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SHORT COMMUNICATION

Superconductor Materials–A Revolutionary Value Addition to Space Electronics

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ABSTRACT

An early success in low temperature superconductor technology has led to the development of a number of high temperature superconductor (HTS) materials, which have critical temperature above 77 K. When the temperature of a solid is lowered below critical temperature, the material loses its electrical resistivity. Because resistance is almost zero, superconductors can carry very high current, generating very large homogeneous magnetic fields. Due to these features, it is possible to design electronic devices with extremely thin profile, offering less weight and low manufacturing cost. Such exceptional properties have made HTS materials useful in military and space sectors, where airborne systems have already provided with cryogenic infrastructure which can be used for cooling a high temperature superconductor at no extra cost.

Keywords: Superconductors, critical temperature, substrate materials, HTS materials, quality factor *Q*, antenna efficiency, *YBaCuO* infrared detector, superconductor materials

1. INTRODUCTION

Superconductivity was discovered by Kamerlingh Onnes at the University of Leiden in 1911. It is known that the electrical resistance in a superconductor is almost zero, it can carry very high currents at low voltages and operates in much smaller volume and weighs less than the conventional conductors. Even very large homogeneous magnetic fields can be generated from a superconducting wire or a small coil. High temperature superconductor (HTS) materials (with superconducting transformation temperature above 77 K) represent a new exciting technology. Due to the above unique properties, superconducting materials have been used extensively in many Defence applications, such as missiles, rockets, aircraft, global positioning systems, satellites, remote sensing, infrared detectors, command, communication, guidance, radar, etc.

Immense technological breakthrough in the development of HTS materials (1986), have led to the advances in the deposition of high temperature superconducting thin films on relatively low-loss substrate materials. High quality superconducting transmission lines, filters, resonators, etc, have been developed and recently, superconducting antennas with enhanced efficiency have been demonstrated in high frequency systems.

High temperature superconductor technology in practical microwave systems have been found in satellites and spacecraft, where partial passive cooling is feasible or where cryogenic infrastructure is already available or where the weight and volume advantages of the superconducting components make up for the additional cooling equipment and the power consumption. With the availability of highly efficient and small size cryogenic coolers, application

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of HTS technology has become feasible in a variety of airborne systems.

The major contribution that superconductivity has made to the passive microwave components is a drastic reduction in size and the achievement of much higher Q values (low-loss) than feasible with conventional technology.

Since liquid hydrogen is used in advanced chemical/nuclear propulsion systems as fuel/propellant liquid hydrogen refrigeration and handling systems are fairly common elements of space infrastructure. Liquid hydrogen at 20 K has more than twice the latent heat as liquid nitrogen has at 77 K. For future aerospace applications, large quantities of hydrogen, called as slush hydrogen, ie, at the triple point at 14 K and 1 psia would be stored. Both the density and the latent heat are about 15 per cent higher than liquid hydrogen at 1 atm and 20 K. Thus, a thermal environment suitable for 20 K superconducting system is available in a spacecraft and a satellite at no extra cost. This has made possible the effective use of HTS technology in space electronics.

2. SUPERCONDUCTIVITY

The success achieved in liquefying helium gas enabled Kammerlingh Onnes (1908) to measure the electrical resistance of metals at the lower temperature. The boiling temperature of liquid helium is 4.2 K at atmospheric pressure. In 1911, while studying the variation of the electrical resistance of mercury with temperature within a few degrees of absolute zero, Onnes observed that the electrical resistivity of mercury disappeared almost completely below 4.2 K. This state of material, in which the resistance is zero, is called the superconducting state. The current flows without any attenuation in this state, and it has been estimated that the decay time of a current in a superconductor material is about 100,000 years. The temperature below which a superconductor material loses its electrical resistivity is called the superconducting transition or critical temperature.

2.1 Theory of Superconductivity

In 1957, Bardeen, Cooper, and Schrieffer proposed a theory of superconductivity in which they expressed the superconducting transition temperature (T_C) in terms of an interaction between the electrons and the lattice vibrations of a solid. The lattice vibration is the periodic oscillation of the atoms in a crystal lattice about their equilibrium position. The electrical resistance of a metal at room temperature arises primarily from the scattering of the conduction electrons by the vibrating atoms. The higher the temperature, more violent the vibrations of the atoms; the more the scattering of electrons, the higher the electrical resistance. The quanta of lattice vibrations in a solid is called phonon. According to this theory, when the temperature of a solid is lowered, an interaction between the electrons and the phonons causes an attractive force between the conduction electrons forming Cooper pairs. These Cooper pairs are in paired states with equal and opposite momentum at zero super current. When a current is passed through a superconductor material, all the electron pairs have the same momentum directed parallel to the electric field. Due to this coherent motion, the electron pairs do not collide with the lattice, and hence, there is no electrical resistance[1-3].

2.2 High Temperature Superconductor Materials

High temperature superconductor materials are those materials which have critical temperature above 77 K. These HTS materials are inherently different from the low temperature superconductor materials in that these are copper oxide materials as opposed to low temperature superconductor materials which are metallic in nature. High temperature superconductivity has been found in the following family of compounds: *LaSrCuO*, *YBaCuO*, *BiSrCaCuO*, *HgBaCaCuO* and *TlBaCaCuO*. Each family of compounds has at least one superconducting phase.

