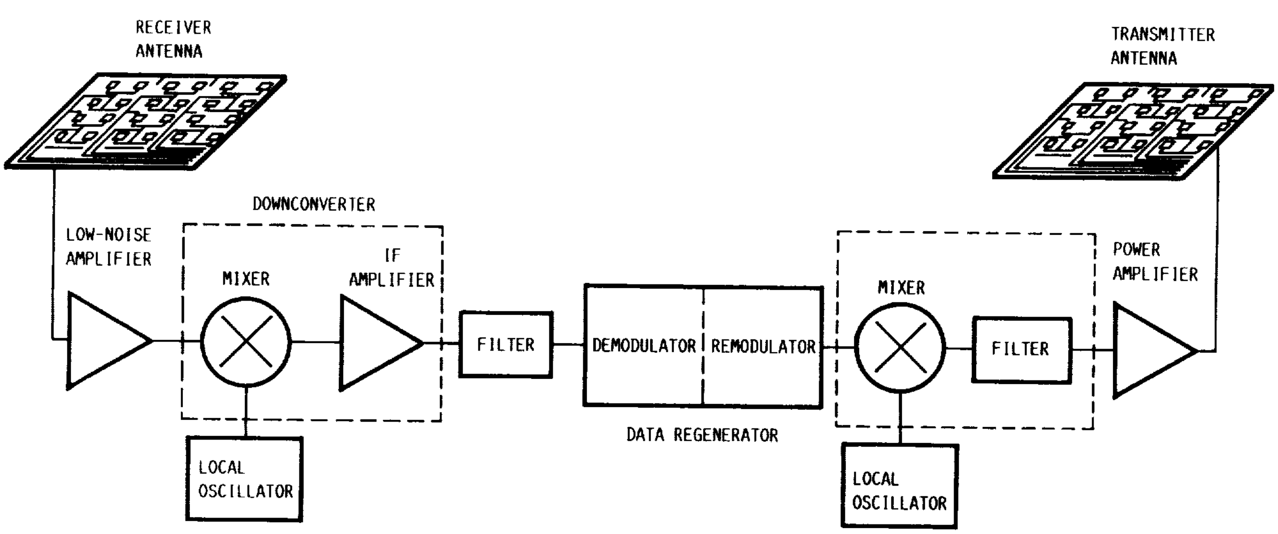
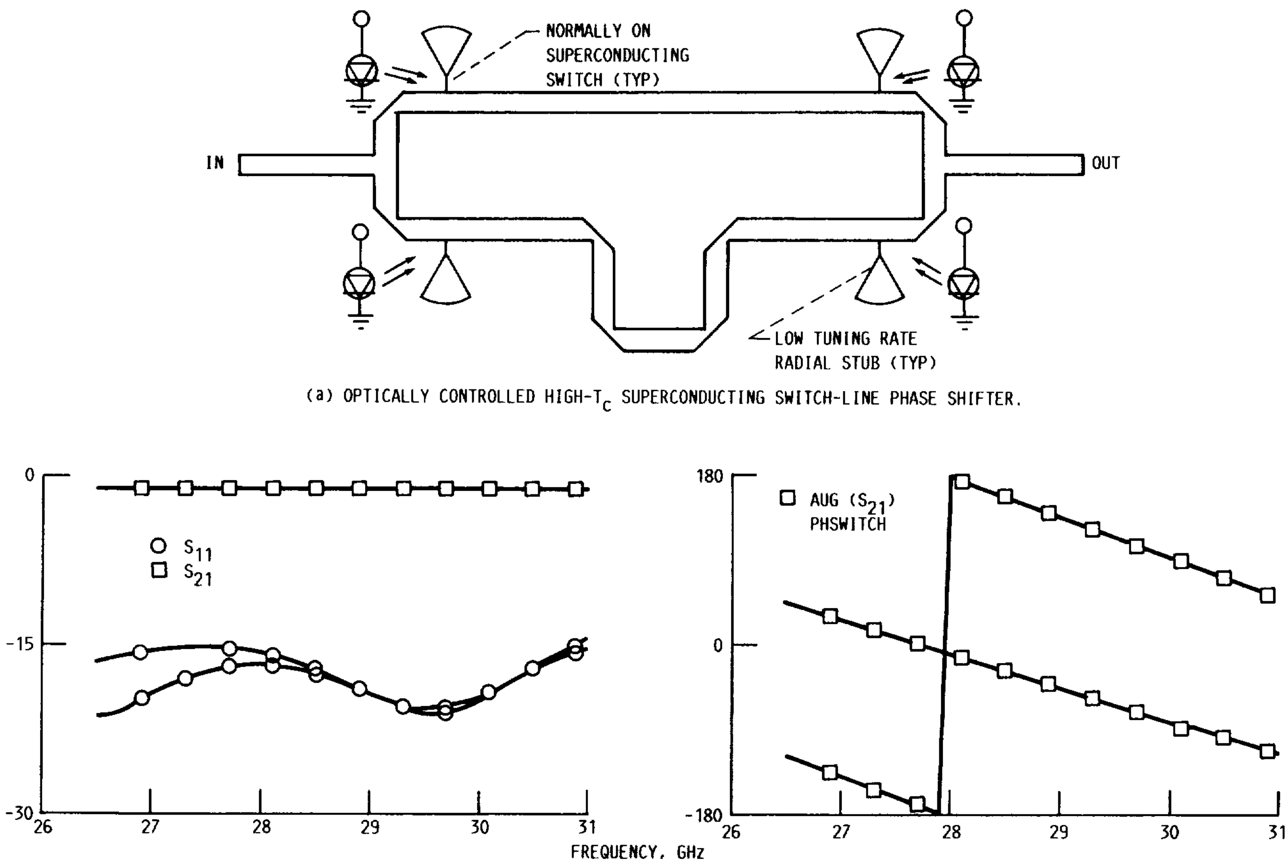


