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High Temperature Superconductor Analog Electronics for Millimeter- Wavelength Communications

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HIGH TEMPERATURE SUPERCONDUCTOR ANALOG ELECTRONICS FOR MILLIMETER-WAVELENGTH COMMUNICATIONS

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ABSTRACT

The performance of high-temperature superconductor (HTS) passive microwave circuits up to X-band has been encouraging when compared to their metallic counterparts. The extremely low surface resistance of HTS films up to about 10 GHz enables a reduction in loss by as much as 100 times compared to copper when both materials are kept at about 77K. However, a superconductor's surface resistance varies in proportion to the frequency squared. Consequently, the potential benefit of HTS materials to millimeter-wave communications requires careful analysis. A simple ring resonator has been used to evaluate microstrip losses at Ka-band. We have also investigated additional promising components such as antennas and phase shifters. Prospects for HTS to favorably impact millimeter-wave communications systems are discussed.

INTRODUCTION

Thin film analog signal processing electronics was envisioned as the first practical application for high temperature superconductors. The major prerequisite for microwave circuits was comparatively low surface resistance as opposed to high current density or high critical magnetic field performance, although the parameters are correlated. The surface resistance (R_s) of normal conductors varies in proportion to the square root of frequency due to the skin effect, whereas for a superconductor the surface resistance is proportional to the frequency squared. The strong dependence of R_s on frequency for superconductors is a consequence of the reactive voltage associated with the oscillating supercurrent interacting with unpaired (normal) electrons to induce loss. The proportion of normal electrons varies from 0 at $T=0$ to 1 at $T=T_c$.

This property can be exploited to enhance passive microstrip circuitry, such as filters and phased array beam forming networks (BFNs). HTS microstrip enables tremendous miniaturization of filters without any concomitant degradation in performance compared to a waveguide implementation. HTS microstrip may also enable high directivity arrays because of

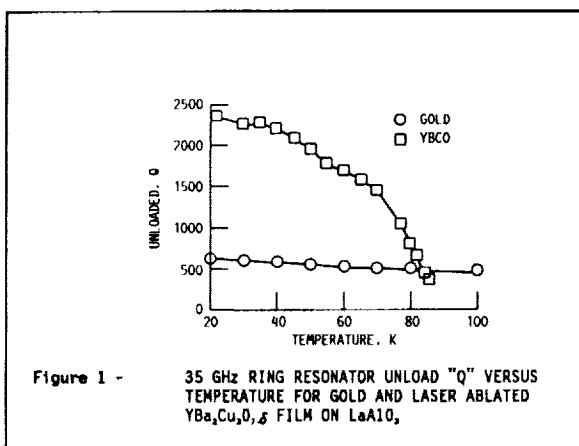
the greatly reduced gain degradation in BFNs. Antennas, phase shifters, hybrid superconductor/semiconductor circuits and other components are likely to profit from this property as well. This paper will examine the potential of passive HTS circuitry to favorably impact millimeter-wave communications.

The greatest contribution to millimeter-wave communications may ultimately result from active low- or high- T_c superconducting electronics. Digital signal processors utilizing Josephson junction (JJ) technology will almost surely evolve because of the three-to-four orders of magnitude improvement in the delay-power product. Low- T_c JJs operate ten times faster than any high density semiconductor device and consume 1000 times less power. The eventual possibility of high- T_c JJ chips has been suggested as researchers learn to intentionally manufacture arrays of large angle grain boundary junctions. It has been established for conventional superconductors that energy gap is approximately $3.5 kT_c$ at zero temperature where k is Boltzmann's constant. This gap varies slowly with temperature up to about $1/2 T_c$. Beyond about $2/3 T_c$, the gap diminishes precipitously, becoming zero at $T=T_c$. Consequently, in practice, device operation may be restricted to temperatures below $0.67 T_c$. It cannot be stated with certainty that this same phenomenon will govern high- T_c electronics. A novel active high- T_c device termed the superconducting flux flow transistor (SFFT), may lead to a new class of microwave electronics. The SFFT uses a current control line to create a magnetic field and induce flux motion which changes the terminal voltage. Hence, the SFFT is the electrical dual of the FET. The SFFT can produce a net gain and has been demonstrated in basic microwave devices. Although this paper will not focus on active high- T_c electronics, revolutionary advances in communications and high speed data processing will likely be derived from this facet of the technology.