For understanding the mechanism of superconductivity of high critical temperature (Tc) materials, the crystal structure of unit cell of $YBa_2Cu_3O_7$ (Tc = 93 K) is shown in Fig. 1. One generally accepted theory is that superconductivity occurs due to the flow of carrier pairs in the *Cu-O* planes of which there are two for each unit cell of the *YBaCuO* material shown in Fig. 1. The *Cu-O* planes lie just above and below the *Y* layer. The orbitals of the *Cu* and *O* atoms are strongly linked

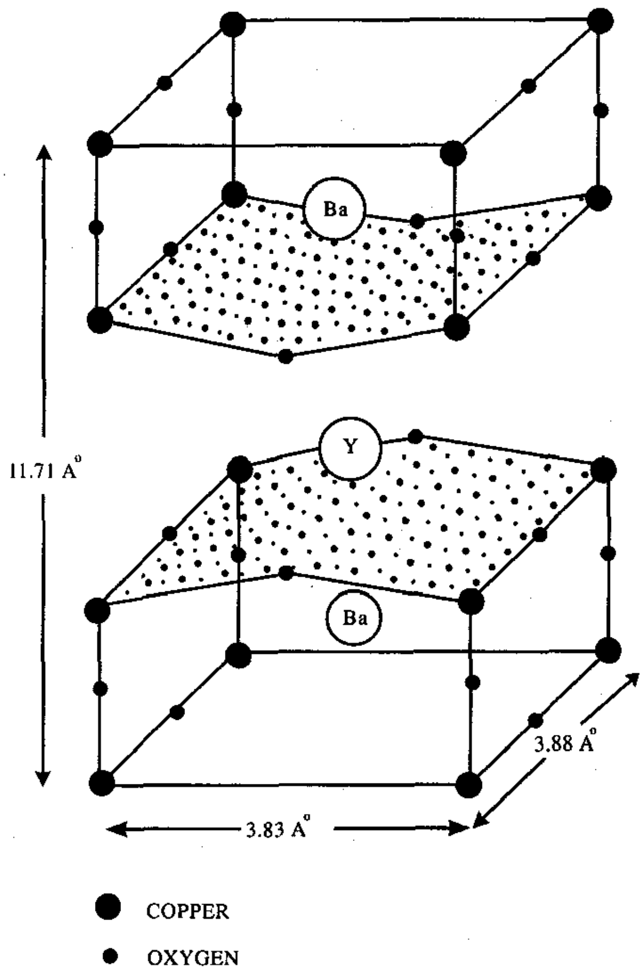

Figure 1. Crystal structure of *YBaCuO* material

in these planes, thereby accommodating conduction in the *Cu-O* plane. Perpendicular to these planes, conduction is poor and is attributed to the relatively weak linkage between the *Cu* and *O* orbitals across the *Y* layer. As a result, the conductivity is highly anisotropic.

Presently, it is unclear whether phonon interactions or some other type of mechanism is responsible for superconductivity of HTS materials. Critical temperatures of some common high temperature copper oxide superconductor materials are given in Table 1.

High temperature superconductor materials are used in two basic forms: Bulk and thin films. Thick films are less common. Bulk superconductors are simply independent polycrystalline or single-crystal samples of the material whereas thin-film superconductors are polycrystalline or single (epitaxial) crystal films of superconductors grown on a substrate materials. The dc resistance of these polycrystalline materials drops rapidly at the transition temperature, but these have high ac losses. The ac losses are attributed to several factors, such as lossy or insulating boundaries between the individual crystals within the material, poor orientation of the grains, and the presence of other superconducting phases. In addition, roughness, poor connectivity between regions, and impurities on the surface of the sample contribute to the high frequency losses.

Many of these factors are eliminated in single-crystal bulk materials, which have very low microwave surface resistances. Unfortunately, large single-crystal samples cannot be presently grown. Advances in bulk material fabrication, eg, the liquid phase or melt textured processes have produced highly oriented large area samples. These materials have large critical current densities and low surface resistance towards the eventual application of bulk superconducting materials.

The early technological difficulties associated with the development of large high quality bulk HTS materials amplified the interest in thin-film superconductors. The early thin film HTS materials had many defects leading to high losses. However, rapid advances in material deposition techniques like laser ablation and sputtering deposition, yield

Table 1. Critical temperatures of copper oxide super-conductor materials

Material	Critical temperature (K)
$YBa_2Cu_3O_7$	93
$Tl_2Ba_2CaCu_2O_8$	110
$Tl_2Ba_2Ca_2Cu_3O_{10}$	123
$Bi_2Sr_2CaCu_2O_8$	90
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110
$HgBa_2Ca_2Cu_3O_8$	135

very high quality thin films on a variety of substrate materials[2,3].

2.3 Substrate Materials

In printed-board technology, the substrate materials physically support the printed elements and give the thin-planar structure its rigidity and mechanical strength. The substrate also has the effect of concentrating the fields beneath the conductor materials. The basic requirements for microwave and millimeter wave substrate materials on which high quality HTS film can be grown, are as follows:

- Good lattice match with the superconducting material or the ability to support buffer layers that provide good lattice match .
- Low-loss tangent. Loss tangent is introduced in the design calculation to account for conductor loss, dielectric loss and radiation loss. Loss tangent (tan δ) significantly alters the magnitude of the input impedance.
- Low dielectric constant as far as possible.
- Nonreactive with superconductor or buffer layer at processing temperature.

At present, the substrate material that best satisfies all the above requirements and on which very high quality HTS thin films can be grown is lanthanum aluminate ($LaAlO_3$). Lanthanum aluminate has nominal dielectric constant of 24 and low-loss tangent (nominal) of 10^{-5}. It has a good lattice match with $YBaCuO$, therefore the films grown on these substrate materials are highly oriented, have fewer grain boundaries, and are more uniform than those grown on other microwave substrate materials. As a result, good $YBaCuO$ films on $LaAlO_3$ substrate materials have low surface resistance of 0.5-0.75 m ohm/□ at 10 GHz and 77 K and high transition temperature of 89-93 K. But the disadvantages of $LaAlO_3$ substrate include their high dielectric constant brittleness and large number of twin regions. The high degree of twining weakens the substrate and is often responsible for introducing loss in HTS films, causing weak links and grain boundaries. High degree of twining also causes variation of dielectric constant of $LaAlO_3$ not only from sample-to-sample, but even over a particular substrate materials. This uncertainty causes variation in device performance. To make matter worse, $LaAlO_3$ experiences a phase transition at the temperature required for the deposition of HTS films. Thus, the characteristics of the substrate often change during the deposition process. Several other competing materials like $SrTiO_3$, MgO, ZrO_2 (Y_2O_3), $NdGaO_3$ and γ-plane Al_2O_3 (sapphire) exist but these have to gain universal acceptance for various reasons, eg, films grown on these have higher surface resistance and sapphire being highly anisotropic.

It is also chemically incompatible with HTS materials, and hence, buffer layer is required.

- Magnessium oxide does not have good lattice match with HTS materials. It is hydroscopic, and therefore, has a variable-loss tangent.
- $ZrO_2(Y_2O_3)$ also requires a buffer layer as otherwise, it chemically reacts with HTS film at the processing temperature.

