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Improvement in short-circuited coaxial flange for evaluating microwave superconducting properties at low temperature

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In the present study, we have proposed an improvement in terms of the determination of S-parameters of an open flange from its characteristic impedance and propagation constant. With the help of these S-parameters, the actual reflection coefficient of YBCO films deposited on LAO substrate is obtained from the measured reflection coefficient. The surface impedance of three YBCO films is obtained in the range of few ohms in the frequency range from 1 GHz to 40 GHz. The surface resistance of the films reduces at liquid nitrogen temperature, i.e., 77 K, whereas, the surface reactance slightly increases due to kinetic inductance. The conductivity and skin depth are also determined to validate the improvement in the method.

Keywords: Thin superconductor film, Surface impedance, Microwave conductivity, Skin depth

1 Introduction

Superconductivity plays an important role in the world of physics. The study of the superconducting material either bulk or thin or nano-patterned structures at microwave frequency is fascinating among all the basic experiments. Since, superconducting materials exhibit low losses at *rf*, these materials have drawn attention for the device applications[1-3].

Several techniques have been suggested and used by the researchers for the study of the superconducting thin films at microwave frequencies[4-7]. Each of these measurement techniques has its own advantages and disadvantages.

An alternative way of the characterization of the thin film at microwave frequency is the application of the open - end coax line. This measurement method is not only simple and non-destructive, but a wide frequency range measurement is possible as it is based on the TEM wave resonance. This measurement technique relies on the perturbation of the electromagnetic waves by an unknown material at the open end of the coaxial line. The shape of the material under test also doesn't matter until the homogeneity of the material under test is maintained.

This paper aims to study the superconducting thin films of YBCO at microwave frequency. Thin films of the high temperature superconductor YBCO are of significance in fundamental studies of oxide superconductors and for prospected electronic applications based on superconductors operating at liquid nitrogen temperatures (T= 77 K)[8]. This study is helpful to understand the effects of parameters like thickness, the temperature on the reflection coefficient and thus help to select the appropriate measurement geometry for the measurements of the films.

2 Proposed Theory

To characterize the superconducting YBCO thin film on LAO at microwave frequency, we have used the coaxial open flange based measurement[9] as shown in Fig. 1(a), where a thin film under characterization is attached with the help of a Cu sheet and acts as a short. After the calibration at the 2.92 mm connector male (Z_0=50 Ω) using the calibration kit, a female open flange is connected which is terminated by a thin film followed by the Cu short.

The value of measured reflection coefficient depends on the thin film properties as well as of the open flange. Then the load reflection coefficient (Γ_L) is defined in terms of open flange impedance (Z'_0) and impedance of thin film (Z_L). On

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*Corresponding author: (E-mail: dryogitakalra@gmail.com) connecting the open flange at the calibration plane as shown in Fig. 1(b), the measurable input reflection coefficient (Γ_{in}) is related to the S-parameter of open flange and Γ_L by the following equation[2,10]:

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L} = \frac{Z_{in}-Z_o'}{Z_{in}+Z_o'} \quad \ldots (1)$$

where, Z_{in} is the input impedance looking towards the terminated open flange and S_{ij} (i,j = 1,2) are the S-parameters of open flange. Γ_{in} can be measured from vector network analyzer (VNA) and used to obtain the load reflection coefficient with the knowledge of S-parameters of open flange. So, to obtain S-parameters or transfer the calibration plane at the end of open flange, the characteristic impedance (Z'_0) and propagation constant (γ) of the open flange are required. To obtain these parameters, we have used Cu sheet and teflon films as open[11]. We know that the input impedance of open terminated transmission line and short terminated transmission line are given as $Z_{oc} = Z_0 \coth(\gamma l)$ and $Z_{sc} = Z_0 \tanh(\gamma l)$, respectively[10], where l is the physical length of open flange. These two impedances give then, $Z_o = \sqrt{Z_{oc}Z_{sc}}$ and $\gamma = \tanh^{-1}\left(\sqrt{Z_{sc}/Z_{oc}}\right)/l$. The [ABCD] parameters of open flange is then obtained from the evalauted values of Z_0 and γ, which are converted to S-parameters of open flange[10]. Once, the S-parameters of open flange are known, the load reflection coefficient (Γ_L) is calculated from the measured $S_{11m}(\Gamma_{in})$ parameter using the vector network analyzer (VNA) as follows:

$$\Gamma_L = \frac{S_{11m}-S_{11}}{S_{11m}S_{22}-S_{11}S_{22}-S_{12}S_{21}} \quad \ldots (2)$$

where, S_{11}, S_{22}, S_{12} and S_{21} are S-parameters of the open flange.