FIGURE 8. - BLOCK DIAGRAM OF A SATELLITE TRANSPONDER.



(a) OPTICALLY CONTROLLED HIGH-T_C SUPERCONDUCTING SWITCH-LINE PHASE SHIFTER.

(b) INSERTION LOSS AND RETURN LOSS FOR BOTH REFERENCE AND DELAY STATES.

(c) INSERTION PHASE FOR REFERENCE AND DELAY STATES.

FIGURE 9.

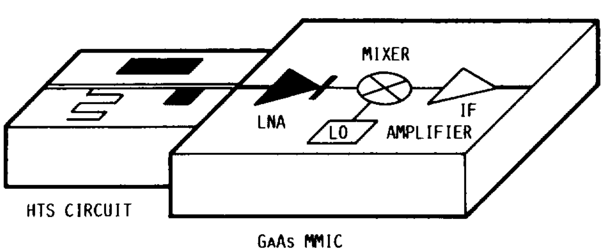


FIGURE 10. - SUPERCONDUCTING GaAs MMIC HYBRID RECEIVER.

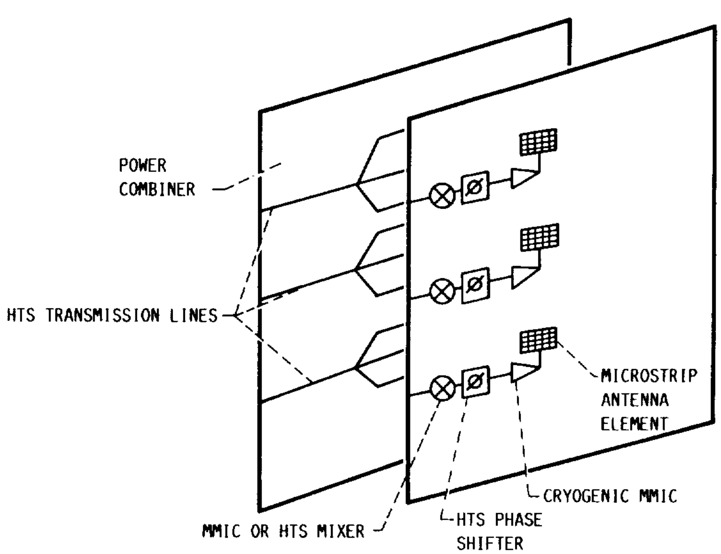


FIGURE 11. - CONCEPTUAL DIAGRAM OF A MMIC-SUPERCONDUCTING HYBRID PHASE ARRAY ANTENNA.

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16. Abstract

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