The relatively high value of dielectric constant for $LaAlO_3$ allows for the miniaturisation of microstrip devices, such as patch antennas. In an antenna array, this results in more space between the radiators, thus allowing for more flexibility in the layout and the inclusion of other devices. However, as a consequence of the high relative permittivity, the edge impedance of patch antennas becomes extremely high and the impedance bandwidth is reduced. Edge impedance for a rectangular microstrip patch antenna may become over 1000 ohm for 0.254 mm thick $LaAlO_3$ substrate. As a result, directly-coupled feeds must be inset well into the patch and these significant inset distances produce input impedance that are extremely sensitive to the inset depth.

An attractive alternative feed mechanism for planar-antenna structures is the gap coupling. Instead of directly connecting the microstrip feedline to the patch elements, a small gap is introduced between the end of the line and the edge of the antenna. When appropriately dimensioned, gap coupling provides a simple, yet effective impedance transformer between the low-impedance feedline and the high impedance patch.

To offset the reduced bandwidth resulting from the use of a high relative permittivity substrate material, the thickness of the substrate can be increased. This approach, however, has a significant drawback because increasing the substrate thickness also increases surface waves losses. For many applications, the effects of increased surface wave excitations are generally more serious than the reduced bandwidth. Designs with multiple layers of dielectric materials offer potential solutions to some of these problems, although these designs are complicated and present cooling problems because it is difficult to ensure low-loss thermal and electrical bonds between the layers[2,4].

3. ADVANTAGES OF SUPERCONDUCTOR MATERIALS

The primary advantage of using superconductor materials in high frequency electronic devices is the reduction in the ohmic losses compared to the identical devices constructed from the normal conductors. Therefore, the electrical parameter of interest is the surface resistance per unit area of the surface. For example, at 10 GHz and 77 K, the skin depth for oxygen-free high conductivity copper and the effective penetration depth of $YBa_2Cu_3O_7$ are both approx. equal to 0.25 µm, but surface resistance for copper is about 10 m ohm/□ and surface resistance for *YBaCuO* is as low as 0.15 m ohm/□ at 77 K.

Another advantage of using HTS materials is that it is possible to achieve a very high total quality factor Q which otherwise is not possible to be achieved using any other technology.

Due to the above reasons, it is possible to design electronic devices with extremely thin profile offering four outstanding advantages, namely low weight, low profile with conformability, low manufacturing cost, and increased mission life of the spacecraft on account of thermal savings by the superconductive leads. The conformality property of printed antennas, whereby radiating elements can be made to fit flush with nonplaner surface, is indeed an attractive design feature in aerospace technology.

4. APPLICATIONS

Because of these attractive features, numerous high temperature superconducting electronic devices have been fabricated for use in the military and space sectors. These include functions, such as guidance, fuzing, telemetry, command, communication, radar, ECM, ECCM, altimeters, beacons, GPS, etc.

Since the discovery of the *YBaCuO*, which is a high temperature superconductor material having high critical temperature, NASA has pursued a wide variety of HTS applications. Because the spaceborne systems already employ cryogenic refrigeration, no additional power or weight is required for incorporation of HTS devices. One use of space-based cryogenic systems is for cooling infrared and far-infrared detector systems. In general, infrared detector systems operate more efficiently at cryogenic temperatures, requiring the use of stored liquid helium to maintain the temperature at approx. 4 K. High critical temperature superconductors are used in such systems as detectors, detector leads, grounding straps, and magnetic shields. Several other space applications have been visualised using the environment of space to passively cool the devices on the shaded side of a spacecraft, radiating directly into the space. Specific components include waveguides, band-pass fi lters, and antennas in which the low surface resistance results in reduced RF losses.

Yttruim barium copper oxide is unstable in high humidity environment and in direct contact with water. When exposed to aqueous environment, $YBa_2Cu_3O_7$ breaks down to Y_2BaCuO_5 and $BaCO_3$. Degradation can be prevented using an encapsulation system or immersing the superconducting device in liquid cryogen during preflight storage. It has been found that during the normal life of 5-10 years of satellites and spacecraft, various detrimental aspects of the space environment like radiation effect, thermal cycling effect due to temperature changes in exposure to sun and shade, and vibration encountered during space flight have little effect on the performance of superconductor devices.

Some typical applications of HTS in space electronics are described.

4.1 Microstrip Antenna

Since the late 1970s , the international antenna community has carried out research on microstrip and printed antennas, which offer the advantages of low profile, compatibility with integrated circuit technology, and conformability to a shaped surface. This research has contributed to the success of these antennas not only in military applications, such as aircraft, missiles and rockets, but also in commercial areas, such as mobile satellite communication, the direct broadcast satellite systems, global positioning systems, remote sensing and hypothermia, and in spacecraft.

The evolution of microstrip antennas, or more generally, printed antennas has brought about a remarkable change in antenna design, and not the least, in generating multifunction configurations where constructional simplicity and low manufacturing cost are retained. The printed conductor element of a printed antenna can have a wide variety of sizes, shapes, and geometry, giving various benefits, namely control of bandwidth, beam shape and polarisation bandwidth extension, dual-band operation, etc. Due to the conformity property, the printed antenna can be mounted on the curved surface of a spacecraft or a satellite, including conical nose of a missile.

The basic form of microstrip antenna is shown in Fig. 2. It consists of a single-conducting metallic or HTS patch printed on a grounded substrate. The patch can be either rectangular or can have other geometrical shapes as per the requirement. Microstrip antennas are commonly fed by one of the three methods: (i) coaxial probe [Fig. 2(a)], (ii) stripline connected directly to the edge of a patch [Fig. 2(b)], and (iii) stripline coupled to the patch through an aperture [Fig. 2(c)]. Field lines are schematically shown in Fig. 2(d). Feeding by a coaxial probe has the advantage of ease in impedance matching and low spurious radiation and the disadvantage of having to physically connect the centre conductor to the patch. The advantage of directly connecting a stripline to the edge of a patch is ease of fabrication.

