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Emerging Applications of High Temperature Superconductors for Space Communications

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EMERGING APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTORS FOR SPACE COMMUNICATIONS

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SUMMARY

Proposed space missions require longevity of communications system components, high input power levels, and high speed digital logic devices. The complexity of these missions calls for a high data bandwidth capacity. Incorporation of high temperature superconducting (HTS) thin films into some of these communications system components may provide a means of meeting these requirements. Space applications of superconducting technology has previously been limited by the requirement of cooling to near liquid helium temperatures. Development of HTS materials with transition temperatures above 77 K along with the natural cooling ability of space suggest that space applications may lead the way in the applications of high temperature superconductivity.

In order for HTS materials to be incorporated into microwave and millimeter wave devices, the material properties such as electrical conductivity, current density, surface resistivity and others as a function of temperature and frequency must be well characterized and understood. The millimeter wave conductivity and surface resistivity have been well characterized, and at 77 K are better than copper. Basic microwave circuits such as ring resonators have been used to determine transmission line losses. Higher Q values than those of gold resonator circuits were observed below the transition temperature. Several key HTS circuits including filters, oscillators, phase shifters and phased array antenna feeds are feasible in the near future. For technology to improve further, good quality, large area films must be reproducibly 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 the suitability for advanced communications systems.

INTRODUCTION

Space application of superconducting technology has previously been limited by the requirement of cooling to near liquid helium temperatures. The discovery of HTS materials with transition temperatures above 77 K along with the natural cooling properties of space suggest that space operations may lead the way in the applications of high temperature superconductivity. Proposed space missions require longevity of communications system components, high input power levels, and high speed digital logic devices. The complexity of these missions calls for a high data bandwidth capacity. To ensure adequate efficiencies, the microwave surface resistance of the component materials must be reduced to as low a level as possible. Incorporation of high critical temperature superconducting (HTS) thin films into some of these communications system components may provide a means of meeting these requirements as well as offering enhanced efficiency and reductions in size and weight.

The use of high T_c superconductors in a microwave system requires development of thin films on microwave substrates which 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 in devices such as microstrip or ring resonator circuits to determine the quality factor, Q, and various loss factors before appropriate microwave circuit applications can be developed.

STATUS OF HIGH-T_c SUPERCONDUCTOR PROPERTIES

To obtain high quality YBaCuO films on suitable substrates, the lattice constants of the substrate must be matched to those of the film, and there must be no detrimental chemical reactions between the substrate and the film. In addition, the film composition must be as close as possible to the desired stoichiometry. Many of the physical and chemical deposition techniques used to obtain high quality films require post-annealing at high temperatures. This high-temperature anneal causes undesirable chemical interactions at the film-substrate interface, making it unsuitable for microwave applications (ref. 1). To circumvent this problem, an in situ annealing procedure, which allows lower growth temperatures, has been used to grow epitaxial films using a laser ablation technique (ref. 2).

The best laser-ablated film had a T_c of 89.8 K immediately after deposition, as determined by a standard four-point resistance measurement. From x-ray diffraction data, the film was determined to be c-axis aligned. In table I, we list the performance of $YBa_2Cu_3O_7$ thin films on various microwave substrates along with physical properties of these substrates. As can be seen, the value of J_c was greater than 10^6 A/cm^2 at 77 K.

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

$$R_s = 0.5\sigma_1\mu/\sigma_2^{3/2} \qquad (1)$$

where σ_2 is related to the penetration depth λ by

$$\sigma_2 = 1/\omega\mu\lambda^2 \qquad (2)$$

To obtain superconducting film surface resistance values that are lower than those of a normal metal, the smallest values of σ_1 and λ are desired. Miranda, et al., (ref. 6) have measured microwave transmission in a waveguide for superconducting films. From the transmission data, using the two-fluid models, σ_1 and λ have been obtained. The surface resistance for films deposited on $LaAlO_3$ was calculated. In figure 1, which is adopted from reference 7, we show the quadratic variation of the surface resistance for laser-ablated YBaCuO films on microwave substrates. The surface resistance is several orders of magnitude lower than that of copper. Surface resistance, penetration depth, and microwave conductivity measurements provide valuable information on the quality of these films for microwave circuits.

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 YBaCuO thin films deposited on lanthanum aluminum substrate (ref. 8). Several groups have studied resonator circuits at lower frequencies (refs. 5, 9 to 11). The resonator circuits we fabricated were patterned by standard photolithography using negative photoresist and a "wet" chemical etchant. These resonators were characterized using a Hewlett-Packard 8510 Automatic Network Analyzer, operating in a WR-28 waveguide. 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. This change is a consequence of the dependence of internal impedance of the strip on the varying normal and superconducting electron densities.

