[Emerging Device Technology](#) > **The Physics of Superconductors at Microwave Frequencies**

Measurements of the microwave properties of superconductors has been going on for over a decade in the EDT research group. The objectives of the work are three fold, to enhance our understanding of superconductors, to optimise the superconducting for low loss and to provide information to microwave device designers on the properties. Measurements have taken place on thin and thick film materials, single crystals and bulk polycrystalline specimens. All have helped in meeting the three objectives of the work.

The characterisation tools for measuring the surface resistance and penetration depth of the superconducting materials are now well established. The main ones being the coplanar resonator for patterned films, the dielectric resonator for un-patterned surfaces and a cylindrical cavity resonator for single crystals and other small pieces of superconductor. With all these techniques the surface impedance of the superconductor can be measured as a function of frequency, temperature, magnetic field, microwave power and more recently two-tone intermodulation. Examples of some of these techniques and the results obtained are given below.

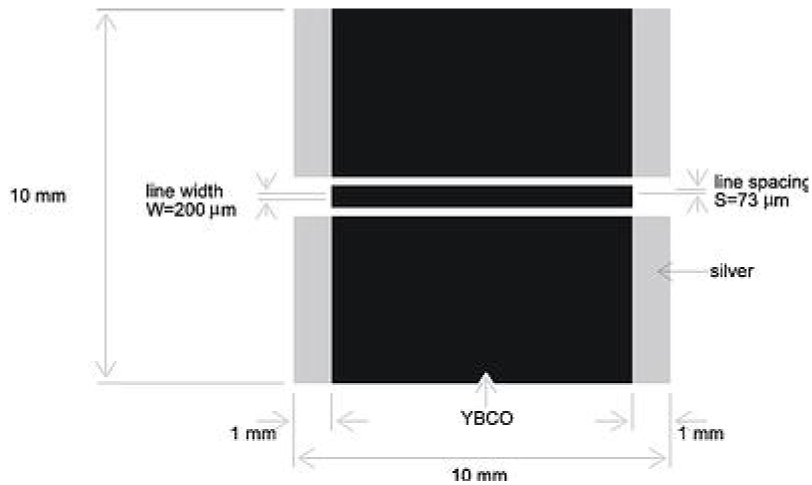

Figure 1. Coplanar resonator

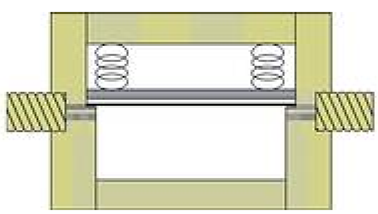

Figure 2. Package for coplanar resonator

The coplanar resonator (shown in figure 1) consists of a substrate (usually magnesium oxide or lanthanum aluminate) on which the black superconducting film is grown. For this measurement it does not matter what is on the base of the substrate. The thin film is then patterned in the shape of the coplanar resonator as shown, with two large area ground planes and one narrower central strip. This is placed in the package shown in figure 1. The device has a resonance frequency of about 8 GHz and by measuring the quality factor or bandwidth of the resonance, together with changes in frequency the surface resistance and penetration depth can be found.