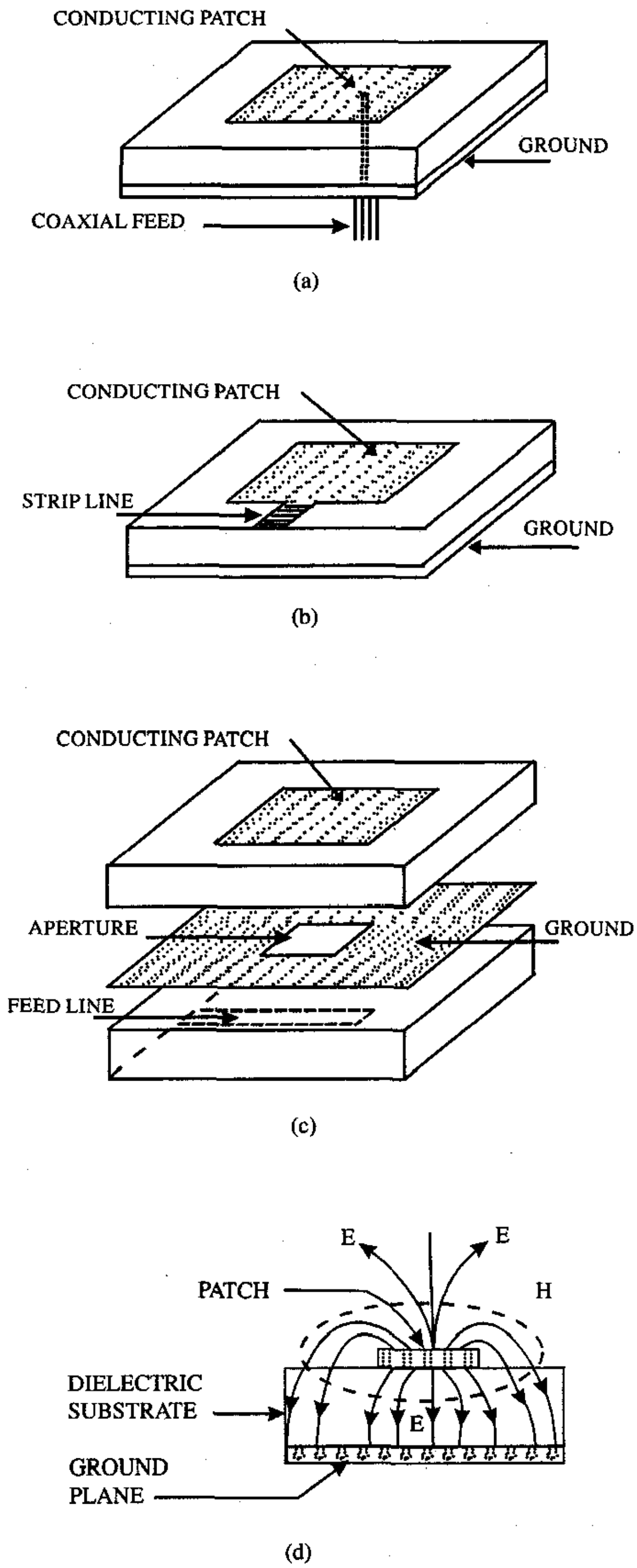

Figure 2. Basic form of microstrip antenna

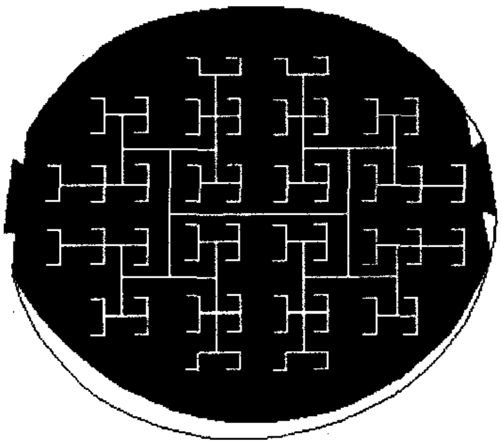

Figure 3. Microstrip dipole array used in Mars Pathfinder Mission.

However, there is a problem of impedance matching and there may be unwanted radiation from the feedline. Aperture coupling has the advantage of practically no spurious radiation as the feed network is isolated from the radiating element by the ground plane. Moreover, active devices can be fabricated in the feed substrate, leading to substantial reduction in size of the device.

To suit the particular application, a number of single patch elements are clubbed to have series fed, parallel fed, or a combination of series and parallel fed arrays. One such combination of microstrip dipole array is shown in Fig. 3 and was used in Mars Pathfinder Mission for deep-space telecommunication. Relative to a gold array at room temperature, the above HTS antenna exhibits an improvement of approx. 5 dB at temperature below 90 K.

The use of superconductor materials in passive antennas does not affect their radiation characteristics. These characteristics are usually associated with the physical construction of the antenna, and therefore, the antenna's radiation pattern and directivity will be unaffected by the use of superconducting materials.

The primary advantage of using superconductor in antenna systems is the reduction of the loss associated with transmission line-matching circuits, filters, and feed networks, particularly at microwave and millimeter wave frequencies, where the ohmic losses begin to significantly affect system performance. For the large antenna arrays with long elaborate corporate feed networks, the use of HTS transmission lines can substantially increase the gain of the antenna. These benefits become pronounced as the number of radiating elements in an array become large.

Results from the direct measurement of antenna efficiency of copper and *YBaCuO* rectangular microstrip patch antennas fabricated as per the geometry shown in Fig. 4(a) corroborated higher efficiency for the HTS antenna due to reduction in ohmic losses.

The antenna as shown in Fig. 4(a) is fabricated from 0.25 μm thick *YBaCuO* film deposited on 0.508 mm $LaAlO_3$ substrate using an *in situ* scanned, large area laser ablation system. The planar structures are patterned using standard photolithography with a negative photoresist, and the films are etched using ion beam milling. Coplanar waveguide (CPW) feedline is used. This CPW feedline is terminated in a loop to provide a monolithic low-voltage standing wave ratio (VSWR) feed.

A very good impedance match is obtained for CPW loop-fed patch antenna over a broad range of feed positions. The antenna element efficiency can be expressed as the ratio of power radiated into the space and the total power input. Power is lost due to losses in the dielectric, conductors, and radiation into surface waves.