The best resonators measured to date have shown unloaded Q values 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 that of copper at the same temperature and frequency. The 33 to 37 GHz YBaCuO ring resonator circuit developed at NASA Lewis is viewed as a precursor to frequency-selective filters and may have potential application in enhancing the efficiency of radiating antenna elements. Such HTS resonating circuits have a high Q as compared to equivalent normal metal circuits and may afford reduction in size and mass of electronically-steered millimeter wave antennas.

POTENTIAL APPLICATIONS

Passive Microwave Circuits

High T_c superconducting thin films have shown lower surface resistance than copper. Low conductor losses have been demonstrated for a high T_c superconducting ring resonator circuit. Low surface resistance and conductor losses are desirable in passive microwave circuits used in communication and radar systems since they offer increased bandwidth, reduction in loss and size, and provide low noise. A complete system analysis of the impact of high T_c superconducting microwave circuits remains to be undertaken. From a block diagram of a satellite transponder (fig. 2), we have considered several potential applications of HTS microwave circuits in satellite communications system components. Based on results obtained to date on the performance of superconducting microstrip resonator circuits with high Q values, one can easily project the application of superconducting passive circuits as low loss, high Q filters (ref. 12), high Q resonators, delay lines, power splitter combiners, and resonator stabilized oscillators.

HTS materials may be most effective in enhancing the efficiency of phased-array antennas when incorporated into interconnects and power dividers. Thin films of YBaCuO offer a reduction in resistive heating loss relative to gold and copper, and could conceivably be designed into microstrip lines. This frequency-dependent resistive heating loss effect is most significant at frequencies below Ka-band (~20 to 30 GHz). However, as frequency increases individual elements become smaller. The number of required elements increases, necessitating more complex interconnects, thereby making the overall savings from HTS materials more significant.

At submillimeter frequencies ($f \gtrsim 300$ GHz), RF ohmic losses in antenna elements of normal metals are on the order of a fraction of a decibel. HTS antenna patch elements would thus yield only a slight advantage over normal metal components in this frequency range. However at millimeter-wave operation ($30 \text{ GHz} \lesssim f < 300$ GHz), ohmic losses in antenna elements and interconnects are significant in normal metals, making benefits from HTS materials appreciable. The small antenna sizes required at these frequencies are more readily encapsulated in cryogenic envelopes than are microwave-frequency elements. The critical current density of HTS thin films should exceed the current densities in proposed space communication antenna systems, which is expected to be on the order of 10^5 A/cm^2 or less.

Granular YBaCuO and BiCaSrCuO detectors have been fabricated and tested at 77 K, between 24 and 110 GHz (ref. 13). Superconducting microstrip lines were used as IF and/or video output lines. All detectors showed a dramatic increase in sensitivity below 77 K. The theoretical high-frequency limit (determined from the superconductor energy gap) for these detectors is in the low terahertz range. However, the experimental video response decreases by about one order of magnitude when the carrier frequency is increased from 100 to 300 GHz. This research determined that the properties of HTS ceramics, and thus the resulting detector performance, are highly dependent upon the substrate material and are most likely tied to the dielectric properties of the substrate.

In addition to these applications, extremely low loss phase shifters using superconducting switches are also feasible. In figure 3, we show a phase shifter which utilizes superconducting-normal-superconducting switches in place of FET/diode switches. The switches are fabricated from high T_c thin films of YBaCuO. 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 too 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 3 shows the predicted behavior for a 180° phase shifter, with an exceptionally narrow insertion loss envelope and excellent return loss.

Figure 4 illustrates an example of a 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 of their use in low loss, low noise superconducting phased array antennas in space communications systems such as shown in figure 5. HTS transmission lines can provide low loss feed networks for antenna arrays.

E-BEAM DEVICES

There are several areas for possible application of HTS material in electron beam devices. These include the slow-wave circuit, the cathode, and the focusing magnet. Superconducting slow-wave circuits are likely only in very limited applications due to the heating caused by interception of the electron beam by the slow-wave circuit. Another possible area of application of HTS material is in the cathode. Electron field emission from the cathode may be enhanced when the cathode surface is in the superconducting state. Research in this area is in its very early stages and not likely to be applied in the near future.

What is likely to be the first application of HTS material in e-beam devices is for use as the focusing magnet. At the present time most traveling wave tubes used in space employ periodic permanent magnet (PPM) focusing to confine the electron beam because PPM focusing is lightweight and requires no power. The disadvantage of it is that the attainable magnetic fields are less than that required for optimum performance of the tube. This results in reductions in frequency stability, gain flatness, attainable output power, and overall efficiency. A larger solenoidal field can be used for confined flow focusing to overcome these problems resulting in a much improved tube. Because of the large number of potential applications of HTS magnets there are many groups working toward their development.

