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Microwave Measurements of Surface Resistance and Complex Conductivity of NdBaCuO Films

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Abstract. Typically microwave properties of High Temperature Superconducting films are defined in terms of surface resistance R_s computed from Q-factor measurements obtained using one of resonant techniques. While NdBaCuO films are known to have higher T_C and J_C than YBaCuO films, not much is known about their loss at high frequencies. In this paper we report on microwave properties of NdBaCuO films of varying quality and thickness based on measurements with a 25GHz sapphire Hakki Coleman resonator and computations using two approaches: the surface resistance and the complex conductivity as primary variables for rigorous electromagnetic solutions.

Introduction

Microwave measurements of rare earth copper oxide superconductors started soon after $YBa_2Cu_3O_{7-\delta}$ materials were first synthesized in 1987 [1]. Due to very low loss of YBCO thin films, they were envisaged for mass market applications to wireless base station filters, to provide better coverage and bigger capacity in the presence of interference than conventional technologies. Hence microwave characterization with high precision and small uncertainty became important, and it was necessary to develop suitable measurement techniques for HTS materials, to evaluate the losses at high frequencies represented by the surface resistance R_S.

Initial microwave measurements of HTS films utilized the transmission method [2] as well as copper and niobium resonating cavities [3-4]. Soon after the dielectric rod resonator technique was proposed [5-6] including the parallel-plate dielectric resonator version [7], Hakki-Coleman [8-9] and open-ended type [6]. In parallel the stripline and microstripline resonators [10] were employed. The sapphire Hakki-Coleman resonator was suggested as a standard for R_S measurements of HTS films in 1997 [11] and pronounced the standard by the International Electrotechnical Commission TC 90 (with a two setups configuration of resolution of 10μΩ at 10 GHz frequency) in 2001.

Among all rare earth copper oxides $YBa_2Cu_3O_{7-\delta}$ has become the material of choice for HTS microwave applications in filters for Base Station receivers for wireless communication. A lot of research has been done around the world on microwave properties of YBCO films. As a result optimised YBCO films on various substrates were developed for this application, with the thermal co-evaporation technique [eg.12] and MgO substrates considered the best for large area, stable and low loss films.

For techniques employing resonating test structures the surface resistance of HTS materials is computed from the measured unloaded Q-factor of a resonator containing films under test. The extracted value of R_S is often an effective value, depending on the sample thickness and possibly on its substrate (especially for temperatures higher than $T_C/2$ and films thinner than 3 penetration depth). The effective values are important from the point of view of applications, however they do not allow for comparison of intrinsic properties of YBCO films of varying thickness. To enable such a comparison the intrinsic surface resistance R_S and conductivity σ are more suitable parameters.

Recently a new approach was introduced [13] in which, the rigorous electromagnetic analysis is applied to obtain the complex conductivity σ of the HTS films under test. Only then values of R_S (intrinsic and effective) are computed from values of σ. YBCO films were used for illustration of the concept and theory behind it in [13]. In this paper we apply the same approach to measurements of NdBaCuO films of differing microwave losses. Values of R_{Seff} computed in the traditional way from the Q_o-factor and from the complex conductivity (as in [13]) are compared and discussed.

Experiments

A Hakki-Coleman sapphire resonator operating at the TE_{011} mode of 25GHz was used in the measurements. The sapphire rod was cut from a very low loss crystal, and its loss tangent is assumed to be 5×10^{-8}. The test resonator is illustrated in Fig. 1 and has the following parameters: sapphire rod diameter = 4 mm, height = 4 mm, cavity diameter = 9.25 mm, cavity height = 4mm, geometrical factors $A_S = 561.3$, $A_{met} = 12{,}162.3$, $p_d = 0.9464$.