Efficiency for the *YBCuO* antenna is approx. 97 per cent and for copper antenna, the same is about 77 per cent at 4.9 GHz as can be seen from Fig. 4(b). The design adopted in both the cases is as per Fig. 4(a). This gain is quite substantial.

In designing microstrip antenna for space application, three critical areas need to be considered are:

- The antenna must be able to survive the violent vibrations during launch from the earth. Generally, a shock of 10 Gs or more must be tolerated.
- The soldering points of connectors and the HTS films/substrate need to be made strong enough to survive the violent vibrations. Whenever possible, noncontacting feeds, such as proximity or aperture coupling must be used.

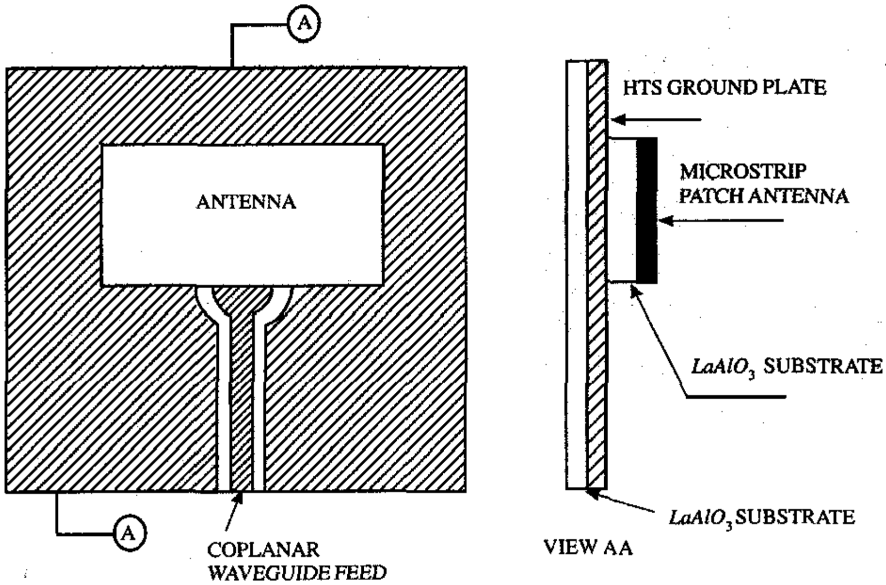

Figure 4(a). Coplanar waveguide

- The extreme temperature variations can occur in the space. Depending on whether the electronic device is facing the sun or is in the shaded area, the temperature on an average can vary between 173 K and 373 K.

The device shall have to be designed accordingly to survive this temperature variation. Otherwise if the device made of the HTS is kept at these high temperatures, it will no more be in the superconducting state. The RF power handling capability of the system is also there. Due to vacuum in space, a particular breakdown phenomenon known as multipacting generally occurs at pressure lower than 10^{-2} torr. At this low gas pressure, the electrons are more free to leave an electrode and move across to the opposite electrode. For a microstrip antenna, the two electrodes are the patch and its ground plane. Thus, to handle higher power in space, the microstrip antenna or microstrip transmission line must be designed with proper thickness.

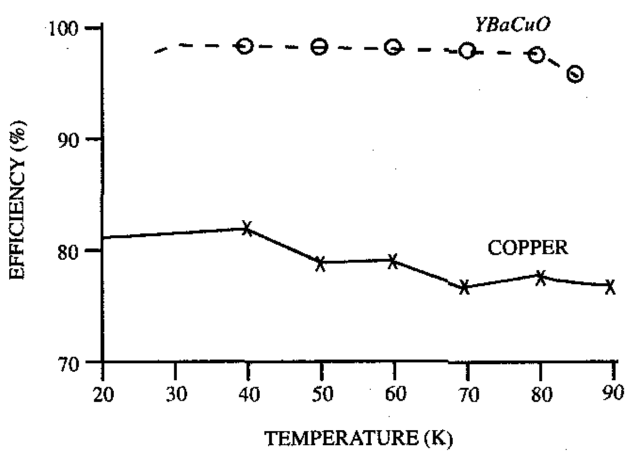

Figure 4(b). Efficient of *YBaCuO* and copper microstrip antenna.

Figure 5(a) shows a 20 GHz, 16-element microstrip array with a proximity coupled *YBaCuO* feed network. One of the advantages of proximity coupled design is to improve the bandwidth of the antenna. The array consists of 16 copper rectangular patches printed on a (1 mm thick) quartz superstrate that also functions as a window for the vacuum environment of the cryochamber. This superstrate is separated from the *YBaCuO* feed network by a small vacuum gap. Small (0.5 mm thick) teflon spacer are used to electromagnetically couple to the larger patches on the quartz. A thin copper film is evaporated on the backside of $LaAlO_3$ substrate as a ground plane for the HTS patches and the feed network. The measured gain versus frequency at 80 K for the HTS feed and an identical room temperature copper feed is also shown in Fig. 5(b). Over most