CONCLUSIONS

Microwave components have been fabricated from HTS materials which have superior performance over similar nonsuperconducting components. The development of HTS devices has large potential impact on the communication system for future space missions. There remains a significant amount of progress to be made in the development of materials and devices to the extent of applications of HTS technology to microwave systems. System studies must be performed to determine any overall advantage of HTS system along with the necessary coolers over conventional technology.

REFERENCES

1. Valco, G.J., et al.: Sequentially Evaporated Thin Y-Ba-Cu-O Superconducting Films on Microwave Substrates. NASA TM-102068, 1989.

2. Warner, J.D., et al.: Growth and Patterning of Laser Ablated Superconducting $YBa_2Cu_3O_7$ Films on $LaAlO_3$ Substrates. NASA TM-102436, 1989.

3. Klein, N., et al.: Millimeter Wave Surface Resistance of Epitaxially Grown $YBa_{2C}u_3O_{7-x}$ Thin Films. Appl. Phys. Lett., vol. 54, no. 8, Feb. 20, 1989, pp. 757-759.

4. Miranda, F.A., et al.: Millimeter Wave Surface Resistance of Laser Ablated Y-Ba-Cu-O Superconducting Films. Accepted for publication in Appl. Phys. Lett., Sept. 1990.

5. Fathy, A., et al.: Microwave Properties and Modeling of High T_c Superconducting Thin Film Meander Line. 1990 IEEE MTT-S International Symposium Digest, IEEE, 1990, pp. 859-862.

6. Miranda, F.A., et al.: Microwave Conductivity of Superconducting Bi-Sr-Ca-Cu-O Thin Films in the 26.5 to 40.0 GHz Frequency Range. Physica C., vol. 168, nos. 1-2, June 1, 1990, pp. 91-98.

7. Inam, A., et al.: Microwave Properties of Highly Oriented $YBa_2Cu_3O_{7-x}$ Thin Films. Appl. Phys. Lett., vol. 56, no. 12, Mar. 19, 1990, pp. 1178-1180.

8. Bhasin, K.B., et al.: Performance and Modeling of Superconducting Ring Resonators at Millimeter-wave Frequencies. 1990 IEEE MTT-S International Microwave Symposium Digest, IEEE, 1990, pp. 269-272. (Also, NASA TM-102526).

9. Valenzuela, A.A.; and Russer, P.: High-Q Coplanar Transmission Line Resonator of $YBa_2CU_3O_{7-x}$ on MgO. Appl. Phys. Lett., vol. 55, no. 10, Sept. 4, 1989, pp. 1029-1031.

10. McAvoy, B.R., et al.: Superconducting Stripline Resonator Performance. IEEE Trans. Magn., vol. 25, no. 2, Mar. 1989, pp. 1104-1106.

11. Takemoto, J.H., et al.: Microstrip Ring Resonator Technique for Measuring Microwave Attenuation in High T_c Superconducting Thin Films. IEEE Trans. Microwave Theory Tech., vol. MTT-37, no. 10, Oct. 1989, pp. 1650-1652.

12. Fiedziuszko, S.J., Holme, S., and Heidmann, P.: Novel Filter Implementations Using HTS Materials. To be published.

13. Konopka, J., et al.: Microwave Detectors Based on Granular High-T_c Thin Films. IEEE Trans. Microwave Theory Techniques, vol. 38, no. 2, Feb. 1990, pp. 160-165.

TABLE I. - KEY PROPERTIES OF MICROWAVE SUBSTRATES MATERIALS

Material	Highest T_c achieved	Dielectric constant	Loss tangent	Lattice size, Å
Magnesium oxide (MgO)	88	9.65	$4x10^{-4}$	4.178 (100)
Lanthanum aluminate ($LaAlO_3$)	90	22	$5.8x10^{-4}$	4.792 (110)
Lanthanum gallate ($LaGaO_3$)	88	27	$2x10^{-3}$	3.892 (110)
Sapphire (Al_2O_3)	71	9.4	$1x10^{-6}$	5.111 $(0\overline{11})$
Yttria stabilized zirconia (ZrO)	89	27	$6x10^{-4}$	3.8795 (100)
Silicon (Si)	--	12	$10x10^{-4}$	5.43 (100)
Gallium arsenide (GaAs)	--	13	$6x10^{-4}$	5.653 (100)

