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APPLICATIONS OF HIGH TEMPERATURE SUPERCONDUCTORS IN ANTENNA SYSTEMS

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Abstract

This paper will present an overview of of the history of superconductivity, the basic physics which is the foundation of the phenomena, an approximate engineering model which provides insight into the electrical behavior, and an investigation of several high frequency superconducting monolithic antennas.

1. Introduction

The discovery of superconductivity in copper oxide materials at temperatures above that of liquid nitrogen (77K), has gained the attention of scientists and engineers around the world. In the time since the initial investigations a great deal of progress has been made. Significant advances have been made in the deposition of high-temperature superconducting (HTS) thin films on relatively low-loss substrate materials. Commercial quality superconducting transmission lines, filters, and resonators have been developed [1-2]. More recently superconducting antennas systems [3-9] have also been demonstrated that provide for efficient radiation at microwave and millimeter wave frequencies.

The primary advantage of using superconductors in antennas systems is the reduction of ohmic losses associated with the radiator and the ancillary feed and matching networks. This is especially appropriate for higher frequency applications where such losses typically have a serious effect on system performance. The additional complexities inherent in the use of superconducting materials limit applications to those where the conductor losses using normally conducting materials becomes prohibitive.

2. History

The history of superconductivity began in 1911 with the Dutch physicist, Kamerlingh Onnes, who discovered that mercury lost all its resistance to the DC conduction of electricity when its temperature was lowered to a point near absolute zero (4 K). Other superconducting metals were discovered at various times over the next 85 years with lead having the highest critical temperature (7 K). During the time period from 1950 to 1980 several superconducting compounds and alloys were developed with Niobium - Germanium providing the highest critical temperature of 23 K.

In the late 1980's and early 1990's the whole world of superconductivity was revolutionized by the discovery of several families of copper oxide materials that produced critical temperatures above that of liquid nitrogen (77 K). This was a most significant step since the previous "low" temperature superconductors relied on liquid helium (4 K) for their cooling. The new "high" temperature materials could use liquid nitrogen, which is much more economical, both because it is less expensive, and because a lesser volume is required to cool the same mass.

3. Superconducting properties

The superconducting state possesses two very distinctive properties. First it effectively has zero DC electrical resistivity at temperatures below its critical temperature (Tc). This does not mean, however, that a pure superconductor will have negligible resistivity for higher frequency applications. Indeed its losses vary significantly with frequency, and depending on the material and the frequency of operation, could be even larger than conventional conductors. The second property is the near-perfect diamagnetism in the presence of a weak magnetic field. This results in the exclusion of the magnetic flux from the interior of the superconductor, except within a thin region at the surface. It is this property that distinguishes a superconductor (even at DC) from a theoretical "perfect conductor".

It should be noted, however, that these superconducting properties are somewhat fragile in nature. As mentioned earlier the superconductivity is destroyed if the temperature is raised above the critical temperature Tc. Its immersion in a magnetic field above a critical field level, or the presence of current densities beyond a critical limit, also result in the loss of the superconducting properties. An upper limit on frequency is also present, but for HTS materials it is usually so high that it is not a concern in ordinary applications.

4. Engineering model

High temperature superconductors have a complex conductivity which is a function of frequency, temperature, and its intrinsic material properties. It is a macroscopic constitutive parameter of the material for which no exact theory has been developed. An approximate, empirical model called the two-fluid model, however, adequately predicts its most important electrical properties. It assumes that a fraction of the conduction carriers are in the superconducting state and the remaining ones are in the normal state. The current then has two components, one which is superconducting and the other which is normally conducting. The normal component satisfies Ohm's Law and is responsible for the losses that are found. The number densities of the normal and superconducting carriers are critically dependent on both the temperature and the frequency. This simple model is seen to predict the basic loss structure for AC applications with practical HTS materials at microwave and millimeter wave frequencies.

5. Substrate materials

The quality and superconducting properties of a HTS thin film are critically dependent on the substrate material on which the film is deposited. The dielectric material must have both a good lattice match with the superconductor and also have similar thermal properties. Ideally these substrate materials should have very low loss tangents at microwave frequencies. The most commonly used substrate at he present times lanthanum aluminate. It satisfies most of the criteria, but does have a rather high dielectric constant and is also quite brittle.

6. Microstrip antennas

A typical microstrip antenna may have a quite high efficiency, but its level is limited by radiation into the surface wave associated with the dielectric substrate. For this reason and others microstrip patch antennas are often designed on electrically thin substrates.

Unfortunately this results in an increase in both the conductor and dielectric losses and thereby decreases the efficiency. These losses can be decreased substantially by the use of high quality HTS thin films to fabricate the antenna. These materials can typically provide microwave surface resistivities that are one to two orders of magnitude less than that of copper at the same temperature. Thus, properly designed microstrip antennas can show a reasonable increase in efficiency without a serious decrease in bandwidth (since the Q is still limited by the dielectric loss).

7. High frequency arrays

There are many applications today for large antenna arrays with long, elaborate corporate feed networks which operate at high frequencies. Microstrip or stripline feeds can be very lossy at these frequencies and waveguides can be quite bulky. As the size of the array increases the directivity increases, but so does the complexity and total length of the feed system. At some point the overall gain of the array eventually reaches a maximum. As the size of the array is increased further the ohmic losses in the feed network increases more rapidly than the directivity and the gain begins to decrease with the increasing size of the array. The use of HTS materials in fabricating the feed structure and any associated matching networks can, therefore, reduce the ohmic losses and allow larger arrays to be utilized efficiently.

8. HTS Leaky-Wave Antenna

At high frequencies electrically large leaky wave antennas become feasible sources of simple, highly directive radiation [10]. They typically consist of a highly reflective interface over a grounded substrate. The use of layers of dielectric materials to provide the interface results in a structure that is very dependent on the exact thicknesses and dielectric constants of the layers. A normally conducting layer would provide a simple highly reflective interface, but its skin effect losses would result in an antenna of essentially zero efficiency. A very thin film of HTS material, however, appears to be ideal for this purpose. The fact that the field penetration into a superconductor is independent of frequency and is intrinsic to the material, combined with the low loss properties, can result in a efficient high gain leaky wave antenna. It is an extremely simple monolithic structure and consists of a substrate backed by an HTS ground plane that is then covered by a very thin film of HTS material, fed from behind the ground plane by a waveguide feed. The design is most appropriate in the millimeter wave frequency range because high gains can be obtained even with the use of small diameter substrate materials.

9. Future challenges

Many technological challenges remain to be investigated before practical HTS antenna systems can be made available for a broad range of system applications. Better packaging and economical cooling of the overall radiating system need to be developed. Larger area thin films are required for lower frequency applications and for more complicated radiating structures. Substrate materials with lower values of dielectric constants that retain favorable loss tangents would allow additional radiators to be designed. Good quality double-sided substrates would also be most beneficial to aid in practical design of simple antennas.

HTS materials are not appropriate for most antenna applications. The added complexity of the cryogenic cooling eliminates many applications before they could even be considered. The requirement of the use of high dielectric constant substrates likewise adds significant restrictions on their use. However, under special circumstances the use of HTS materials offers the potential of overall gains in efficiency and simplicity of fabrication.

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