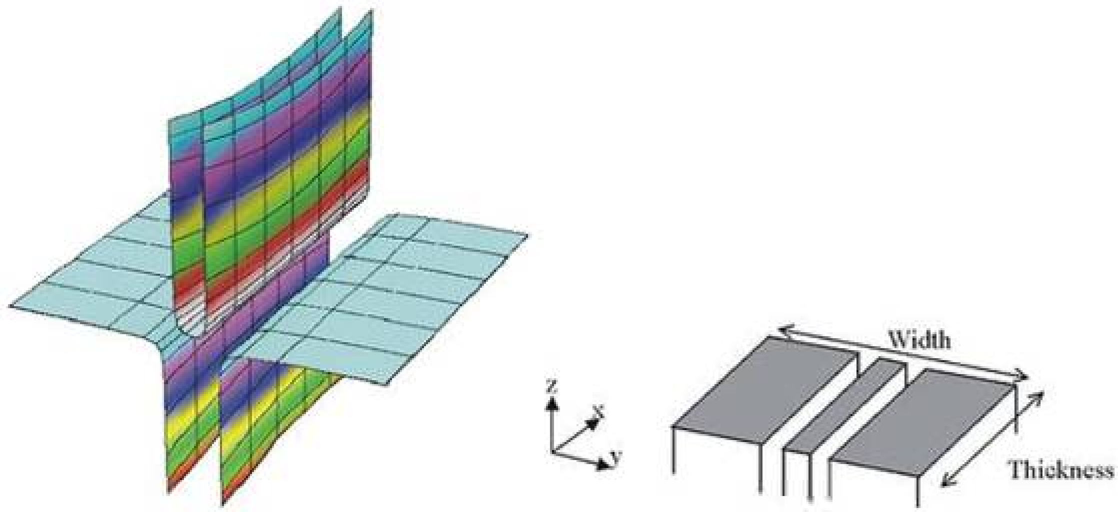

Figure 3 The current distribution on the coplanar resonator

In order to extract the surface resistance and penetration depth fully the completed current distribution inside the superconductor has to be calculated. This is done by a numerical simulation using code developed in the group. The result of the simulation is the current distribution in the volume of the superconductor depicted in figure 3.

By using this calculation and measuring two coplanar resonators with different geometries the properties of the superconductor are extracted. No one else in the world is able to extract the absolute value of penetration depth of superconducting thin films by this technique.

An example of one measurement is shown in figure 4, it is the surface resistance and change in surface reactance of two superconducting films at a temperature of 15K against increasing microwave power. One film is good and increasing the power has little effect up until higher power levels. The other film is not as good and quickly deteriorates with power

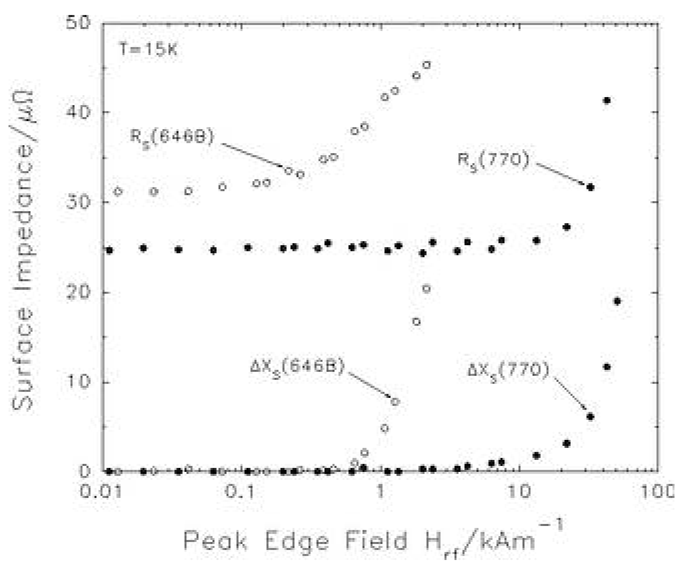

Figure 4. Measurement of the surface resistance.

Another example of the many types of measurements made is intermodulation effects on superconducting films. Here two highly stable microwave signals are input to a superconducting resonator. Both signals lie within the bandwidth of the resonator. Due to non-linear mixing intermodulation products arise and these products can be measured. The graph in figure 5 shows results from both patterned and un-patterned superconducting films at 60K. The two shorter graphs on the left represent patterned films and the longer graphs on the right represent un-patterned films. The two graphs at the top have a slope 1:1 and are for the fundamental frequency showing the power input is equal to the power output. However the other graphs for the 3rd order intermodulation product show slopes of 2:1 and 1.5:1.