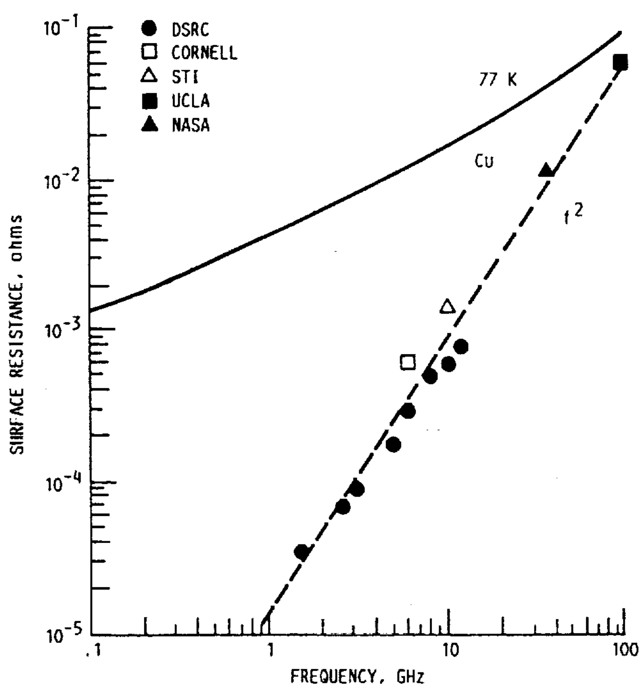


FIGURE 1. - SURFACE RESISTANCE OF LASER ABLATED Y-Ba-Cu-O FILMS ON $LaAlO_3$ SUBSTRATE VERSUS FREQUENCY. ADOPTED FROM APPLIED PHYSICAL LETTERS VOLUME 56, P.P. 1178-1180. NASA DATA OBTAINED BY MICROWAVE CONDUCTIVITY MEASUREMENTS.

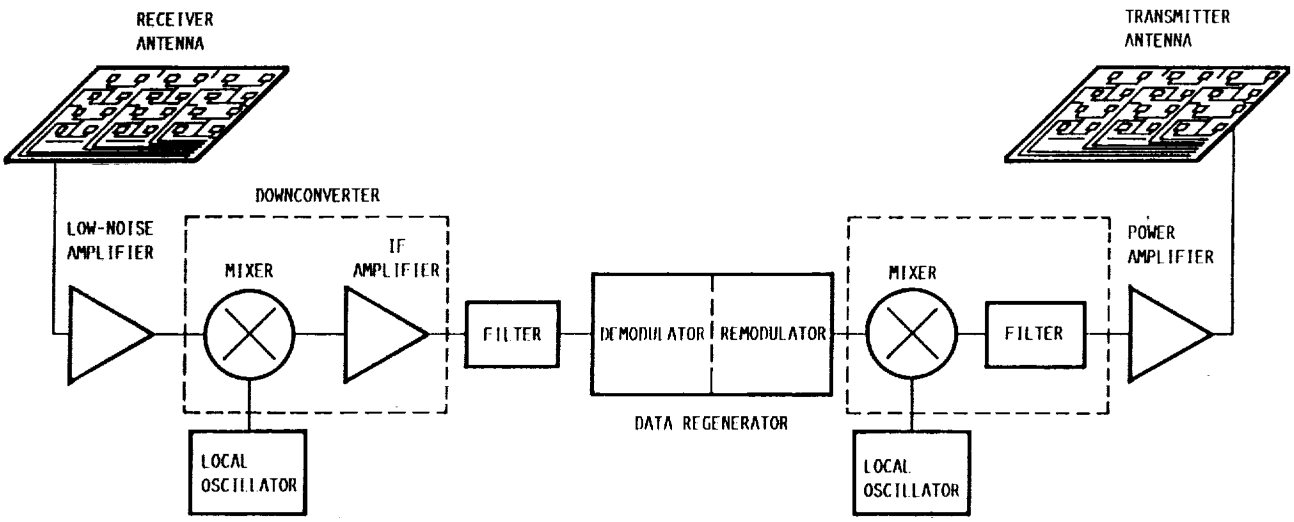
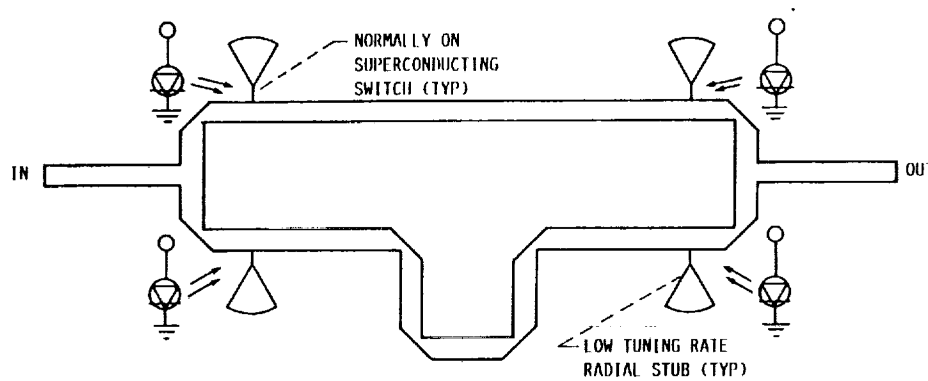
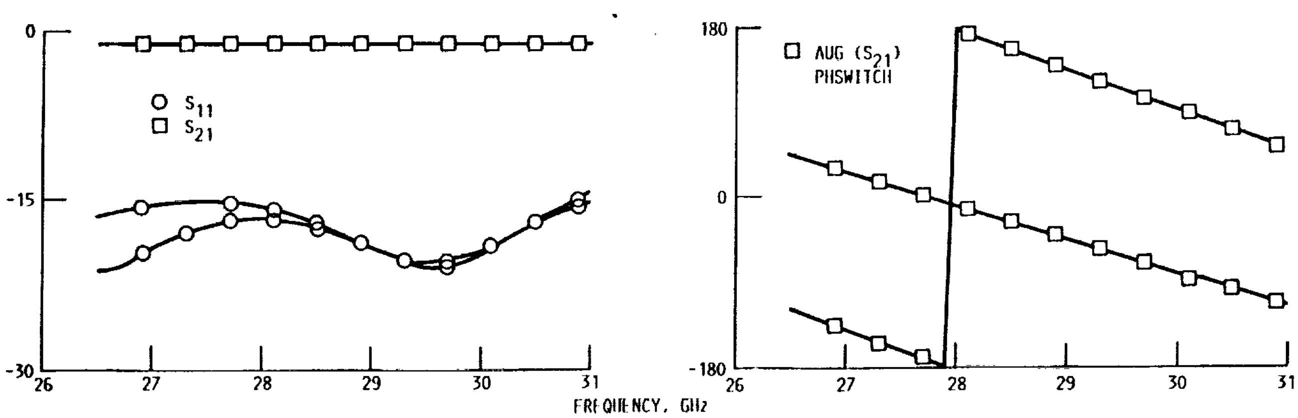


