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NASA Space Applications of High-Temperature Superconductors

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NASA SPACE APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTORS

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SUMMARY

The application of superconducting technology in space has been limited by the requirement of cooling to near liquid helium temperatures. The only means of attaining these temperatures has been with cryogenic fluids which severely limits mission lifetime. The development of materials with superconducting transition temperatures (T_c) above 77 K has made superconducting technology more attractive and feasible for employment in aerospace systems. In this paper, potential applications of high-temperature superconducting technology in cryocoolers and remote sensing, communications and power systems will be discussed.

INTRODUCTION

There has been a great deal of interest in low temperature technology for space applications from the beginning of the space age. The initial interest was chiefly in using cryogens for rocket fuel and life support systems. The interest shifted later to scientific instruments. An example of such an application is Gravity Probe B (GPB) which is being developed to test certain tenets of Einstein's general theory of relativity. The experiment is designed to measure the gyroscopic precession which should result from the influence of the mass of the Earth on space-time. GPB makes extensive use of superconducting technology. It will have superconducting lead sleeves to attenuate the Earth's magnetic field. Rotating superconducting niobium-coated quartz spheres will act as gyroscopes, and SQUID magnetometers will measure their magnetic moments. There are many other examples of past and planned space missions which require low temperatures. One of the common elements of these missions is the use of liquid helium (up to 4000 L) to reach the low temperatures. Use of helium limits the lifetimes of the missions to less than 5 years.

This limited mission lifetime has been one of the key factors which has limited the applications of superconducting technology. Until the discovery of high temperature superconducting (HTS) materials, liquid helium was necessary to reach the temperatures at which materials were in their superconducting states. HTS materials with transition temperatures above liquid nitrogen temperature significantly reduce the cooling required to use these materials in space. A satellite using liquid nitrogen or hydrogen as a cryogen would have a much longer lifetime than a satellite which had the same volume of liquid helium. Mechanical coolers capable of cooling to 80 K are much further along in development than coolers capable of cooling to <10 K. Passive cooling can also be used to reach the 70 to 80 K range for very low heat loads. Because of the dramatic increase in transition temperature, superconducting technology may now be feasible for use in space for communication, power, and propulsion systems. Before HTS materials will be used in space, their long term stability must be demonstrated, especially in the space environment. Also, the added weight, power requirements and complexity of the necessary cooling must be included when estimating the benefits of using superconducting technology. Many applications have been suggested and investigated to determine the benefits of incorporating superconducting technology in space systems and are described below.

APPLICATIONS OF HTS MATERIALS

Cryocoolers

Space cryocoolers typically operate at or below 77 K and provide a natural cryogenic environment for HTS applications, with no additional weight/energy penalty to refrigerate the HTS component. Applications are being developed that potentially can significantly enhance cryocooler performance, efficiency, reliability and lifetime, such as HTS electrical leads for thermal isolation in space borne liquid helium dewars, damping of vibrations induced in the focal plane by Stirling cycle mechanical cryocoolers and passive magnetic bearings for turboexpander-type cryocoolers.

Some of the future NASA mission such as the Earth Observing System (EOS) will employ cooling of infrared and other types of sensors in order to obtain the required sensitivity and energy resolution. A large number of electrical leads, typically manganin wire, are needed to connect the sensors situated on the cooled focal plane at <10 K to instrumentation at a much higher temperature located outside the dewar. Another mission, the Advanced X-ray Astrophysics Facility (AXAF) will have immersed in liquid helium an adiabatic demagnetization refrigerator requiring nearly 3 A of current for operation. Although the sensor leads usually carry only microamps or less of current, they nevertheless comprise a significant parasitic heat load. For example, in the case of the Spectroscopy of the Atmosphere by Far Infrared Emission (SAFIRE) mission, the sensor leads constitute 33 percent of the instrument and 17 percent of the total heat load.