Microstrip Ring Resonator

Microstrip ring resonators with a design center frequency of 35 GHz were fabricated from laser ablated YBaCuO thin films

deposited² on lanthanum aluminate substrates². The ring resonator technique provides a useful method for evaluating patterned film characteristics and includes film-substrate interface effects. Reflection coefficients were measured over a wide temperature range and performance was compared to identical resonators made of evaporated gold. The performance crossover, in terms of resonator "Q" which is inversely proportional to loss, occurred at about 80 K. The unloaded Q of the superconducting resonator was about 4 times better than gold at 20 K. Unloaded Q data as a function of temperature is shown in figure 1. As expected because of the dependence of internal inductance of the strip on the changing normal/superconducting electron densities, the resonant frequency was observed to have a negative temperature coefficient. This prototype device indicated the potential for HTS to enhance millimeter-wave microstrip circuitry.

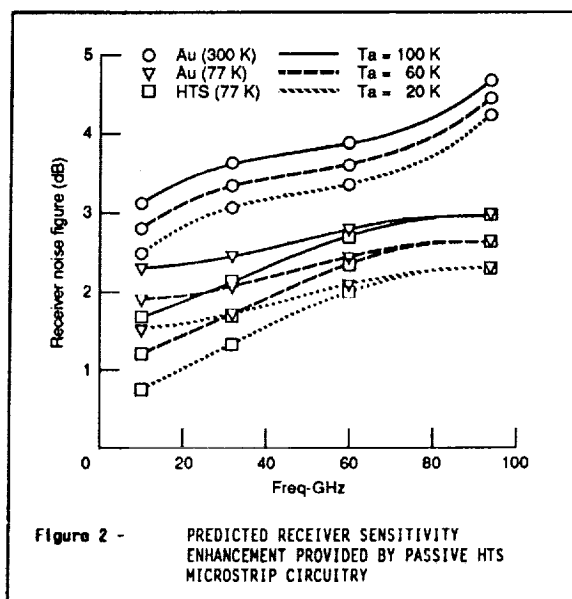


Low Noise Receivers

Because of the extraordinary distances involved and scarce transmitter power, receivers for deep-space links have extremely demanding sensitivity requirements. At the present time, maser amplifiers provide the only practical technology for interplanetary communications. The drawback to these systems is cost and the complexity of the necessary 4.5 K refrigeration. A promising alternative to maser technology is cryogenically cooled high electron mobility transistor (HEMT) low noise amplifiers (LNAs). Noise figures of HEMTs cooled below liquid nitrogen temperatures are approaching the performance of maser amplifiers. The minimum noise figure of a metal semiconductor field effect transistor (MESFET) scales as the reciprocal of the cutoff frequency (or transconductance). The high carrier mobility of a HEMT results in a much larger transconductance when compared to a conventional MESFET. Furthermore, the noise conductance is inversely proportional to the square of the

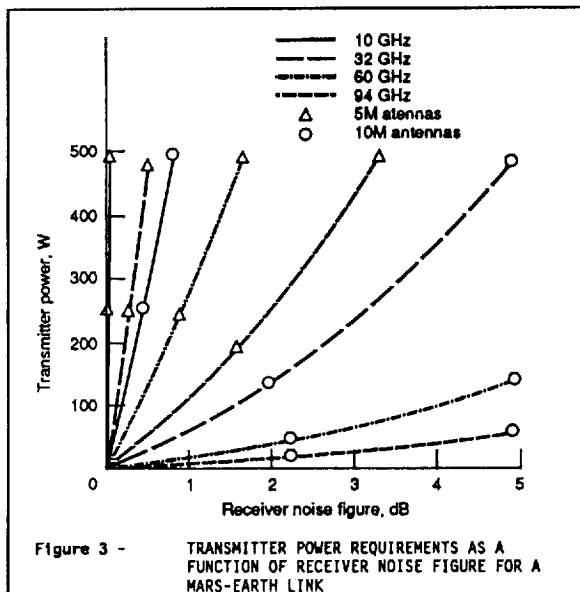
cutoff frequency. This reduces the HEMT's susceptibility to impedance variations and enables high performance over a wide bandwidth. The HEMT's performance also improves much more rapidly upon cooling than a conventional MESFET.