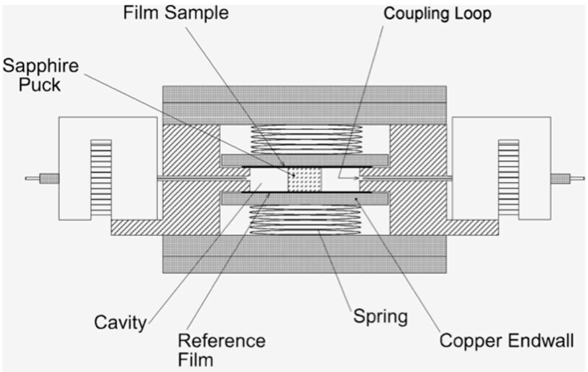


Fig. 1 Schematic diagram of Hakki-Coleman test resonator

The NdBaCuO films used in the experiments were deposited on MgO substrates 0.5mm thick using the thermal co-evaporation technique [12]. The films were of varying intrinsic microwave loss and of two thicknesses d: large (d=700nm and 800nm) and small (d=50nm). The thicker films contained 25nm YBCO buffer layers deposited on MgO and were of medium loss. The low loss films had thickness 50nm and contained no buffer layer. Parameters of the films are given below and SEM pictures in Figs. 2-5.

X170112A: d=800nm, T_C=93.9, J_c>5MA/cm^2,
X170112B: d=700nm, T_C=93.8, J_c=5.8.MA/cm^2,
X030812BM1: d=50nm, T_C=88.7K, J_c=1.25MA/cm^2,
X240513AM: d=50nm, T_C=88.6K, J_c=0.75MA/cm^2.

