Abstract: In order to understand the possible processes of charge transport common to ferroelectric ceramics and high T\textsubscript{c} superconductors a variety of investigations are underway. Microwave studies on these materials have attracted the attention of scientists in recent years. Some potential experimental techniques for studying ferroelectrics and superconductors will be discussed. Some common intrinsic features of these materials will be highlighted.

Results on dielectric behavior, microwave absorption, and surface impedance of some of these materials will be discussed.

Introduction

Discovery of high T\textsubscript{c} superconductors has brought a kind of scientific and technological revolution. Expectations are high and a long journey has just become.

Recently a possible relationship between ferroelectricity and high T\textsubscript{c} superconductivity has been pointed.\textsuperscript{1,2} Müller\textsuperscript{1} initiated these efforts that have been extended to a larger extent.\textsuperscript{2,3} The presence of ferroelectric like polarizabilities in superconductors may exist in the phase preceding the metallic or the superconducting state. To further strengthen these possibilities, experiments with a variety of probing tools are going on.

Why microwave studies? There are several favorable situations to support microwave investigations.

It is being strongly felt that first useful applications of high T\textsubscript{c} superconductors will emerge in the area of microwave devices and circuits. In fact, cavities, filter circuits, and interconnects using these materials have been successfully fabricated. If materials are going to be handled at microwave frequencies their properties need to be investigated in that frequency region since low frequency extrapolations will sometimes be wrong and often inaccurate. Further, in many situations (often encountered with ferroelectrics and superconductors) microwave measurements offer advantage over their low frequency counterpart. Some of these advantages are:

1. Higher accuracy of measurement arises due to large Q's (~ 10,000) of cavities often used in microwave measurements and due to very high signal detection efficiency (~ KHZ in GHZ up to 80/90 dB dawn).

Considerations of measurement accuracy become important, for example, in the detection of intermediate phases. Phases even in dilute concentrations are detectable. Figure (1) shows a result on 0.7 PMN-0.3 PT ferroelectric relaxor.\textsuperscript{4} A mild hump (region A) in the low frequency dielectric response turns to a well formed peak in the microwave measurements. This peak indicates the presence of morphotropic boundary in the 0.7 PMN-0.3 PT system. X-ray and pyroelectric studies also support this observation.

2. Microwave studies are capable of revealing information on the behavior of high T\textsubscript{c} superconductors below transition temperature also. As an example, results are shown in Fig. (2) on the effect of magnetic field on temperature dependence of the transmitted power for YBaCuO sample.\textsuperscript{5}

3. Microwave measurements are basically electrodeless and therex no need for fixing electrodes on the specimen. Microwave results, therefore, represent true material characteristics free from possible modifications arising due to space charge/electrode effects.

4. The microwave measurements are less susceptible to pathological current geometries as compared to dc methods and thus represent intrinsic nature of the material.

5. Many microwave techniques require extremely small quantities of the specimen. For example, the perturbation resonance technique\textsuperscript{6} uses a superconductor specimen of volume 0.004 cm$^3$. This may be a useful consideration for studying small crystal, for example.

Experimental Techniques

In the study of high T\textsubscript{c} superconductors two types of microwave measurement techniques have been normally used.

1. Resonance cavity perturbation techniques.

2. Reflection/transmission techniques.

Cavity Perturbation Techniques

In these techniques, the presence of small amounts of a material changes the resonance frequency and the quality factor Q of the microwave cavity.

Cylindrical and rectangular shaped cavities are often used in practice. Also cavities made from purely superconductor materials as well as from conventional metals have been used and both yield identical results.

![Figure 1. Dielectric constant of 0.7 PMN-0.3 PT as a function of temperature. Small hump (region A) in low frequency data is observed as a peak at 10 GHz due to higher sensitivity of microwave technique (Lanagan et al.\textsuperscript{7}).](image-url)
Figure 2. Effect of magnetic field on the temperature dependence of the transmitted microwave power for a YBa2Cu3C>7-8 sample (Wijeratne et al. 7).