A possible Mars-Earth communications scenario calls for relay satellites in orbit about each planet. Because of the increased operating temperature, reduced cost, and improved reliability, HEMT LNA receivers may prove enabling. In order to assess the performance enhancement that HTS could provide to such a system, mock hypothetical receivers were designed at 10, 32, 60, and 94 GHz. Each simplified receiver consisted of an ideal antenna, 1.5 wavelengths of feed loss, a five-pole band-pass filter, three (10 and 32 GHz), four (60 GHz), or five (90 GHz) gain stages, and a mixer. Scattering and noise parameters of the hypothetical HEMTs were consistent with state-of-the-art performance^{3,4}. Since the LNA gain was nearly 40 dB in each case, any marginal improvement in HEMT gain upon cooling was neglected since it would not impact system sensitivity. A surface resistance of 5 milliohms at 30 GHz with a frequency squared dependence was assumed for the HTS. Figure 2 shows the modeled receiver noise figure as a function of frequency for gold microstrip at 300K and 77K and for HTS at about 77K. The shapes of the curves are largely an artifact of the chosen device parameters and the curve fitting algorithm. Obvious advantages of HTS over gold are indicated at lower microwave frequencies. An improvement in sensitivity of about 0.1 dB exists at 60 GHz. The enhancement diminishes to zero at 80-90 GHz.



The salient issue is the significance of the marginal improvements even at

millimeter wavelengths. Figure 3 demonstrates the merit of even minor sensitivity improvements for a Mars-Earth link. Channel assumptions were based primarily on an earlier study. For example, power efficient modulation permitting a receiver (energy per bit)/(noise power) ratio of 1.5 dB was assumed. A different range of 2.7×10^7 km, which would place the planets roughly at quadrature, was assumed. Data is plotted for both five and ten meter transmit and receive antennas. A reduction in receiver noise figure by several tenths of a dB corresponds to a transmitter power reduction of tens to perhaps hundreds of watts, or alternatively to a reduction in antenna size. The development of large deployable antennas represents a significant technical challenge. Voyager, for example, utilized a 3.7 meter X-band antenna. The NASA Advanced Communication Technology Satellite's 3.2 meter dish is the largest Ka-band antenna developed to date.

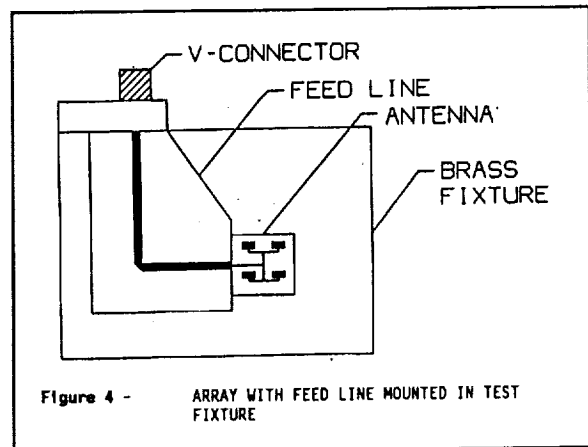


Superconducting Microstrip Antennas

Application of high T_c superconductivity to electrically short antennas, superdirective antenna arrays and millimeter wave array feed networks has been analyzed by several researchers recently^{6,7}. Their work has shown HTS may be most beneficial when used in the feed and matching networks for microwave and millimeter wave microstrip arrays. This is due to the fact that the maximum obtainable gain from an antenna array is limited by the ohmic losses in the metal microstrip transmission lines which form the feed network. Thus, even though the antenna directivity increases with an increasing number of elements, the gain is limited by the feed network losses. At millimeter waves the problem becomes even

more serious. However, recently Hansen⁷ showed an HTS 100 element linear array at 35 GHz could experience a gain increase of 8 to 10 dB over an identical copper array.

NASA Lewis Research Center and Ball Aerospace have designed, fabricated and tested 30 GHz four element superconducting microstrip arrays on various substrates. The antennas were assembled into a brass test fixture with a 50 Ω gold microstrip feed line patterned on an alumina substrate separating the coax-to-microstrip transition (Wiltron V-connector) from the antenna (Fig. 4). Wire bonds connect the feed line to the antenna. Wire bonds were made directly to the YBCO. To test the devices, each test fixture was in turn mounted at the second stage of a 2-stage closed-cycle helium refrigerator. A hermetically sealed coaxial feedthrough passes the RF into the vacuum chamber. A high-density polyethylene (HDPE) cap serves as both a vacuum jacket and a radome. The entire cryostat was mounted on the rotating pedestal of a far-field antenna range for pattern measurements in the receive mode.



The measured H-plane patterns are shown in Fig. 5 normalized to the highest received power for a magnesium oxide substrate. The antenna demonstrated a received power maxima at approximately 30.3 GHz and 31.7 GHz. H-plane co- and cross-polarization measurements suggest that the lower frequency resonance is primarily due to feedline radiation. The amplitudes of the received antenna patterns at 70K are comparable to gold levels. These results were anticipated for a first experiment because the HTS arrays are not yet fully optimized and the films used had a relatively low (below 85K) critical temperature T_c . Higher quality films and the use of ohmic contacts are expected to yield greater received powers for the HTS antennas relative to the gold circuits. It should be noted, though, that only 1 dB of improvement over the gold circuits can be expected for such a small number of

elements.