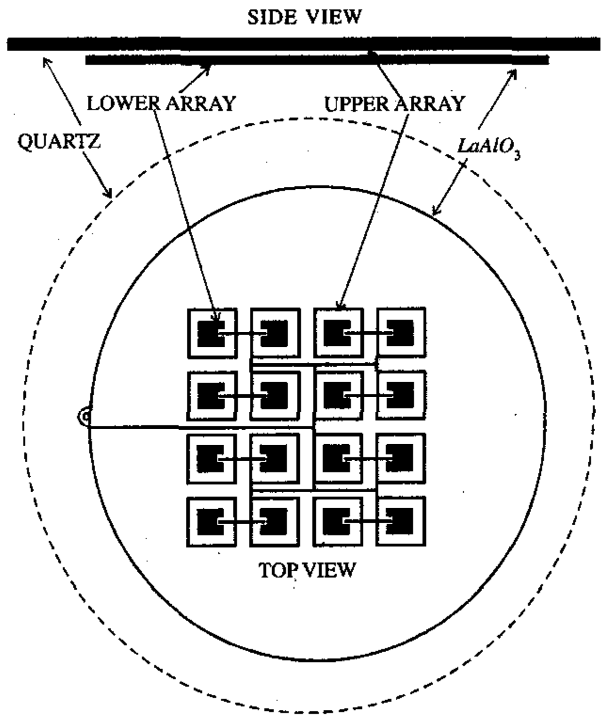

Figure 5(a). Proximity coupled microstrip array

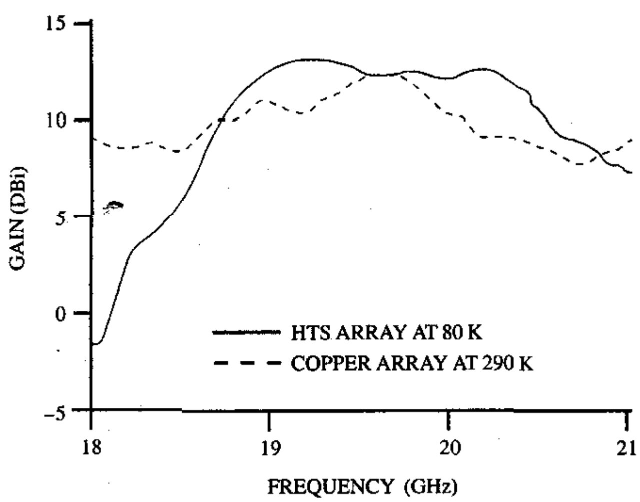

Figure 5(b). Gain *vs* frequency at 80 K for the HTS array

of the approx. 10 per cent operating band, the HTS antenna has significantly higher gain.

One of the primary advantages of using superconductor materials in an antenna system is the reduction of the loss in large transmission line feed networks, particularly at high frequencies where the ohmic losses of normal conductor materials are large. Figure 6 shows the efficiency of a 20 GHz corporate microstrip feed as a function of number of array elements. The antenna elements are assumed for simplicity to be matched to their corresponding feedline and the radiation efficiency of each element is assumed to be 100 per cent. Element spacing is $\lambda_0/2$ and substrate is 0.254 mm thick $LaAlO_3$. The results in Fig. 6 are representative of efficiency of feed network only, which is a single component of overall efficiency for the antenna system. The result shows that as the number of elements in the array increases, the efficiency of copper array decreases noticeably. On the other hand, the efficiency of the *YBaCuO* array remains relatively constant[5,6].

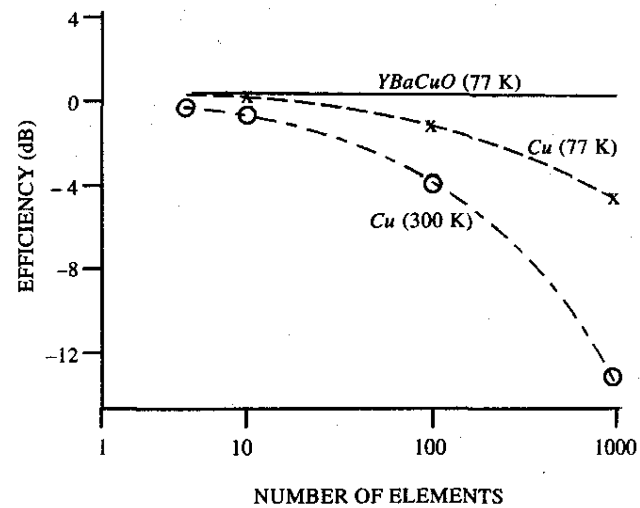

Figure 6. Efficiency vs number of antenna elements

4.2 HTS Thermal Bridges for Cryogenic Infrared Detectors

High temperature superconductor connector developed by NASA for remote sensing system offers potential advantages. Several infrared sensors used for detection in these systems require liquid helium cryogenic refrigeration for optimum signal-to-noise performance. The useful mission lifetime is limited by the rate of cryogen evaporation. Data acquisition and storage electronics are kept at a higher temperature, around 80 K. The conventional electrical connections using manganin wires connecting the cryogenically cooled detector and the storage electronics subsystem accelerate the evaporation of the liquid cryogen due

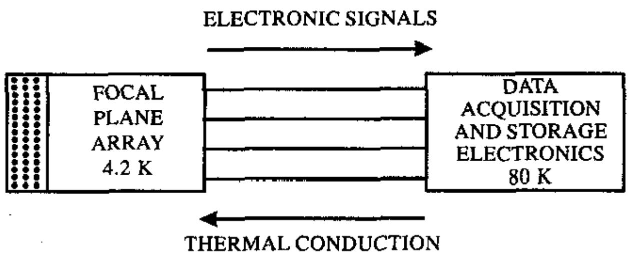

Figure 7. Thermal gradient

to thermal conduction along the wires, reducing the mission lifetime. The scheme of the thermal gradient is shown in Fig. 7. High temperature superconductor elements made of *YBaCuO*, screen printed onto ceramic substrates, if used, replacing the currently employed manganin wires would result in a substantial decrease in the thermal losses due to connections. The substrate would provide mechanical support for the weaker superconductive element. Substrate selection is the most critical parameter in device production as it contributes to 87 per cent of heat load for single-side printing and 80 per cent when superconductive leads are printed on both sides of the substrate. The balance heat loads are contributed by HTS. Yttria-stabilised zirconia (YSZ) has low thermal conductance and does not react with *YBaCuO*, and hence, presently is the best substrate material for this application. Yttria-stabilised zirconia substrate is found to reduce the heat load significantly, due to the glass-like thermal behaviour of these materials in the cryogenic region. The thermal savings for superconductive leads printed on both sides of YSZ substrate is about 14 per cent translating to about 1 year extension on a 7-year mission. Current density of this type of HTS has been found around 30-50 A/cm^2 for a thick film, which is more than adequate for detector applications in which a minimum current density, of the order of only 0.05 A/cm^2 is required[7].

