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A novel method for the measurement of frequency-character of surface resistance of HTS thin film

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A novel method for microwave surface resistance measurement of high temperature superconductor thin film at multi-frequency by multimode of sapphire rod is introduced. This method has the advantages of high sensitivity and large dynamic range of the measurement. By using this method, the frequency dependent microwave surface resistance of a single piece of high temperature superconductor thin film can be characterized within one temperature cycle. This method is capable of reducing the amount of work in surface resistance measurement and providing supports to the research and the industrialization of high temperature superconductor thin film.

high temperature superconductor thin film, microwave surface resistance, multimode measurement, frequency-character

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Microwave passive devices made by high temperature superconductor thin films (HTSTF) are more and more widely used in civilian communication equipment and front ends of radar detection equipment. Comparing with the normal microwave passive devices, high temperature devices, including filters, delay lines and antennae, have the virtue of lower in-band loss, better rectangular coefficient, smaller volume, lower loss and higher sensitivity. Thus high temperature superconductor devices have remarkable advantages of promoting the quality of communication, increasing detection range and rejecting interfering signals.

As the industrialization of high temperature superconductor (HTS) moves on, the demand for high quality HTSTF increases rapidly. During the fabrication process of thin films, the microwave surface resistance (R_S) of HTSTF is one of the most important quality indexes. Therefore, by measuring the R_S of HTSTF the quality of thin film can be detected and this is helpful to the adjustment of fabrication process. In the aspect of device design, the R_S of material is indispensable in the simulation of microwave passive devices and an accurate R_S is the precondition for fabricating high performance devices. The design efficiency of high performance superconductor microwave devices can be guaranteed by measuring the R_S of thin films accurately. Therefore the R_S measurement of HTSTF is significant in the industrialization of HTS. In the research of mechanism of superconductor the curves of R_S depended on frequency and temperature are always the concern of the researchers. Since correct theory requires verification in experiment, the measurement of R_S of HTSTF is also indispensable in the research of superconductor.

By far, the methods for measuring the R_S of HTSTF are all based on finding the relationship between R_S and unloaded quality Q_0 of microwave resonant structure. The value of R_S can be calculated after Q_0 is measured [1−3].

Mainstream research for the methods of measuring the R_S of HTSTF is almost in the same way. That is constructing the main electromagnetic energy storage resonant units by

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dielectric rods with low loss and high dielectric constant. The differences between them are that the structures or the theories of the resonant units are not the same. The resonant structure can be single side short-circuited [4] or double sides short-circuited [5]. The working mode can be single mode [6] or double modes [7]. However, these methods can only measure the R_S of HTSTF at single frequency. Thus dielectric rods with different sizes are needed to measure the frequency-character of R_S of HTSTF, which complexes the task.

In this paper, a method using several resonant modes of one single resonant cavity for measuring the frequency-character of R_S of HTSTF is proposed. In this method no preprocess is needed and the R_S of one single HTSTF can be measured directly. The measurement process and calculation formula of this method are both very easy. This method is applicable to the measurement of the frequency-character of R_S of other conductors, including low temperature superconductor.

1 Methods for measurement by multimode

Few methods can measure the frequency-character of R_S of samples directly among numerous methods for R_S measurement. The methods proposed in [8, 9] represent two different types. In [8] resonator with planar structure is used. A section of coplanar waveguide, which is used as resonator, is etched on a two-inch and double-sided YBCO thin film. The working mode of this resonator is TEM mode. The frequency-character of R_S of the sample is calculated after the unloaded quality factor Q_0 of resonance peak of each harmonic wave is measured. This method is capable of measuring the R_S of the sample directly; however, uncertainty is inevitable in the etching process and its sensitivity is restricted by the relatively low unloaded quality factor of the resonance peak. In [9] a sapphire cavity resonator short circuited at both ends by two HTS thin films is used. Firstly, R_S of the HTS thin films and $\tan\delta$ of the sapphire at one single frequency point are obtained by measuring the Q_0 values of two adjacent TE modes. Then the Q_0 values of another two TE modes of this resonator are measured. By using the principle that the $\tan\delta$ of sapphire is proportion to frequency, the values of R_S at corresponding frequencies is calculated. Thus the curve of the frequency-character of R_S of the sample is fitted. In this method no preprocess and no other sapphires with different size are needed. However, it is unable to obtain the R_S frequency-character of single piece of HTSTF directly. And the frequency interval of the two adjacent resonance peaks needs careful consideration, because the model will fall if the interval is too large while the uncertainty will increase if the direct coupling between the two adjacent modes arises when the interval is too small.

In this paper, a method using several TE modes of the testing cavity for the measurement of R_S of single piece of HTSTF at different frequencies is proposed based on the measurement principle of sapphire image method [10].

Based on the method in [10], the unloaded quality factor Q_0 of working mode in the testing cavity is expressed as

$$Q_0^{-1}=A+B\times R_S,$$

where A and B, which are independent of surface resistance of the sample, are unknown constants. The values of A and B can be obtained by “Calibration” [10]. In the calibration process the values of unloaded quality factor of the testing cavity loaded by calibration cavity (Q0H) and silver coated copper plate (Q0N) are measured respectively. The structures of calibration cavity and testing cavity are the same. The surface resistance (RSN) of silver coated copper plate (silver plate for short) is already known. When the testing cavity is loaded by calibration cavity, the distribution of the electromagnetic field in the two cavities is identical and the interface is a symmetric plane in which only radial magnetic field exists and there is no presence of any real conductor. Therefore, it seems that the testing cavity were loaded by perfect conductor (R_S=0) and $A = Q_0^{-1}$. When the testing cavity is loaded by silver plate, $Q_0^{-1}=A+B\times$RSN, therefore, $B=(Q_{0N}^{-1}-Q_{0H}^{-1})$/RSN. After the values of A and B are calculated the surface resistance of HTSTF RSHTS is obtained by measuring the unloaded quality factor Q_{0HTS} of the testing cavity loaded by HTSTF

$$R_{SHTS}=(Q_{0HTS}^{-1}-A)/B.$$

“Calibration” including obtaining the zero resistance plane and measuring the surface resistance R_{SN} of the silver plate accurately is the key in this method. A zero resistance plane is guaranteed as long as only radial direction magnetic field exists in the interface of the testing cavity and the calibration cavity. After the testing cavity is loaded by the calibration cavity, a resonance structure whose diameter is the same as the testing cavity while its length is doubled can be created. From the principle of electromagnetic filed we knew that no longitudinal electric field exists in all TE modes. Thus each TE mode with identical distribution of electromagnetic field is located on both sides of the interface of the testing cavity and the calibration cavity. For these TE modes the interface in which only exist radial direction magnetic field is a “symmetric plane”, and “zero resistance plane” is obtained at the resonance frequencies of each TE mode. Therefore, all TE modes in the testing cavity can be used as working modes for the R_S measurement. Thus the calibration process and calculation formula in the earlier work [10] are extended from one single TE_{011} mode to several TE modes. Firstly, measure the unloaded quality factor Q_{0Hi} (i=1,2,3…, representing the corresponding working mode) of each working mode of the testing cavity loaded by the calibration cavity. Secondly, load the testing cavity with a metal plane of which the value of R_S is already known and then measure the unloaded quality factor Q_{0Ni} of each working mode. Thus the values of A_i and B_i of each mode are obtained. Finally, measure the unloaded quality factor Q_{0HTSi} of each working mode of the testing cavity loaded by HTSTF. And the surface resistance R_{SHTSi} at different frequencies can be calculated.

As shown in Figure 1, the resonator used in this paper is short-circuited at one end. The testing cavity consists of sapphire rod, support ring, cutoff waveguide, input/output ports and shielding cavity. The supporting ring is made by Teflon with low loss and low relative dielectric constant. Coupling loops are used for the stimulation of electromagnetic field. The distribution of frequency in the testing cavity is determined by the size of the sapphire rod (d, h) and the inner diameter and height (D, H) of the shielding cavity. Frequencies of other modes adjacent to the ones of working modes can be adjusted slightly by changing the diameter of the cutoff waveguide in case the interference occurs. The R_S frequency-character of the sample can be described by measuring its R_S with optimized sizes of sapphire rod and shielding cavity and appropriate distribution of resonance frequencies of working modes.