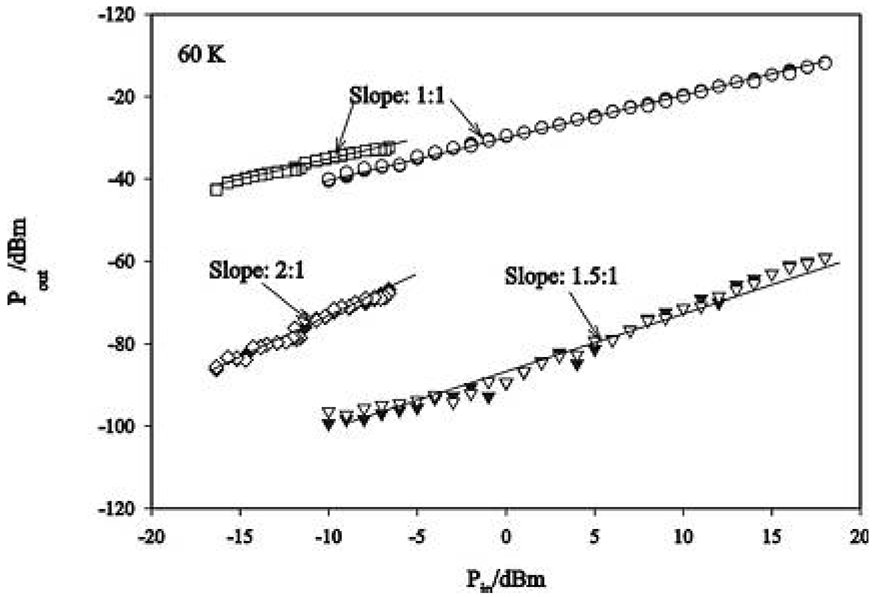

Figure 5. Intermodulation distortion

In microwave engineering is very unusual to find slopes other than 3:1 for these intermodulation products and this measurement shows something very unusual is going on.

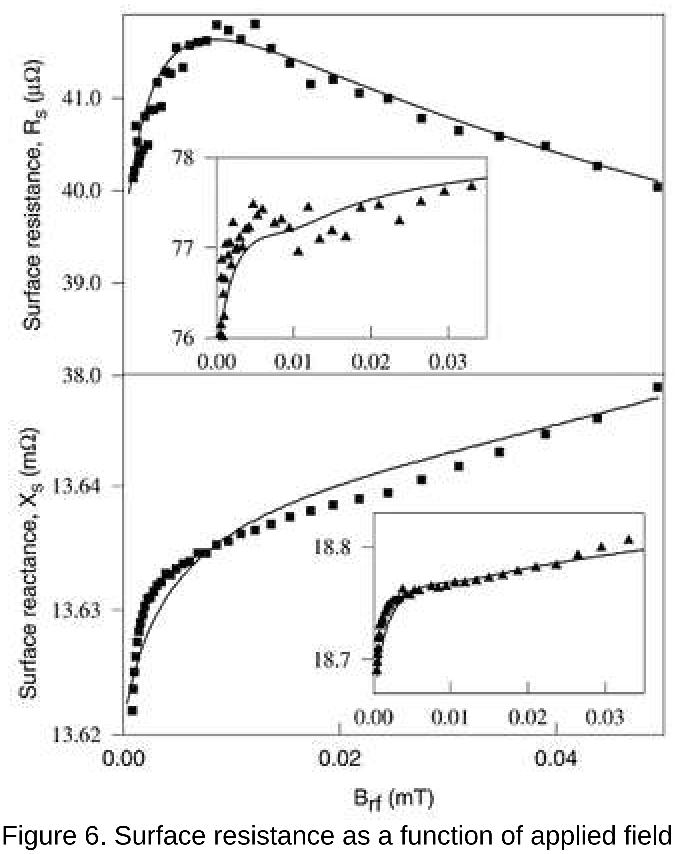

Figure 6. Surface resistance as a function of applied field.

In addition to microwave measurements on superconductors the group has developed a number of mathematical models describing the properties of the superconducting materials at high frequencies. For example, one model has been developed based on a number of connected grains. Movement of flux inside and across grain boundaries explains the non-linear impedance behaviour of the materials. An example of theoretically calculated dependence together with the experimental data showing the so-called “anomalous” non-linear behaviour is shown in figure 6. The measurements are done using the coplanar resonator made of e-beam evaporated YBCO film on MgO substrate at 15 K (main figures) and 60 K (the inserts).

Superconducting films are also examined by other techniques in order to help understand the microwave properties. Two examples are given in the diagrams. The figure 7 is produced by optical probing. A pump laser causes local heating and the reflection of a probe laser is recorded. The result is a measurement of the local electron carrier concentration. A defect can be observed cutting across the central yellow in the diagram. This is the centre conductor of the coplanar resonator. We have also found that the intensity of the reflected optical signal correlates with the low temperature penetration depth and the surface resistance at 60 K, whereas the uniformity of the signal seems to correlate with the microwave power-handling capability of HTS films. The technique is also capable of detecting large-scale defects in resonators with a strongly degraded microwave response, including defects that cannot be seen by conventional optical microscopy. The work is in collaboration with the University of Bath.