A high degree of thermal isolation can be achieved if the sensor leads are replaced by HTS copper oxide ceramics, which have thermal conductivities of less than one-fourth that of manganin. Using $YBa_2Cu_3O_{7-\delta}$ for just the 158 sensor leads in the SAFIRE dewar would reduce the total heat load by at least 8 percent and extend the mission life by more than 5 percent. Much larger extensions of lifetime have been estimated for other missions. Another important benefit of using HTS electrical leads, in addition to thermal isolation, is an estimated 10 to 100 times improvement in signal-to-noise ratio.

Stirling cycle mechanical cryocoolers are a leading candidate to provide the detector cooling required for the many far-infrared (>10 μm) experiments planned for the EOS missions of the late 1990's and early 21st century. In order to achieve precision imaging and high optical resolution, vibrations of the detectors induced by the cryocooler operation, as well as spacecraft induced resonances, must be damped. The generally accepted goal is 0.01 to 0.02 lb of force at the focal plane. One approach that is showing some success is back-to-back cooler operation supplemented by active electronic suppression of the fundamental cryocooler frequency (~40 Hz) and higher harmonics (ref. 1).

This approach, however, is unlikely to satisfy all the vibration damping requirements and it may be that an additional, and preferably passive, damping mechanism will still be required. $YBa_2Cu_3O_{7-\delta}$ materials, which have an inherent magnetic damping capability due to dissipation of energy by flux motion (ref. 2), could potentially provide this mechanism. Magnetic Technologies, Inc. laboratory experiments using nonoptimum materials and magnetic field geometry have demonstrated that presently available $YBa_2Cu_3O_{7-\delta}$ materials can provide at least an order of magnitude greater damping at 77 K than with no superconducting material.

Advanced turboexpander-type cryocoolers based on the Brayton thermodynamic cycle are being developed by NASA for future long duration missions. Important advantages offered by the turboexpander type, which use noncontact gas bearings, over the Stirling cycle mechanical cryocooler are potentially vibration free performance and greater reliability and lifetime. A disadvantage of the gas bearings is the need to run warm, which causes a large heat leak between the warm bearing zone and the cold expansion turbine, resulting in inefficient operation at low temperatures. Therefore, the need exists to improve the efficiency. A promising approach to eliminating the heat leak is to replace the rotary gas bearings with HTS passive magnetic (Meissner) bearings. A study by Creare, Inc. of a 1 W, 10 K cryocooler, where the gas bearings for the coldest turboexpander were replaced by Meissner bearings fabricated from currently available HTS materials, showed that a 40 percent decrease in input power was possible.

With $YBa_2Cu_3O_{7-\delta}$ materials prepared by the melt quench process, levitation forces are now adequate for cryocooler applications although some improvements in stiffness may be required (ref. 3). A rotational speed of 450 000 rpm (surface speed of 150 m/s) has been demonstrated by Creare, Inc. which is more than adequate for cryocooler applications (90 m/s).

Remote Sensing Applications

Many space-based sensing systems are cooled for improved sensitivity and decreased noise. This is another area of application where including HTS materials would have no cooling penalty when compared against nonsuperconducting systems. Three devices which would provide great benefit to near Earth and deep space missions are bolometers, mixers and signal processors.

In missions to the outer planets lasting ten years or longer, passive radiative cooling is presently the only satisfactory option for cooling the focal plane. This means the detector temperature is 70 K or higher. Studies of planetary atmospheres at wavelengths greater than 20 μm will require the use of thermal detectors (ref. 4). A promising candidate for this application is a transition-edge bolometer that uses the resistive transition of a HTS element as the temperature sensing element. Such bolometers have been demonstrated to be superior to pyroelectric detectors. Another type of bolometer is the kinetic inductance bolometer which potentially has much lower noise and higher sensitivity. The operation of this bolometer depends on the temperature dependence of the magnetic penetration depth just below T_c.