The accuracy of such load reflection coefficient depends solely on the standard used for open and short at the end of open flange and tight connection with the thin film under test. Then, the load imepdance Z_L is calculated using, $Z_L = Z_0 \frac{1-\Gamma_L}{1+\Gamma_L}$. In this way, the changes in load impedance values with different temperature would help to obtain the superconducting properties of deposited thin film on suitable substrate. The real and imaginary part of this load impedance are the surface resistance (R_s) and surface reactance (X_s) for the superconducting thin film. The conductivity (σ) and the skin depth (δ_s) are obtained as $\sigma = \omega\mu/(2R_s^2)$ and $\delta_s = 1/(\sigma R_s)$.

3 Thin Film Characterization

3.1 Details of thin film

Many methods have been proposed by various reserchers for the growth of YBCO thin filsm[8,12-14]. For this work, the superconducting films of YBCO were synthesized by pulsed laser deposition (PLD) technique on LAO substrates of thickness 500 um. The substrates were first chemically cleaned in Isopropyl alcohol for 10 min then it was cleaned with acetone for ten min. The excimer laser (λ=248 nm) was used with an approximate energy density 1.2-1.5 J/cm^2. During the deposition, the substrate temperature was maintained at 800 °C. A sufficient amount of the oxygen partial pressure was maintained in a form of continuous oxygen flow during the deposition of the thin film. For the above parameter, the thickness of the deposited film is found to be 100 nm.

3.2 Microwave characterization

For S-parameter measurements, an open flange from M/S southwest is shorted by a custom made Cu sheet of thickness 2 mm with the holes at the corners. Samples for measurements are taken as LAO and YBCO deposited on LAO. The measurement arrangement for S_{11} is shown in Fig. 1(b). The S_{11} parameters for three YBCO films, namely YBCO70, YBCO71 and YBCO95 deposited on LAO are measured at room temparature (RT) and then these films were immersed inside liquid nitrogen (LN_2) to obtain S_{11} at low temperature, i.e., 77 K. From measured S-parameters, R_s, X_s, conductivity (σ) and the skin depth (δ_s) are evaluated for different YBCO thin films as discussed in the section 2.

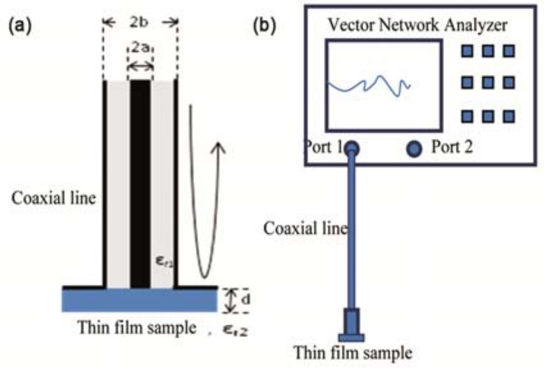

Fig. 1 – (a) Detailed view of thin film-connector interface and (b) schematic of reflection measurement set-up

4 Results and Discussion

4.1 Measured reflection coefficient with different thin films

The measured reflection (S_{11}) parameters are shown in Fig. 2(a-f) for different YBCO thin films. In Fig. 2 (a,c and e), the input reflection coefficient (S_{11}) values for YBCO films at RT are found below 0 dB and it increases slightly to the positive values at low temparature with frequency as indicated for YBCO70 LN_2, YBCO71 LN_2 and YBCO95 LN_2. This means that due to decrease in temperature, the conductor loss has been reduced which indicates the conductivity of YBCO films increased. Although the phase variation of S_{11} is found between +180° to -180° for short backed YBCO films, the more variations are observed at the low temperature.

4.2 Surface resistance and surface reactance of thin films

The variations in R_S and X_S for three YBCO films at RT are shown in Fig. 3. Both R_S and X_S are found to shown resonating behaviour as the sharp peaks and falls are noticed near 11 GHz, 19 GHz, 28 GHz and 36 GHz. This resonating behaviour is due to the open flange terminated by the YBCO/LAO film and short. Also, since R_S and X_S are function of London penetration depth[15] (λ_L), R_S enhances with decreasing the film thickness when the thickness is less than the London penetration depth[16] and it resonates at the film thickness being more than one London penetration depth. The anomalous resonance peaks in R_S and X_S occur when the thickness equals the even multiple of the London penetration depth. In the frequency-dependent surface resistance, the number of the resonance peaks is strongly dependent on the film thickness, as well as the frequency where the peaks are not regularly spaced at a fixed interval. The YBCO71 film has higher R_S and lower X_S values than YBCO70 and YBCO95 films due to different fabrication conditions[17].