4.3 High Temperature Superconductor Filter

HTS filter is not only promising in the microwave range but also at much lower frequencies. Small self-resonant HTS spirals have the potential for extremely high *Q* resonators in device volumes not achievable with any other technology. Figure 8 shows a design of a compact, highly selective filter at 100 MHz using 3 nos self-resonant spirals as resonator element (f-100 MHz; Δf = 50 kHz). Each spiral has 25 turn at 50 mm line spacing. Lanthanum aluminate substrate of 0.5 mm thickness is used

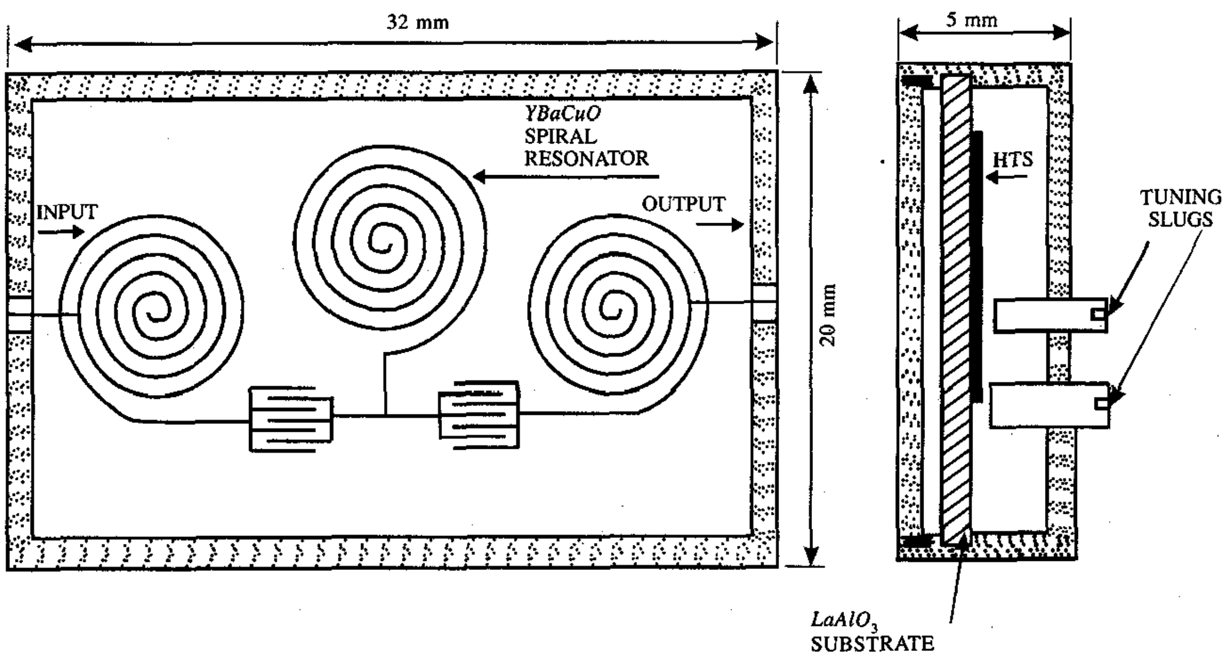

Figure 8. High temperature superconductor filter

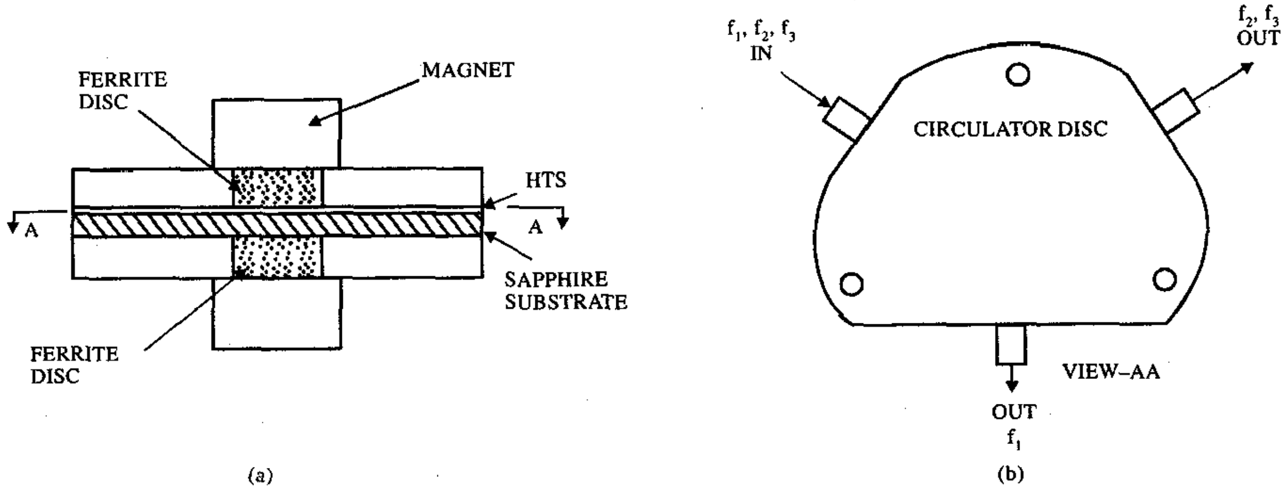

Figure 9. High temperature superconductor circulator

over which *YBaCuO* microstrip spirals are deposited. HTS microstrip ground plane is used. At 77 K and 100 MHz resonance frequency, each of the aforesaid HTS resonator has unloaded Q of about 20,000. High quality factor Q is the ratio of reactance to resistance. It is worthwhile to mention that Q of a resonator made of copper and with the same geometry is only 50 at the fundamental frequency of 100 MHz. Further at a centre frequency of 282 MHz, a rejection of 12 dB over 3 dB bandwidth of 21 kHz can be achieved using a single HTS resonator with the above geometry. The insertion loss is less than 0.1 dB, whereas the same for copper spiral at 77 K is 18 dB. Such high performance with a tiny device volume (32 mm × 20 mm × 5 mm) was unthinkable earlier. Multiple pole response can easily be obtained by coupling additional spirals to the main line or to the existing spirals[8].

Using planar resonators fabricated from superconducting films, it has become possible to implement stable microwave oscillators. Such a structure would be highly amenable to integration with semiconductor components and would have the advantages of having very small size, reduced circuit complexity, and increased reliability. Typically, one would anticipate unloaded Q's near 10,000 (at 8 GHz) from a planar HTS resonator. Such a high Q resonator makes it possible to have an oscillator with a phase noise better than –100 dB/Hz. Employing the superconducting oscillator, a superconducting input filter described above together with cryogenically cooled normal metal low-noise amplifier and mixer, both of which utilise conventional semiconductor components communication receiver, has been made and is extensively used in space sector[8].