Submillimeter spectroscopy is an important objective of future missions for astrophysics and Earth atmospheric studies. Principle components for these studies are mixers. Thus far the most sensitive mixers in the millimeter to near submillimeter range have been Nb based superconductor-insulator-superconductor (SIS) tunnel junctions. HTS tunnel junctions could possible extend this frequency range well into the THz range. However, SIS tunnel junctions fabricated from HTS materials have not yet been demonstrated. An alternative approach is the superconductor-normal-superconductor (SNS) microbridge. Progress in HTS SNS is proceeding rapidly.

Locating a superconducting signal processor on a focal plane has many advantages over a semiconducting processor in terms of speed, power consumption and thermal loading. The higher speed would allow fewer data lines to the focal plane which means lower thermal loading. The development of such a processor is further in the future than development of HTS bolometers or mixers.

Space Communications Applications

In the past, the need for heavy, short life and complicated cryogenic systems near 20 K prohibited the use of superconducting electronics circuits in space communications systems in spite of their outstanding advantages when compared to room temperature semiconductor electronics circuits. Since this discovery, NASA has been very active in identifying the applications of HTS materials in space communications systems. The approach has been twofold: first to identify subsystems and communications scenarios where superconducting devices and circuits will have the largest impact and second to design, fabricate and characterize generic superconducting devices and components and compare their performance with conventional circuits to quantitatively determine their advantages.

Under the first approach, in-house application analysis (ref. 5) and studies conducted by TRW, Ball Aerospace and Varian were used to identify key applications and are listed below.

1. Ultra Low Noise Hybrid Superconductor/Semiconductor Receivers
2. Phased Array Antennas from 1 to 50 GHz
3. Digital Signal Processors
4. Traveling Wave Tube Amplifiers

These studies included the impact of cryocoolers in their comparison which has often been ignored. One of the key findings is that superconducting circuits can offer outstanding advantages in reducing a spacecraft's power, size and weight in high performance space communications systems. They can also provide low loss, low noise, high data rate subsystems. However, only in a communication scenario where such high performance is required, can one justify the use of cryocoolers.

Under the second approach, NASA has designed, fabricated and characterized microstrip and coplanar resonator circuits from X-band to Ka band frequencies (refs. 6 and 7), X-band filters, phase shifter switches (ref. 8), X-band superconducting resonator stabilized oscillators, Ka-band passive microstrip antenna (ref. 6) and hybrid superconductor/semiconductor low noise amplifiers using $YBa_2Cu_3O_{7-\delta}$ and thallium thin films on lanthanum aluminate substrates. Superconducting resonator circuits have shown higher "Q" values than gold circuits which translates into low loss passive microwave circuits (ref. 9). Superconducting filters have shown low insertion loss and higher "Q"s (ref. 7). Early evidence of superior performance of high T_c superconducting passive microwave components at liquid nitrogen temperatures has led Naval Research Laboratories (NRL) to evaluate their performance in several space experiments and expedite technology development (ref. 10). NASA has participated in NRL's High T_c Superconducting Space Experiment (HTSSE) I. NASA is also planning to participate in HTSSE II expected to be launched in 1996. For this experiment NASA Lewis Research Center and the Jet Propulsion Laboratory will be jointly developing an X-band hybrid HTS/semiconductor receiver. Also under planning is a Ka-band superconducting receiver antenna experiment as a part of a link between shuttle and Advanced Communications Technology Satellite.

For space communication applications, the discovery of high T_c superconductors has led to the development of high performance microwave components operating at 77 K. It is possible that these components may find use in real space communication systems demanding extraordinary performance. However, only the discovery of superconductors operating at 150 K can make their use practical in most of the space communications systems.

Space Power Applications

When high current density superconductors appeared in the early 1960's their potential for application to space power technologies was carefully explored since it seemed certain that a zero resistance conductor could lower the launch weight by reducing the masses of both the conductors and the power system. Further, it could allow the wide use of magnets which would no longer need large and heavy power supplies and/or massive amounts of iron. The price to be paid however was the need to maintain the conductor below its transition temperature. For the conductors then available this meant refrigeration to well below 20 K (typically 4.2 K). This constraint introduced weight, complexity and reliability issues that effectively foreclosed the use of superconducting technology in space power systems. As was found with terrestrial power applications, the use of superconductors offers an attractive payoff only for the very largest systems.