In Fig. 4(a-b), YBCO70 has R_S near to zero at RT which reduces to the negative resistance at

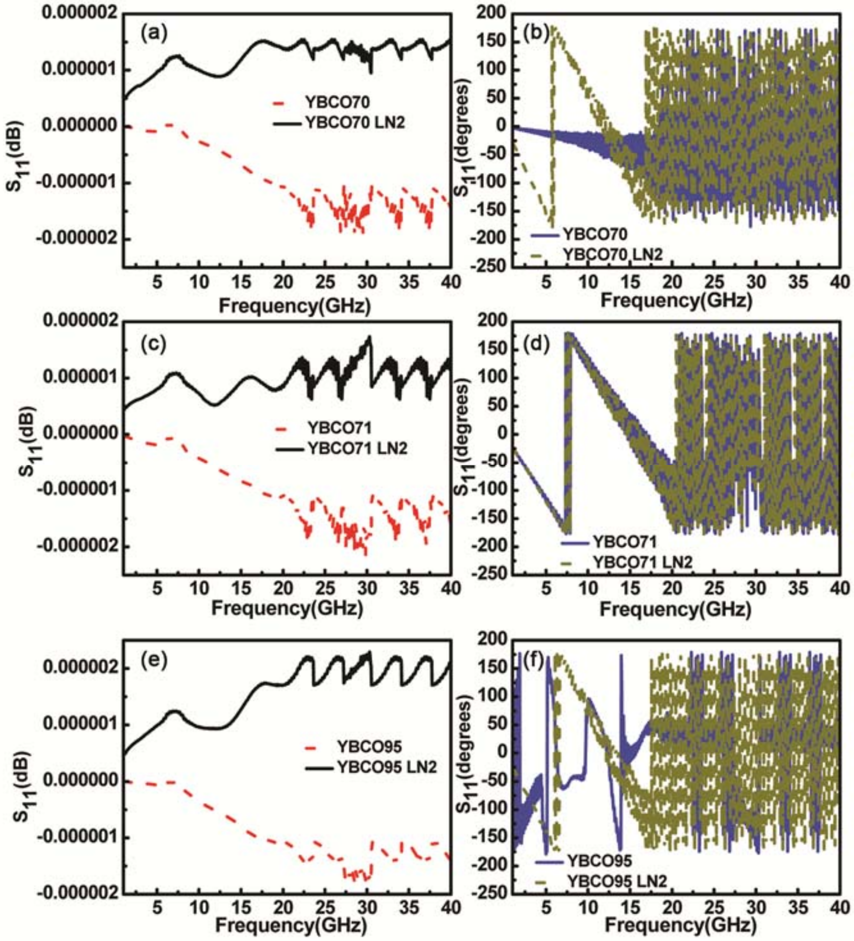

Fig. 2 – Measured S11 parameters for three YBCO films at RT and at low temperature.

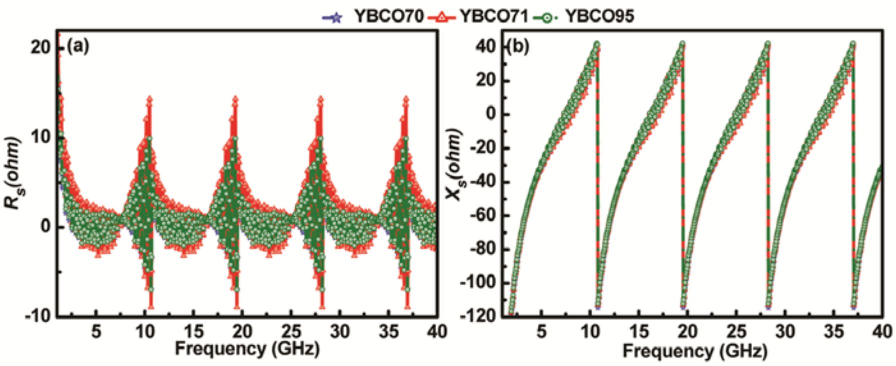

Fig. 3 – Surface resistance and reactance for three YBCO thin films.