For a rectangular cavity, for example, the real and imaginary parts \( e' \) and \( e'' \) of the complex permittivity of the material \( (e^* = e' - je'') \) are related to changes in resonance frequency and in quality factor in the following manner.\(^{3}\)

\[
e'(\frac{f - f_c}{2f_c})^2 + 1
\]

\[
e''(\frac{V_c}{4V_s})\left(\frac{1}{Q_s} - \frac{1}{Q_c}\right)
\]

Here, \( f_c \) and \( f_s \) are resonance frequencies with and without the specimen, respectively, and \( Q_s \) and \( Q_c \) are corresponding loaded Q values of the cavity. \( V_c \) and \( V_s \) are cavity and sample volumes, respectively.

\( e'' \) is the loss factor which is a direct measure of microwave absorption. Losses in the material are sometimes expressed as loss tangent, \( tan\delta = e''/e'0 \).

The surface resistance of the sample can be expressed in terms of the measured Q's as

\[ R_s = \gamma \left(\frac{1}{Q_s} + \frac{i}{Q_c}\right) \]

\( y \) is a geometric factor. It is convenient to normalize the surface resistance with respect to surface resistance at transition temperature.

\[ R_s = 4\frac{1}{\alpha(T_s)} - \frac{2\alpha}{\alpha(T)} - \frac{\alpha}{\alpha(T)}\]

Reflection/Transmission Techniques

In these techniques a small section of waveguide or coaxial line is filled with the material (Fig. 3). The reflection or transmission measurements can be done by connecting these sections to a suitable measurement assembly.

In reflection measurements, the microwave power absorbed is related with \( e \) standing wave ratio \( (VSWR = V_{in}/V_{out}) \).

Let \( r = (VSWR)^{-1} \)

Then the power reflectivity of the specimen \( R \) is given by

\[ R = \frac{(1 - r)^2}{(1 + r)^2} \]

and the microwave absorption \( A \) is expressed as

\[ h = 1 - \frac{A}{\pi} \]

The parameter \( A \) is proportional to the joule loss in the material.

Reflection techniques are more sensitive and accurate but give experimental data either at single frequency or at few discrete frequencies. Reflection/transmission techniques can be used to yield information in a much wider dynamic range.

Now few experimental techniques and some typical results will be discussed on surface impedance, microwave absorption and permittivity of high \( T_c \) superconductors. The surface impedance \( Z_s \) is defined as

\[ Z_s = Z_{f} + jX_{s} \]

Where \( R_s \) is surface resistance and \( X_s \) the surface reactance. The magnitude and temperature dependence of \( Z_s \) is determined by the properties of the ground state and the low-lying electronic excitations. Experiments may reveal information useful to distinguish between various pairing symmetries and the strength of coupling effects. The imaginary part \( X_s \) is proportional to the penetration depth and \( R_s \) determines the suitability of materials in microwave passive component applications such as filters, resonators, and interconnects, etc. Microwave absorption and permittivity studies also reveal useful information about charge transport processes occurring in high \( T_c \) superconductors.

Results and Discussion

Most widely studied among high \( T_c \) superconductors is the \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) system (YBCO). Experiments have been performed on polycrystals, single crystals, films, and polymer composites of YBCO. The results presented here mostly are on YBCO but they represent general behavioral trends of high \( T_c \) superconductors.

Figure 4 shows variation of surface resistance with temperature for \( \text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4 \) (LSCO) and YBCO systems.\(^{9}\) It may be noted from Fig. 4 that fall of \( R_s \) at transition temperature is less sharp and magnitude of residual surface resistance higher for high \( T_c \) superconductors as compared to elemental superconductor. This difference in behavior may be due to i) presence of non-superconducting residues/impurities; ii) weakly

\[ Z_s = Z_{f} + jX_{s} \]
superconducting intergranular regions; in) surface roughness; and iv) surface states.