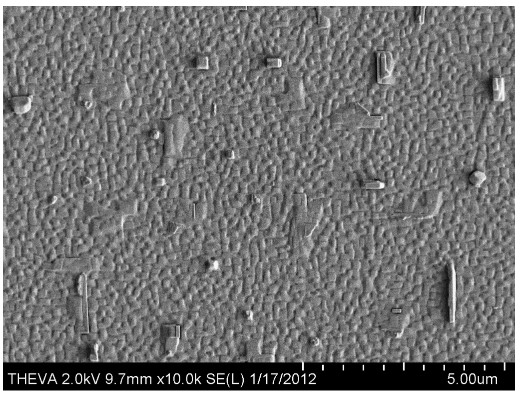


Fig. 2 SEM of X170112A film

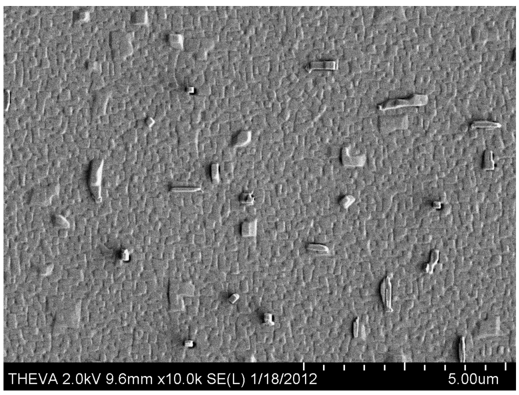


Fig. 3 SEM of X170112B film

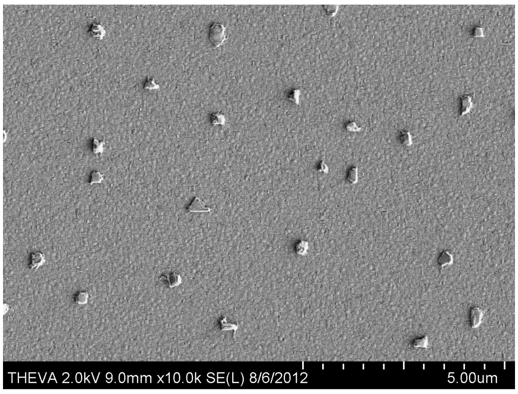


Fig. 4 SEM of X030812BM1 film

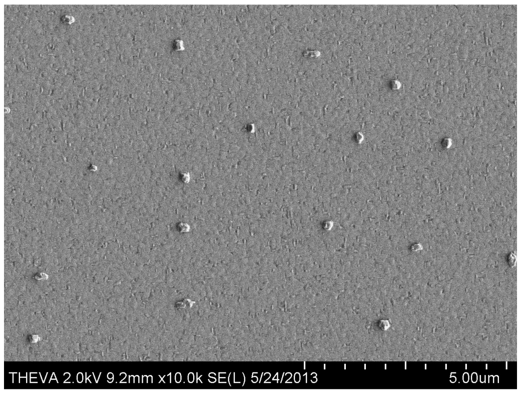


Fig. 5 SEM of X240513AM film

Microwave characterization of the NdBCO films was performed using a two stage closed cycle Stirling cryocooler, Agilent PNA E8364B, a Temperature Controller and a PC, as illustrated in Fig. 6. Custom written data logging and temperature controlling software based on LabView of National Instruments was used in all measurements. 1601 values of S_{21}, S_{11} and S_{22} parameters were downloaded from PNA for each temperature to enable computations of loaded Q_L factor, coupling coefficients β_1 and β_2 and unloaded Q_O-factor. The Transmission Mode Q-factor Technique [14] was used in the computations to account for parasitic measurements effects (noise, crosstalk, uncalibrated lines, coupling loss and coupling reactance).

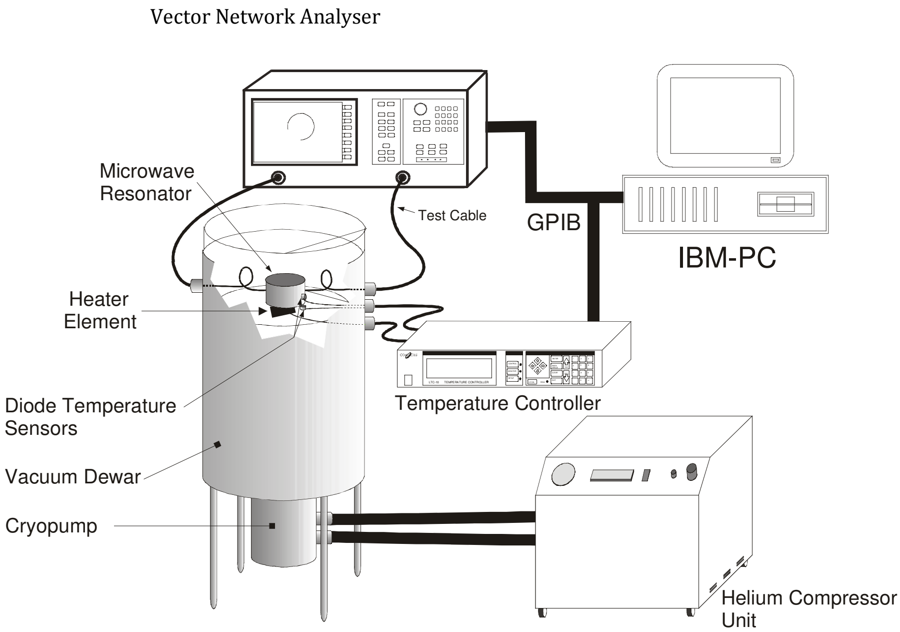


Fig. 6 Microwave characterization system

Surface resistance of the NdBaCuO films under tests were calculated as either:

1. R_{S1eff} from the unloaded Q_O-factor using the well known loss equation:

$$R_{Seff} = A_S\left(\frac{1}{Q_o} - \frac{R_{met}}{A_{met}} - p_d tan\delta\right) \quad (1)$$

or

2. R_{S2eff} and R_{S2int} from the complex conductivity σ computed from rigorous solutions of Maxwell equations as described in [12]. In the latter case also penetration depth λ was also computed.

Measurement Results

Values of effective surface resistance, R_{S1eff} as a function of temperature for two pairs of NdBCO films computed form the loss equation (1) are presented in Figs 7-8. The real and imaginary parts of the complex conductivity, σ_1 and σ_2, and the penetration depth calculated using the rigorous approach are given in Figs 9 and 10, and computed values of intrinsic and effective surface resistances (R_{S2int} and R_{S2eff}) in Fig. 11 a and b.