2 Design of multimode testing cavity

The method used in this paper is the typical application of multimode cavity. In this situation, the resonance modes are so many that energy coupling may exist between working modes and the modes adjacent. Thus working modes may be disturbed. And the design of resonator needs more focus. Unfortunately, the structure of the resonator used in this paper is irregular, thus no existing chart is available for the design. Therefore, finite element method (FEM) is used for the simulation of the frequencies and sizes of the resonator, so that the TE modes of the resonator can be used effectively.

Since the upper limit working frequency of SMA connector is 26.5 GHz, the highest frequency of working mode in this resonator should below this 26.5 GHz. After simulation and optimization, the diameter and height of the sapphire rod and shielding cavity are chosen as 9.95 mm, 5.24 mm and 26 mm, 10 mm respectively. And the diameter of cutoff waveguide is 6 mm. The working modes of the resonator are TE_{011}, TE_{012}, TE_{021} and TE_{013} of which the resonance frequencies are 11 GHz, 17.4 GHz, 19.1 GHz and 25.3 GHz respectively in the simulation results.

3 Measurement and discussion

The testing cavity is shown in Figure 2. During the measurement the testing cavity is installed in a container which is continuously filled with gas for protection. The whole device is immerged in liquid nitrogen (77 K). The sample measured in this paper is a YBCO thin film with 500 nm of thickness. This film is deposited on an MgO substrate by sputtering method. The diameter and thickness of this substrate are 50.8 mm and 0.5 mm respectively. The values of unloaded quality factor of each mode with each loaded state are measured by a vector network analyzer (Agilent E8363A) with –3 dB method. The constants needed in the calculation are A_1=5.36×10^{-6}, B_1=1.62×10^{-6}, A_2=9.11×10^{-6}, B_2=1.42× 10^{-6}, A_3=3.51×10^{-6}, B_3= 7.37×10^{-7}, A_4=9.88×10^{-6}, B_4= 1.03×10^{-6}, where the suffix of A and B are corresponding to the working modes TE_{011}, TE_{012}, TE_{021} and TE_{013} respectively. Since gold is more stable than silver, gold coated copper plate is used in the calibration. Its surface resistance is 66.7 mΩ (12 GHz, 77 K). It is worth noting that since the value of surface resistance R_{SN} of normal metal is proportional to the square root of frequency, the value of R_{SN} should be recalculated according to the frequencies of working mode in the calculation of B.

The curves of transmission coefficient of the four working modes of the testing cavity which is loaded by HTSTF are shown in Figure 3. The values of unloaded quality factor of each mode are 164000, 92400, 206700 and 81200 respectively. It is shown in the figure that there is no disturbance near TE_{011}, TE_{012} and TE_{013} modes. However, there is another resonance peak 30 MHz below the frequency of TE_{021} mode. And the surface resistances of the HTSTF at the four modes are 0.45 mΩ, 1.21 mΩ, 1.81 mΩ and 2.36 mΩ respectively. Results of surface resistance and square law curve fitted according to these results are shown in Figure 4.

4 Conclusions

An R_S measurement method by multimode cavity based on

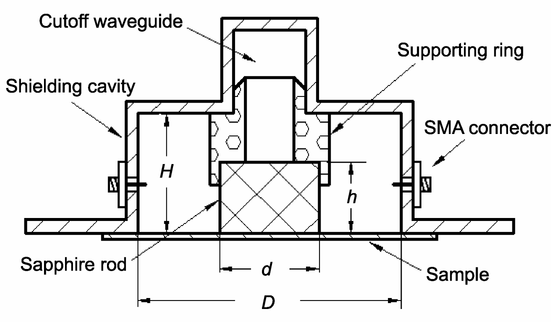

Figure 1 Schematic layout of testing cavity.

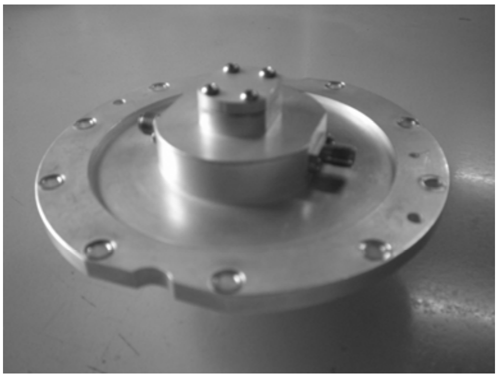

Figure 2 Picture of testing cavity.