The arguments based on the above phenomena draw support when the results are compared for polycrystal and single crystal specimens (Fig. 5). To add further, Fig. 6 depicts the influence of grain size on the superconducting behavior of powders. Larger grains (reduced surface to volume ratio) exhibit more ideal superconducting behavior. Similar inferences can be drawn from the increased residual resistance observed in case of films as compared to bulk sample (Fig. 7).

Figure 8 compares microwave resistance with dc resistance for YBCO. The saturated value of resistance below T_c is larger at microwave frequency. The resistance below T_c is zero for dc but it increases with frequency in the microwave region (Fig. 9). These results can partly be understood in terms of reduction of penetration depth as measurement frequency increases.

The frequency dependence of R_s is used to fit in various models for explaining superconductivity in high T_c materials. Square root dependence for surface resistance on frequency for normal state and quadratic frequency dependence in the temperature region below T_c have been observed. Departures from these frequency dependences have also been reported.

Both BCS and two-fluid theories predict a square dependence of R_s on frequency for temperatures below T_c.

Results discussed so far were obtained by cavity resonance techniques. Fruitful observations may also be made from reflection/transmission measurements. Figure 10 depicts the variation of (VSWR)^1 as a function of temperature and in Fig. 11 microwave absorption is plotted. The general profile of these plots is the same as for previous cases discussed. The microwave absorption is almost complete by the specimen in normal state and it decreases markedly at the superconducting transition due to expulsion of microwave field by the specimen.

The real and imaginary parts of the complex permittivity (e^* = e' - je") are shown in Figs. 12 and 13 for YBCO specimen at 9.2 GHz. The value of e' at room temperature is 130, it falls slowly as the specimen is cooled and passes through two minima. First minima occurs at 137 K and then a sharper minima at the transition temperature at around 91 K. Quantitatively similar structure is observed conductivity also (Fig. 14). The sharp fall in the magnitudes of e' and e" at 91 K is suggestive of the ordering occurring in the material in the vicinity of T_c. Trybula et al. have attempted to explain similar results on the basis of two-fluid theory.

The sharp rise in e' and e" values below 91 K is unusual. Experiments were repeated on superconducting tape (containing roughly 70% polymer); e' and e" profiles of Figs. 12 and 13 were confirmed. Presence of non-superconducting phases in the material perhaps may be responsible for this typical behavior of high T_c superconductors.

Figure 5. Temperature dependence of normalized surface resistance of YBa_2Cu_3O_7 at 24 GHz for polycrystalline and single crystal specimens (Kobayashi et al. 10).

Figure 6. Normalized reflected power as a function of the normalized temperature. 1-powder with smaller grains, 2-powder with large grains (Jackson et al. 11).

References


**Figure 8.** The dc resistance (solid line) and the microwave resistance (xxx) near $T_c$ for YBa$_2$Cu$_3$O$_{7-8}$. Changes in 1/B are proportional to changes in the real part of the sample surface impedance (Li et al.$^13$).

**Figure 9.** Temperature dependence of the surface resistance at 2.9, 21.5, and 86.5 GHz (Müller et al.$^{14}$).

**Figure 10.** $(VSWR)^{**}$ versus temperature at 9.12 GHz (Tateno et al.$^{16}$).

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Figure 7. Temperature dependence of the surface resistance of a bulk ceramic (1) and film specimen (2) of YBa$_2$Cu$_3$O at 6 GHz (Padamsee et al.$^{12}$).

Figure 11. Temperature dependence of the surface resistance at 9.12 GHz (Tateno et al.$^{16}$).
Figure 11. Microwave absorption ratio $A$ versus $1/T$ (Tateno et al.).

Figure 12. Dielectric constant $\varepsilon'$ for YBa$_2$Cu$_3$O$_{7-\delta}$ as a function of temperature at 9.2 GHz (Dube et al.).

Figure 13. Dielectric loss factor $\varepsilon''$ for YBa$_2$Cu$_3$O$_{7-\delta}$ as a function of temperature at 9.2 GHz (Dube et al.).

Figure 14. Temperature dependence of the microwave conductivity $\sigma$ of YBa$_2$Cu$_3$O$_{7-\delta}$ (Kato et al.).