High Temperature Superconductor Analog Electronics for Millimeter-Wavelength Communications

R.R. Romanofsky and K.B. Bhasin
Lewis Research Center
Cleveland, Ohio

Prepared for the
Conference on Advanced Space Exploration Initiative Technologies
cosponsored by the AIAA, NASA, and OAI
Cleveland, Ohio, September 4–6, 1991
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 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-Tc 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-Tc JJs operate ten times faster than any high density semiconductor device and consume 1000 times less power. The eventual possibility of high-Tc 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 kTc at zero temperature where $k$ is Boltzmann's constant. This gap varies slowly with temperature up to about 1/2 Tc. Beyond about 2/3 Tc, the gap diminishes precipitously, becoming zero at Tc. Consequently, in practice, device operation may be restricted to temperatures below 0.67 Tc. It cannot be stated with certainty that this same phenomenon will govern high-Tc electronics. A novel active high-Tc 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-Tc 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.
inversely proportional to the square of the
circuitry. 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/supercon-
ducting 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. 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
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 millionhs 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
gain for gold microstrip at 300K and
77K and for HEMS 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 X 10^6 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.

![Figure 3 - Transmitter Power Requirements As A Function of Receiver Noise Figure For A Mars-Earth Link](image)

**Superconducting Microstrip Antennas**

Application of high Tc superconductivity to electrically short antennas, superdirective antenna arrays and millimeter wave array feed networks has been analyzed by several researchers recently. Their work has shown HTS may be more 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 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 Hansen 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.

![Figure 4 - Array With Feed Line Mounted In Test Fixture](image)

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 directive gains 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
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 switchable 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 metal substrates. The problem for RF switching is compounded by the highly inductive component of the HTS near Tc. 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 Tc. 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-Tc materials, there is still much controversy regarding an analogous response in high-Tc 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 switch. For example, metal loss near 30 GHz on 0.620 inch LaAIO3 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 Tc. 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, Ron, in the high conductivity state. Sokolov defined a suitable figure of merit for FET switching devices as:

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

where $\omega$ 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 per square, the equivalent resistivity at 30 GHz is 8.4e-8 ohm-cm. Assuming a normal 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 Δl/Δf. 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.

**REFERENCES**


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.