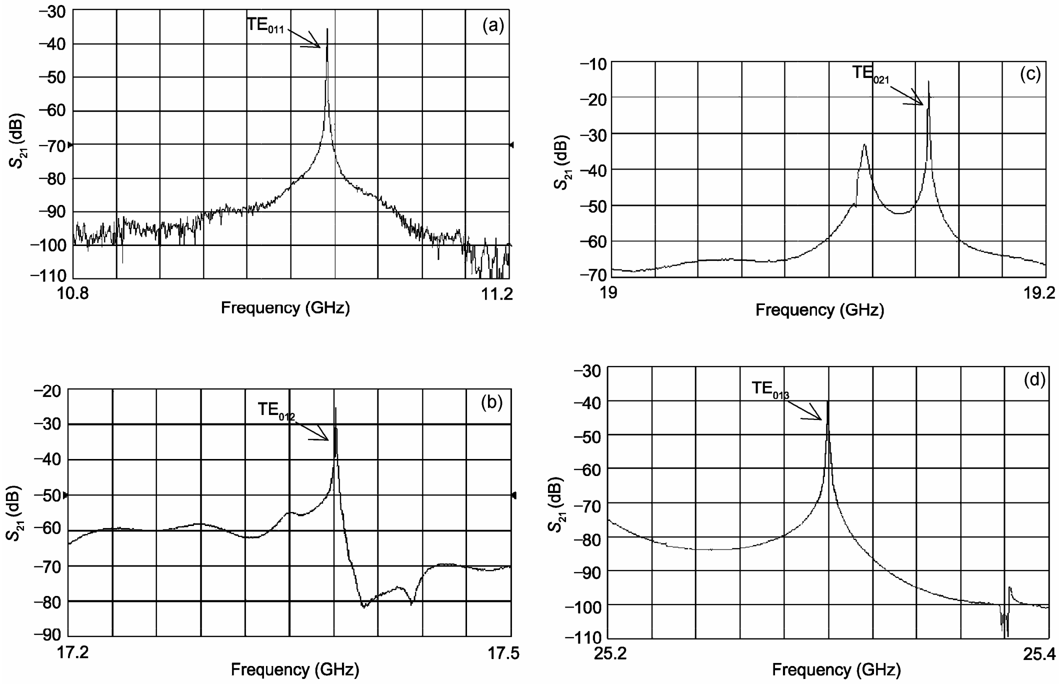

Figure 3 Frequency response curves of resonance peak of each working mode in testing cavity. (a) TE_{011}; (b) TE_{012}; (c) TE_{021}; (d) TE_{013}.

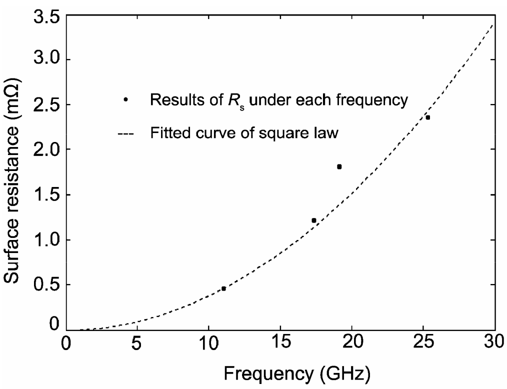

Figure 4 Results of R_S of single piece of HTSTF and its fitted curve.

low loss dielectric rod is proposed in this paper. A testing cavity working at TE_{011}, TE_{012}, TE_{021} and TE_{013} modes is fabricated and the frequency-character of R_S is measured. In this method several TE modes are used simultaneously for the nondestructive measurement of R_S frequency-character of single piece of HTSTF. The shortcoming that sample needs preprocess or the result is the average of two pieces of HTS thin film in the traditional methods for R_S frequency character measurement is overcome by this method. After calibration, the measurement can be done in one temperature cycle, therefore efficiency is enhanced remarkably and the risk of damaging sampling in the iteration of installation is avoided.

The frequency range can be extended to millimeter wave region when (i) the input/output coupling is changed; (ii) microwave connectors with higher frequency limit are used; (iii) the sizes of sapphire rod and shielding cavity are redesigned. This method can be extended to the R_S measurement of low temperature superconductor and other conductors in the appropriate condition of temperature and environment.

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