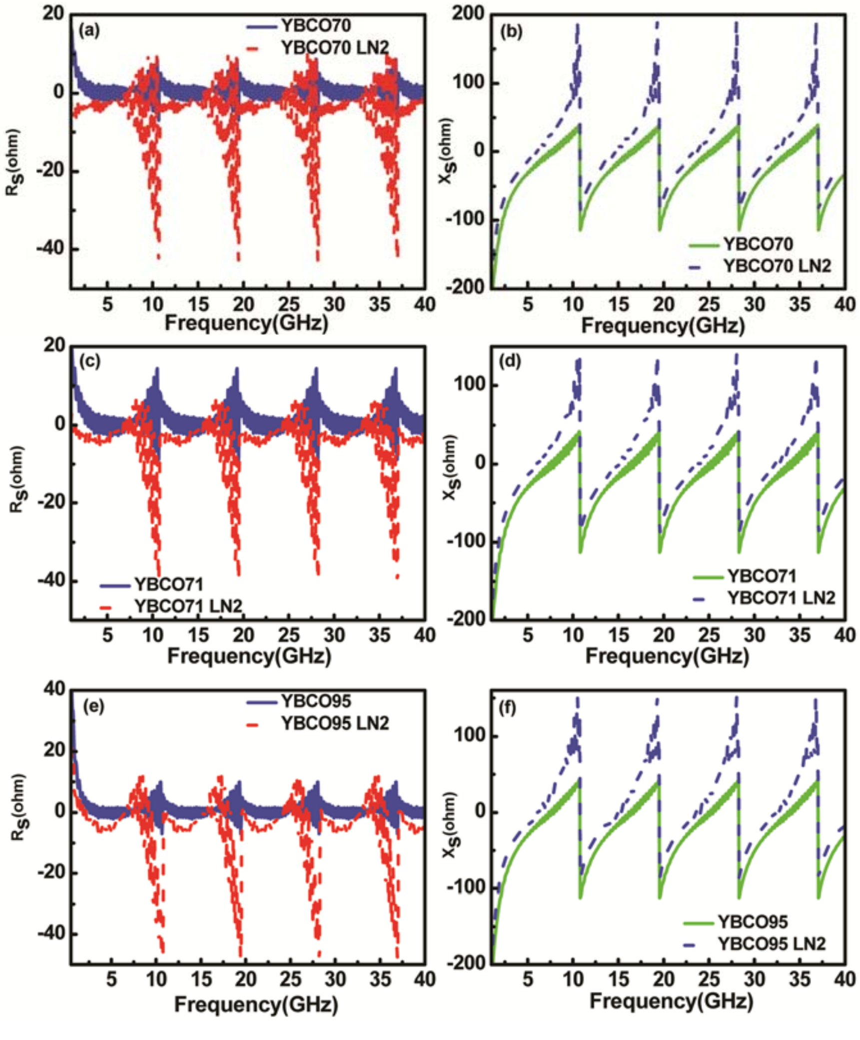

Fig. 4 – Comparison of Rs and Xs at RT and at LN$_2$ temperature for three YBCO thin films.

LN$_2$ temperature whereas X$_S$ values increased slightly. Negative resistance indicates source of energy which means number of free electrons have been increased. As R$_S$ greatly depends on the conductivity, lower R$_S$ at LN$_2$ temperature confirms that deposited YBCO films have superconducting properties. Higher X$_S$ shows that the kinetic inductance of YBCO film became large at LN$_2$

temperature, which in turns indicate the large λ_L for the studied YBCO films. The same behaviour is resulted for YBCO71 and YBCO95 films.

4.3 Conductivity and skin depth of thin films

We obtained the conductivity (σ) and the skin depth (δ_s) of three YBCO films from their R_S values and shown in Fig. 5 and their comparison has been shown as Fig. 6. Although R_S has four peaks only, we observed more peaks in conductivity and YBCO95 film has highest conductivity of the order of 5 megasiemans (MS)/mm at peaks compared to YBCO70 and

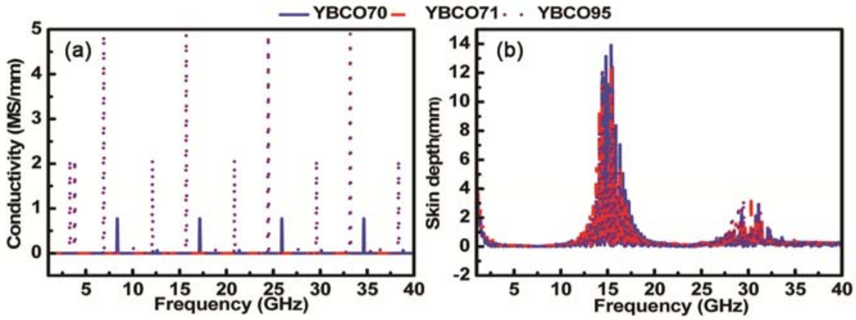

Fig. 5 – Conductivity and skin depth for three YBCO thin films.