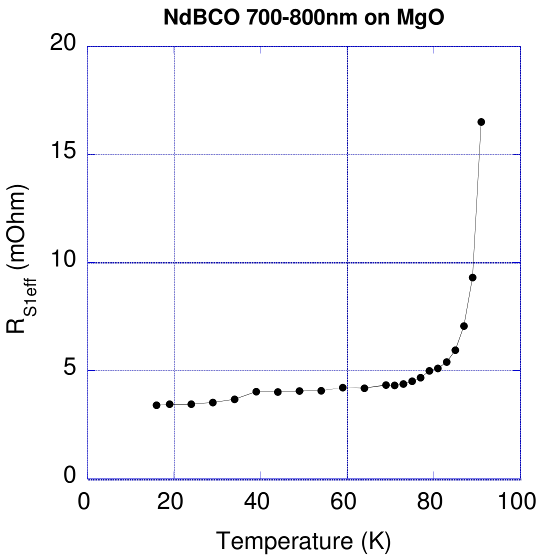


Fig. 7 R_{Seff} from Q_o for 700/800nm films

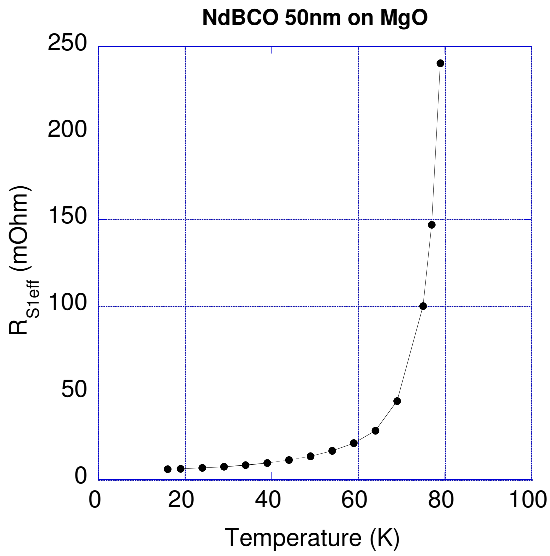


Fig. 8 R_{Seff} from Q_o for 50nm films

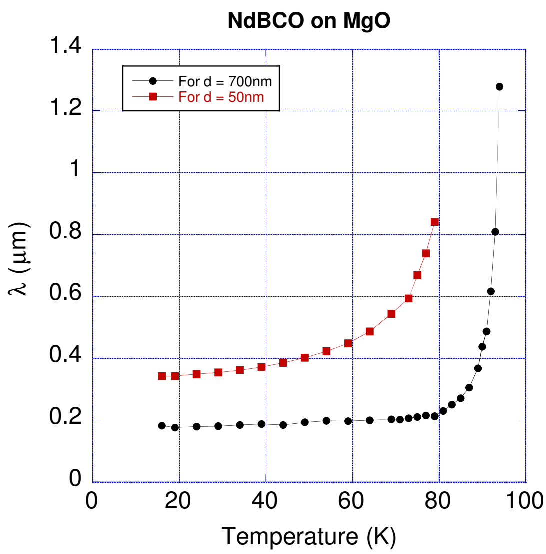


Fig. 9 Penetration depth from f_{res}

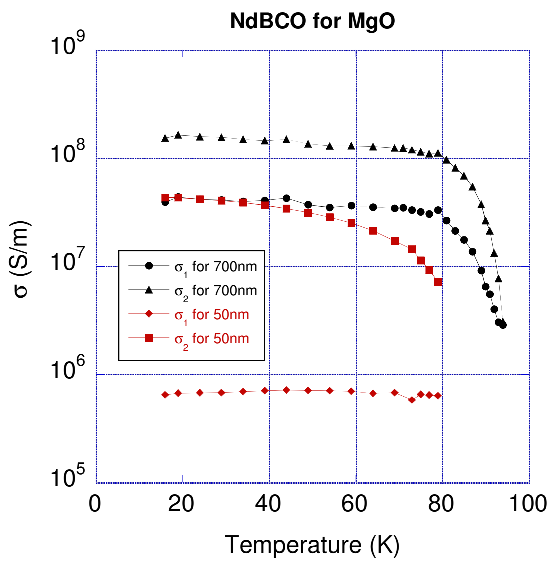


Fig. 10 Complex conductivity from Q_o and f_{res}

As expected values of R_{S1eff} computed from the measured Q_o-factor for "thick" samples are smaller than for the pair of "thin" semi-transparent films (3.4mΩ and 5.8mΩ at 16K. The difference increases significantly with temperature; with 4.7mΩ and 147mΩ at 77K. It is clearly visible that the MgO substrate and the silver plated copper top effect EM fields distributions in the resonator. Computed values of complex conductivity and the penetration depth using the second approach showed that 700nm NdBaCuO films have lower λ but higher σ_1 and σ_2 than 50nm films.

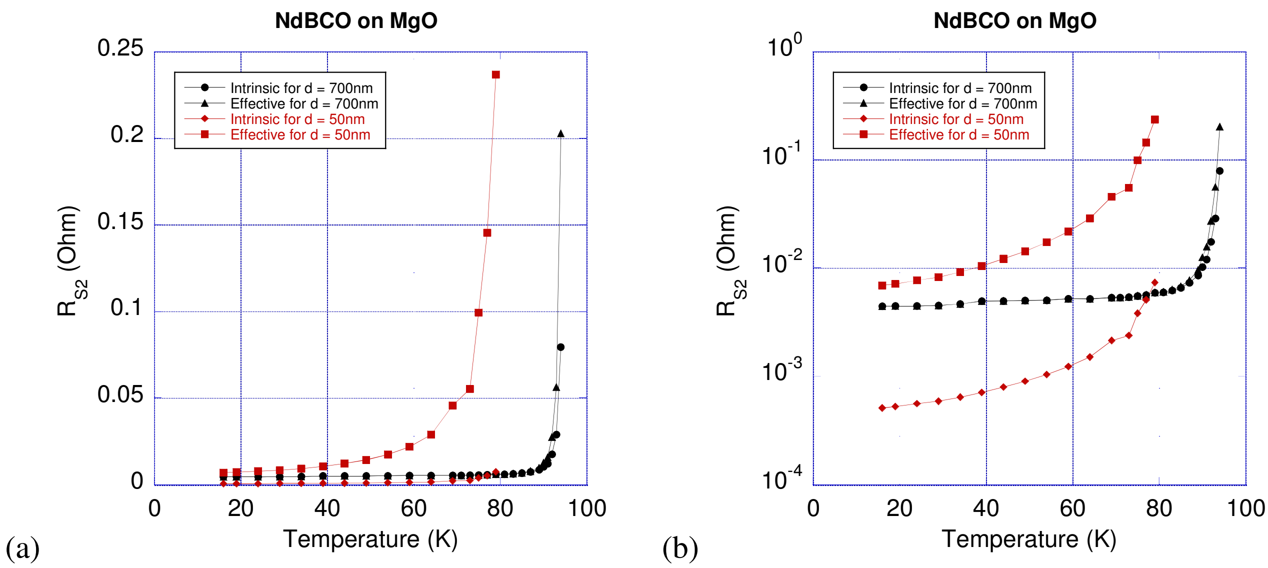


Fig. 11 Computed Surface resistance from σ: (a) linear scale (b) logarithmic scale

Table 1 R_{S2int} for 700/800nm films and 50nm films

T [K] / $\mathbf{R_{S2\,int}}$ [mΩ]	19	39	59	77
d = 50nm	0.52	0.71	1.23	5.09
d = 700/800n	4.48	4.99	5.20	5.64