Now, in the 1990's, this issue is being reexamined as the result of two developments. First, we are seriously considering space missions, such as Moon colonization and Mars exploration, that will require large capacity (>100 kW) electric power systems and second, the discovery of HTS materials.

The most straight forward application of SC is direct power transmission. In this case we look at the wiring harness which carries power and control signals within the power management circuitry and between it and its electrical sources and loads. In reference 11 it was shown that, at a current density of 2×10^4 A/cm^2 a superconducting wire can reduce the launch weight dramatically. Since large space systems will require many kilometers of wire carrying many kilowatts, substantial savings are possible if it all could be operated below the SC transition temperature. In general, this is not possible, but it might be practical if the power source must be located a long distance from its load. Not only would a minimum weight penalty be incurred, but the system designer would have additional flexibility in choosing the system operating voltage. A recent design study (ref. 12) has shown that it is possible to use directional radiators to cool such a line to less than 77 K in orbits as close as 1000 km from the Earth and to even lower temperatures in deep space. The mass of such a system, which uses radiation shields and commercially available HTS materials is still substantially less than a comparable system with copper transmission lines and it requires no active cooling system.

About 30 percent of a transformer's weight is conductor, therefore it is another element of a power distribution system where superconductors might be usefully employed. Because the useful current density in superconducting materials is at least 100X greater than that of copper, the use of superconductors could eliminate more than 99 percent of this mass. In the case of capacitors only a small fraction of a capacitor's mass is conductor and therefore little is to be gained by the direct substitution of superconducting material. Of course, transformers and capacitors are elements of ac systems and the largest impact of superconducting technology on power systems might come from their elimination as the use of superconductivity could make dc systems more interesting (ref. 11).

This long term storage of electrical energy as a magnetic field is only feasible if superconducting inductors are used since the I^2R losses of normal conductors would quickly dissipate the energy. Early examination (ref. 13) of its potential for use as a space "battery" showed that it has some important advantages. Such a storage system has virtually no losses, allowing the recovery of 95 percent of the input, and would tolerate a wide range of charge/discharge rates. Further, it would have an unlimited cycle life. The specific energy, which is limited by the forces that the field exerts on the conductor, has been estimated at near 50 W-hrs/kg, which is competitive with NiH_2 batteries.

Presently most space systems depend on photovoltaic arrays for primary electrical power and with increased power demands the arrays can reach large sizes. Also, in many orbits there is sufficient plasma density such that arcing can be a problem at >150 V. Therefore power from these large arrays may have to be carried to their loads at high currents. The weights of these conductors, presently 3 to 5 percent (ref. 14) of the array mass and the 1 to 2 percent of the array lost to I^2R can be substantially reduced by the use of superconductors. Although the percentages are small, in large or multiple systems the absolute weight and money savings can be nontrivial. It remains to be seen if the system complexity introduced by the need to thermally shield the superconducting components will discourage its use in this application.

Many other space applications of superconducting technology in addition to the ones discussed above have also been identified. These include active bearings for rocket engines and magnets for magnetoplasmadynamic thrusters.

CONCLUSIONS

The discovery of materials which are superconducting above liquid nitrogen temperature has made superconducting technology more attractive and feasible for use in aerospace systems. For some future missions where cooling is necessary to fulfill the mission objectives, the HTS materials meet all the technical requirements and are likely to be used after the material stability issues have been settled. For other missions, the added complexity of cooling must be justified by the improved performance offered by superconducting technology. If materials are developed with higher transition temperatures, cooling will be much less of an issue, and the use of superconducting technology should become much more widespread in space-based systems.

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