4.4 Circulator

Circulators or isolators are widely used in many systems where the emphasis is on tight amplitude phase and group-delay specifications. Direct integration in close proximity with the sensitive components is important to derive the maximum benefit from the introduction of a nonreciprocal element. In addition, multiport circulators are valuable components in transmit /receive modules, modulators, comparators, and other critical-performance circuits. Whenever complex microwave systems are not operating properly, the cure very often is a liberal sprinkling of circulators between the components.

The device consisting of a superconducting *YBaCuO* film deposited on 150 µm thick substrate, 12 mm in diameter that is sandwiched between the two ferrite discs is shown in Fig. 9. A very thin sapphire substrate is chosen as carrier for the HTS film to keep the perturbation of the ferrite cavity, formed by the two ferrite disks at a minimum. The *YBaCuO* film is laser deposited over CeO_2 buffer layer to prevent chemical reaction between HTS film and sapphire substrate. A breadboard circulator of this design exhibits a very low insertion loss of 0.25 dB at 77 K, excluding connector losses. The isolation is better than 20 dB over a 10 per cent bandwidth with a peak value of 34 dB. Superconducting ground plane is required for low insertion losses.

Direct simultaneous detection of multiple signals with high dynamic range is one of the most difficult tasks in advanced communication or surveillance systems. The combination of very small superconducting filters together with a low-loss distribution network could have a revolutionary impact on spaceborne systems. One such multiplexer configuration using HTS filters directly integrated with HTS circulators on the same substrate is shown in Fig. 10.

The major advantages of such an arrangement are that the filters can be individually designed, aligned, and tested, essentially free of interference from their neighbours and amplitude differences, even in long multiplexer chains, could be kept at a minimum due to very low losses in the superconducting circulators and the associated distribution network. In addition, the small size and high Q resonators of the filters would make the volume of such a unit much smaller than the one using conventional technology[8].

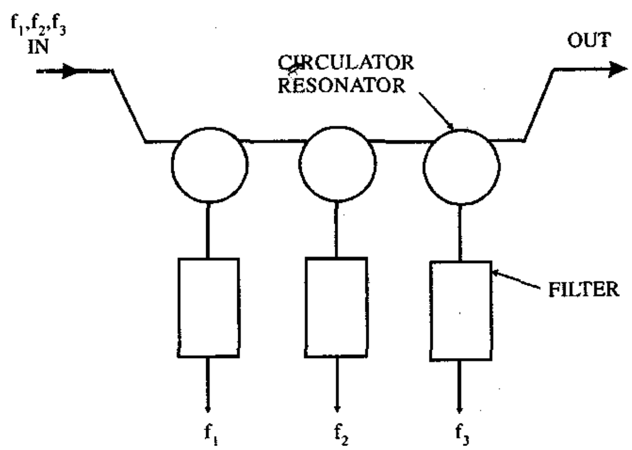

Figure 10. Multiplexer configuration of filter and circulator

4.5 Superconducting Phase Shifter

One device which has benefited greatly using superconductivity is the true time-delay phase shifter. Such a circuit, which is required for electronically-steered phased array antennas, switches an RF signal between the two alternate paths, one of which is physically longer than the other so as to provide a true time-delay phase shifter. Such devices, using a field-effect transistor as the active switching element, typically exhibits insertion losses of 1-3 dB, so that a 5-bit phase shifter, as would be required to obtain phase resolution of 11.5°, would suffer a loss of 5-10 dB.

The use of a superconducting patch as the switching element provides considerable improvement. The layout of such a phase shifter is shown in Fig. 11. Such a device utilises bolometric switching from the normal to the superconducting state with the heat being delivered optically via an optical fibre. Switching time of 100 ms is achievable. Faster switching times are attainable if low thermal conductivity substrate with acceptable microwave properties like YSZ is used[8].

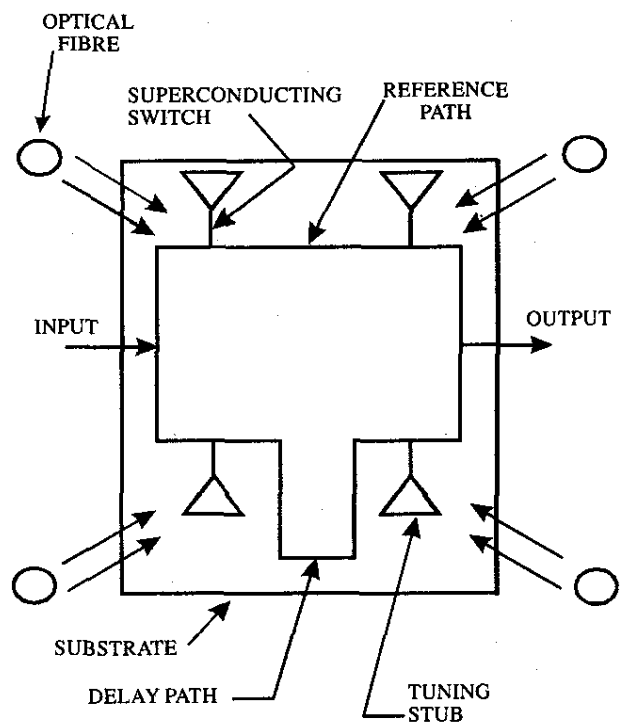

Figure 11. Layout of a true time-delay phase shifter

5. CONCLUSION

During the 20th Century, many revolutionary technological advances were made that substantially improved the quality, reliability, productivity, and reduced cost of various industrial products. HTS materials represent a new breed of technology which has rendered it possible to build highly reliable and cost-effective aerospace and defence electronic systems with hitherto unknown complexity and sophistication. The primary advantage of using the HTS materials in high-frequency electronic devices is the reduction in ohmic losses compared to the identical devices constructed from normal conductors. This makes it possible to design electronic devices with extremely thin profile and low weight with the advantage of low manufacturing cost and high reliability. Due to these outstanding qualities, the HTS materials are expected to dramatically revolutionise defence and aerospace sectors within 5-10 years. Due to technology denial by the advanced countries to India, it is essential to develop this new exciting technology indigenously to achieve the goal of self-reliance in aerospace technologies.

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