Computed intrinsic R_{S2int} of 700/800nm films is higher than that of 50nm films (Fig. 11 and Table 1) up to 80K enabling to qualify the first set as medium and the second as low intrinsic loss. It is feasible to say that if 700nm films of the same intrinsic R_{Sint} as the tested 50nm films are made, their R_{seff} will be approximately 0.2mat 10GHz and 60K. Such NdBaCuO films will create a competition for YBCO films for applications to microwave filters. Computed values of R_{S2int} and R_{S2eff} are very similar for the samples X170112A and X170112B up to 80K, as expected, as in this temperature range the films' thickness is greater than 3λ. This is not the case for X030812BM1 and X240513AM films for which λ>d even for the lowest temperatures.

Conclusions

Performed measurements and computations of microwave losses of NdBCO films using two approaches: the wave impedance and the complex conductivity, showed that both rigorous solutions are suitable for microwave characterization of HTS films of small and medium lossand of thickness $d \geq \lambda$ or $d < \lambda$.

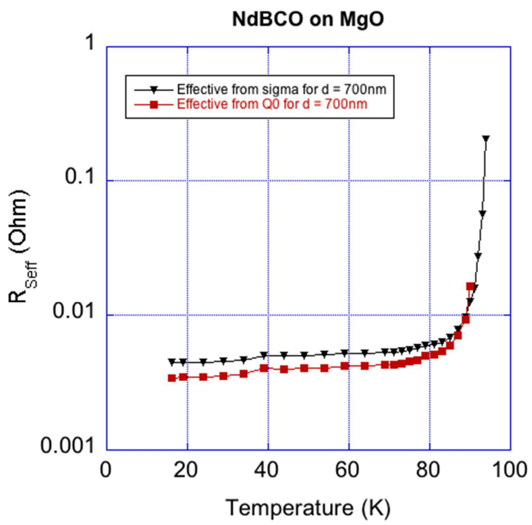
The computed values of R_{Seff} calculated from Q_o and from σ (given in Table 2 and 3 as well as in Figs 12 and 13) are in good agreement for the medium loss "thick" films as well as for the low loss "thin" superconducting samples. The differences in values of the effective Surface Resistance are the biggest at low temperatures and decrease with temperature rising. The discrepancies in R_{Seff} values are probably due to different assumptions used in the rigorous electromagnetic analysis for both computation techniques.

Table 2 R_{Seff} for X170112A and X170112B

T [K] R_{Seff} [mΩ]	from Q_0	from σ
16	3.4	4.46
19	3.5	4.48
39	4.0	4.97
59	4.2	5.22
77	4.7	5.69

Table 3 R_{Seff} for X030812BM1 and X240513AM

T [K] R_{Seff} [mΩ]	from Q_0	from σ
16	5.9	6.92
19	6.2	7.16
39	9.5	10.46
59	21.0	20.18
77	147	145



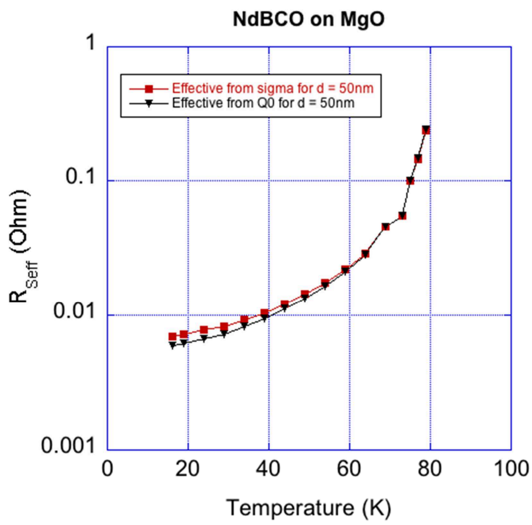


Fig. 12 Effective Surface resistance obtained from two approaches for (a) 700/800nm films and X170112B films, (b) for 50nm films

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