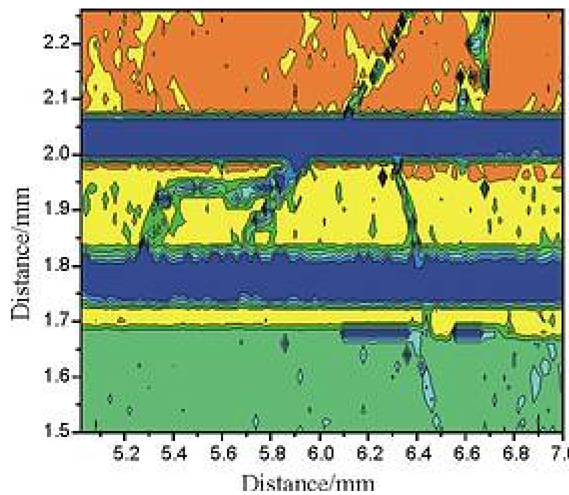

Figure 7. Optical response of a HTS coplanar resonator

The figure 8 is a magneto optic image. Here a laser shines through a thin film on top of the superconductor which is sensitive to magnetic field. Hence flux penetration into the superconductor can be observed as the magnetic field is applied.

In figure 8 the thick green stripes form the coplanar resonator. Other thin lines are observed crossing the superconductor. These are defects in which magnetic flux penetrates more easily. By measurement of the surface impedance of various materials correlations can be built up with defects observed.

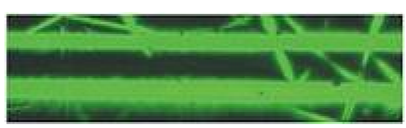
Figure 8. Magneto optic image.

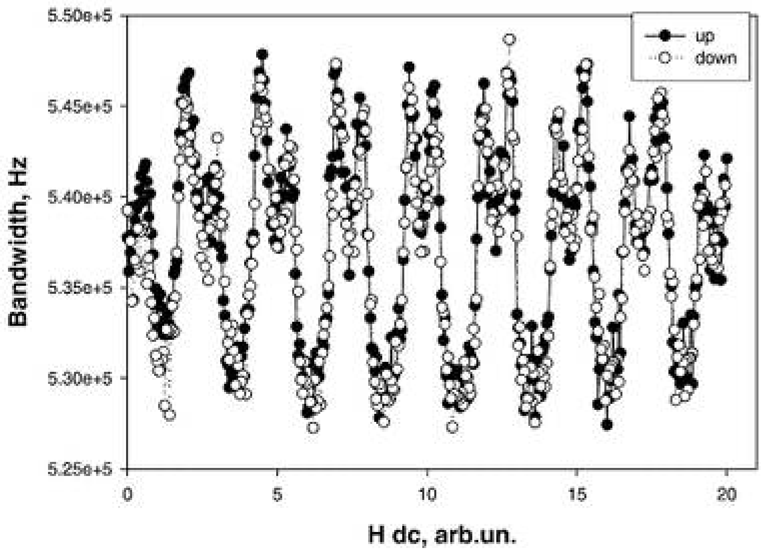

Figure 9. Oscillations as a function of applied field

Some YBCO thin films show highly periodical oscillations in the microwave absorption as a function of small DC magnetic field in the reversible regime (up to ~ 1.2 mT) of zero field cooled experiments. Example of this is shown in figure 9. We believe these oscillations are related to extended weak links, which occur naturally during the film growth. The mechanism responsible for the oscillations is nucleation and motion of Josephson vortices. Although this behaviour is not typical for as grown YBCO films, in artificial resonant structures, containing engineered extended weak links (for example, junctions on bi-crystal substrates), the aforementioned oscillations should be observable and may bear useful information on the dynamics of Josephson vortices in HTS materials.