FIGURE 2. - BLOCK DIAGRAM OF A SATELLITE TRANSPONDER.



(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 3.

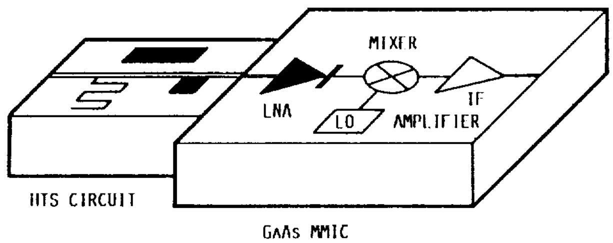


FIGURE 4. - SUPERCONDUCTING GaAs MMIC HYBRID RECEIVER.

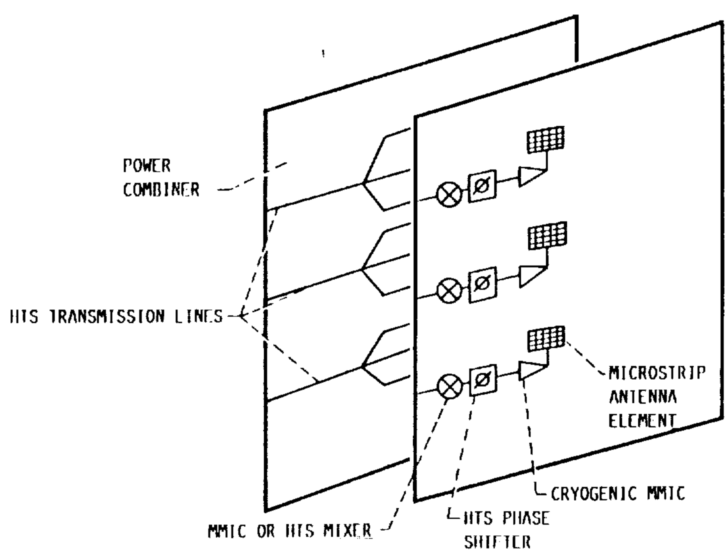


FIGURE 5. - CONCEPTUAL DIAGRAM OF A MMIC-SUPERCONDUCTING HYBRID PHASE ARRAY ANTENNA.

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16. Abstract

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