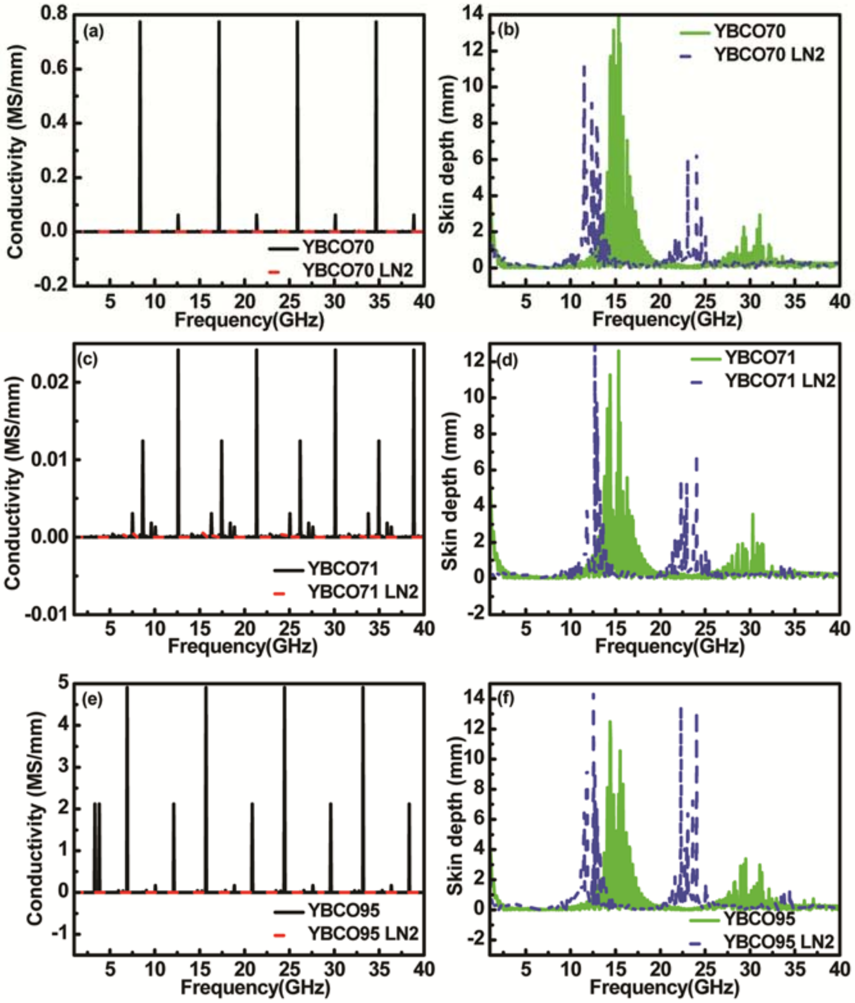

Fig. 6 – Comparison of conductivity and skin depth at RT and at low temperature for three YBCO thin films.

YBCO71 films. In the same analogy, YBCO95 film has minimum skin depth with two broadbands as shown in Fig. 5(b).

At LN_2 temperature, the conductivity is found to near zero as the magnitude of R_S has increased in negative. Through calculation, the lower σ is observed as σ is inversely proportional to R_S. Similarly, a few peaks are observed in the skin depth for three YBCO films. Surprisingly, the peaks are shifted slightly towards lower frequencies at LN_2 temperature.

Method by which both the real and imaginary parts of the surface impedance of superconductors (or other samples) can be measured over a broad range of temperature, magnetic field, and frequency in the rf and mi- crowave regimes.

5 Conclusions

In this work, we presented an improvement in the short cicuited method using open flange for thin film characterization as the real and imaginary parts of the the surface impedance of superconductors (or other samples) can be measured over a broad range of temperature, and frequency. This technique employs a vector network analyzer to measure the complex reflection coefficient of a thin film which forms and electrical short across the end of a coaxial cable. The S-parameters of open flange are obtained from the characterisic impedance and propagation constant and then the actual load refelction coefficient is obatined from the measured reflection coefficient for different thin films. The surface impedance and reactance of three YBCO films deposited on LAO substrate are for verification. Although, the evaluated conductivity and skin depth obtained using this method are different than reported, thier response with the frequency are in agreement. The films of YBCO are reported to be superconductor and the proposed method will be used for study the superconducting properties due to ease of implementation and high accuracy.

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