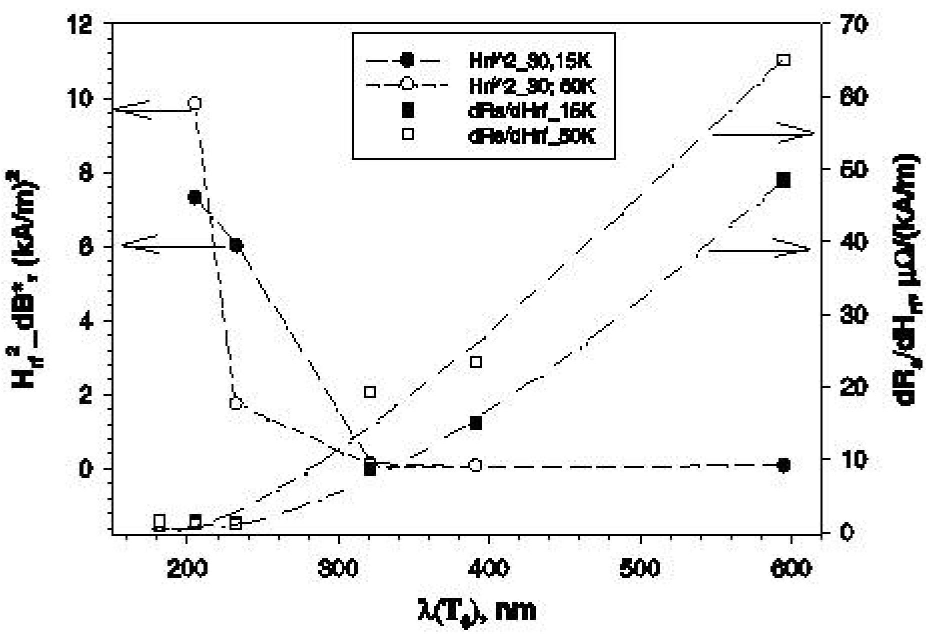

Figure 10. Correlations of penetration depth and field

Studying the nonlinear microwave performance of HTS films not only presents an extremely interesting physical issue (by giving insight into the vortex dynamics, weak links, quasi-particle scattering and condensate depairing), but is also highly important for improving their performance in terms of the microwave applications. However, the nonlinear microwave properties (especially IMD products) are notoriously difficult to measure and often require the film's patterning and expensive sophisticated equipment. Therefore, other techniques which are, on the one hand, simpler and, on the other hand, able to predict the nonlinear performance of the films would be of great help. Recently in the EDT group we have established such correlation of the nonlinear properties with some linear microwave (penetration depth and quasi-particle conductivity) and structural (c-axis length) parameters. An example of the correlation between the slope of $R_s(H_{rf})$ dependence (dR_s/dH_{rf}) and the IMD parameter $H^2_{rf\_30dB}$ $(H^2_{rf}$ at which IMD products are 30 dB below the carrier signal) on the one hand, and the low temperature on the other hand are shown in figure 10

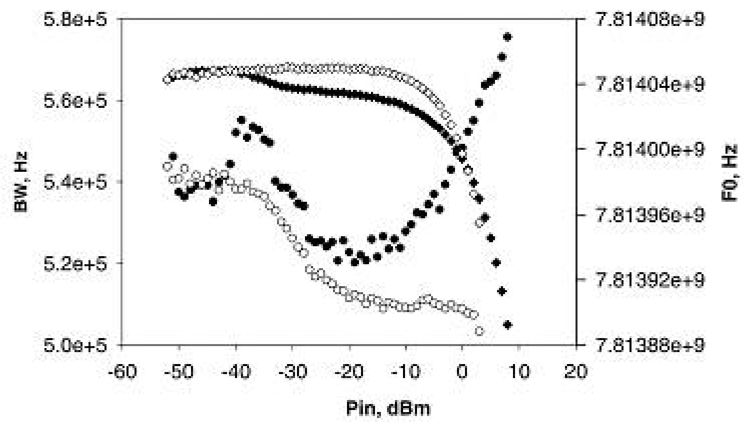

Figure 11. Bandwidth dependence on input power

While the correlation approach described above can be used to give feedback to the film manufactures on how to improve the film properties, there is another approach, called artificial modification, aimed at improving the nonlinear performance by doping HTS films with strategically positioned defects. One of the most efficient ways to achieve that is irradiation of HTS films with heavy ions (such gold or silver, e.g.) This is known not only to reduce the lower power R_s of the films, but also improve their power handling capability.

Figure 11 demonstrates the change in bandwidth and frequency of YBCO coplanar resonator at 8 Hz made of YBCO film on MgO substrate (the irradiated samples are shown by empty symbols). The irradiation is seen to produce a few remarkable effects on the microwave properties:
1) to reduce the low power R_s;
2) to enhance the nonlinear microwave anomaly (makes the minimum in $R_s(H_{rf})$ deeper and extends it to higher fields);
3) to improve the power handing of the film in terms of $X_s(H_{rf})$ by nearly 35 dB!
Thus heavy ion irradiation seems to be a powerful way to control both the low power and the nonlinear microwave properties of HTS films.

A book and comprehensive review paper have been written and published which relate to the work described above. The references are:

Lancaster M. J. ‘Passive microwave device applications of high temperature superconductors’ Cambridge University Press, Cambridge UK 1997. ISBN 0-521-48032-9

Velichko A. V., Lancaster M. J., and Porch A., “Nonlinear Microwave Properties of HTSD Thin Films”, Superconductor Science &.Technology., Vol. 18, pp. R24-R49 (2005).