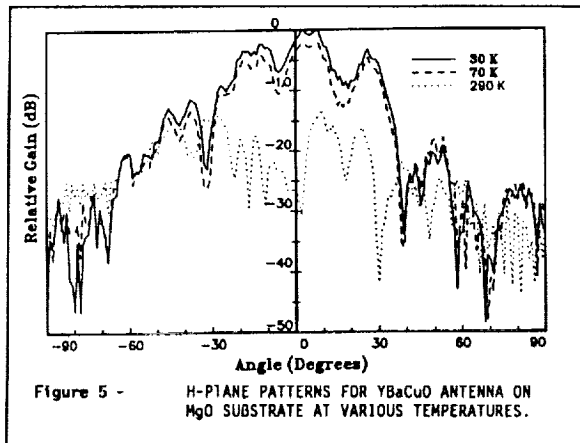


Figure 5 - H-PLANE PATTERNS FOR YBaCuO ANTENNA ON MgO SUBSTRATE AT VARIOUS TEMPERATURES.

The analytical and preliminary experimental work have shown that superconducting microstrip antennas have advantages over conventional antennas. It is also clear that the range of applications of superconducting antennas will be limited due to cryogenic requirements and the performance of superconducting films at frequencies above 50 GHz. However, in applications where high gain from the antenna is desired regardless of other considerations, high performance superconducting antennas will be likely candidates.

Microwave Superconductor Switches

The proposed superconductor switch consists of a rectangular patch of HTS material terminated by a quarter-wave radial stub, positioned one quarter wavelength away from a microstrip tee junction. If the switch is superconducting, its path appears as an ideal open circuit at the center frequency. It was determined that a 0.005 inch long, 25:1 aspect ratio HTS patch was nearly optimum for the design of a 32 GHz switched line phase shifter which will be described later.

Two possible modes of operation exist for a superconductor switch. The simplest is the bolometric mode, for which the film is held near its transition temperature. Normally, this technique exploits the fact that in this region, the temperature derivative of resistance is maximum. Incident radiation from an infrared light emitting diode or a laser raises the temperature and consequently causes the film to become resistive. This technique, although seemingly straightforward, has inherent speed limitations due to the high thermal conductivity of HTS compatible substrates. The problem for RF switching is compounded by the highly inductive component of the HTS near T_c . It is apparent from the observation of HTS resonator Q data that an acceptable reduction in loss

for switching purposes doesn't occur until the temperature falls to about 75% of T_c . Consequently, it is unlikely that a bolometric switch would be practical except under the most forgiving circumstances. To date, the fastest operation we achieved has been on the order of several seconds. Alternatively, magnetic field induced switching may provide a viable solution. The second operational mode is quantum mechanical. Incident photons with energy exceeding the bandgap break up the Cooper pairs and generate a population of quasiparticles. This effect destroys the superconductivity, resulting in a resistive film. Speed is limited only by carrier recombination time. Implementation of this type of switch is hindered by the need to precisely control film stoichiometry, surface quality, and film thickness. Furthermore, although this effect has been well documented for low- T_c materials, there is still much controversy regarding an analogous response in high- T_c films.

In a typical millimeter-wave device requiring RF switching, such as a phase shifter, the majority of insertion loss can be attributed to the parasitics associated with the switches. For example, metal line loss near 30 GHz on 0.020 inch LaAlO₃ is about 0.14 dB per wavelength. The parasitics of a typical MESFET switch could contribute as much as 0.5 dB to the total insertion loss. An "off" FET can be modeled as an RLC tank circuit. The inductor, L, is external to the FET and is included to resonate the circuit and improve the off-state impedance. The capacitor, C, is the total pinch-off capacitance between the source and drain, and the resistor, R, is the channel and contact resistance. An "off" HTS switch can be modeled by an inductor and resistor. The inductor associated with the HTS switch represents the large kinetic inductance term of the superconductor near T_c . It is this reactive term which necessitates operating the HTS switch farther below the transition temperature than normal for a "bolometric" type of device. Both switches can be accurately modeled by a single resistor, R_{on} , in the high conductivity state. Sokolov defined a suitable figure of merit for FET switching devices as:

$$Q^2 = (R_{on}R)^{-1} (\omega C)^{-2} = R_{off}/R_{on}$$

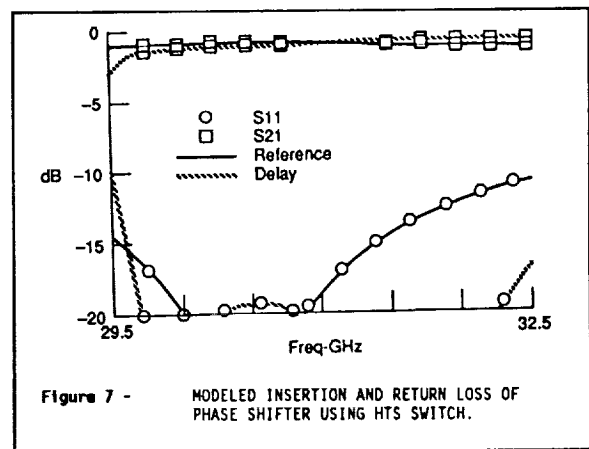
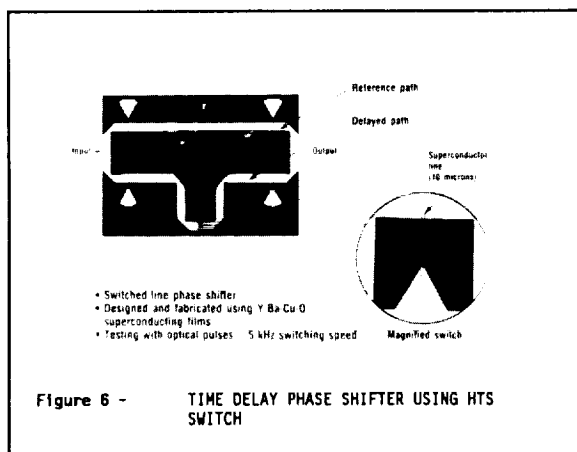
where ω is the radian frequency. For a typical switching FET, taking $R_{on}=10$ ohms, $C=0.07$ pf, and $R=5$ ohms, R_{off} is 1149 ohms at 30 GHz. This yields a figure of merit (Q^2) of about 110. If we consider an HTS switch, using a surface resistance of 0.010 ohms in the superconducting state, the equivalent resistivity at 30 GHz is $8.4e-8$ ohm-cm. Assuming a normal state resistivity of $1e-3$ ohm-cm, by toggling between the two states, the theoretical figure of merit is about 12,000. It is interesting to note that the semiconductor switching Q will degrade as the frequency

squared; hence, it can be expected that an HTS switch will outperform a MESFET switch throughout the millimeter wavelength portion of the spectrum.

An HTS Switched Line Phase Shifter

Phased array antennas require variable phase shift components for each radiating element to achieve spatial scanning. A true time delay phase shifter can theoretically provide frequency independent beam steering for large arrays. A popular method for implementing this concept is referred to as the switched line technique. This method achieves true time delay by switching the signal between two alternate routes; either the reference (zero phase shift) path or the delay path. The phase shift is proportional to the path length difference (Δl) and frequency. Hence the time delay, which is equal to the derivative of phase with respect to radian frequency, will be $\Delta l/c$. The array scan angle will be frequency independent since the radiating element spacing and the delay have the same dependence on wavelength. A minimum of three active devices configured as two single-pole double-through switches are required per bit.

Several disadvantages are inherent to this method of implementation: asymmetric insertion loss between the delay and reference paths, high insertion loss overall, and poor isolation between the radio frequency (RF) and bias signals. The effect of switching Q on insertion loss was discussed earlier. An equally vexing problem results from the interaction of the biasing network required to control the switches and the RF signal. Standing wave patterns are set up on the bias lines causing unpredictable performance and sensitivity to bondwire lengths. The proposed phase shifter is shown in figure 6.



If the switches in the reference line, for example, are superconducting they represent a high impedance path from the junction. Concomitantly, the shunt switches in the delay path are caused to become normal (resistive) via optical illumination or magnetic quenching, passing the RF signal. The switches were modeled as thin film resistors of variable sheet resistance in the design, and the influence of the switch reactance was incorporated as part of the radial stub. Figure 7 illustrates the predicted performance and reveals the exceptionally narrow insertion loss envelope and low total insertion loss.

Conclusions

The potential for HTS devices and circuits to contribute significant performance enhancements to millimeter-wave communications subsystems has been demonstrated. Reproducible, large area films on attractive substrates will be enabling for practical applications, as will economical, compact, and reliable cryogenic cooling systems. It is expected that the combination of superconducting antennas, feed networks, filters, hybrid LNAs, and phase shifters would enormously enhance system performance in terms of the gain/temperature ratio.

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