CHAPTER 1

INTRODUCTION

1.1 General statement of purpose

Measurements of the microwave surface impedance, $Z_s = R_s + jX_s$ with R_s the surface resistance and X_s the surface reactance, and its dependencies on frequency, temperature and magnetic field have been widely employed to characterize the material properties and to explore the underlying physics for the novel high-T_c superconductors since the breakthrough in 1986 [Newman and Lyons 1993; Hein 1996 and references therein]. The measurements can provide information on the superconducting gap, the penetration depth, the critical fields, the dynamics of quasiparticles, the dynamics of flux, the H-T irreversibility line, and even information about the symmetry of the wave function of the Cooper pairs. The studies of Z_s and its functional dependencies are also desired for the application purpose. For example, high-T_c superconductor thin films have already been applied into microwave subsystems and components due to their very low surface resistance available at liquid nitrogen temperatures compared to even best pure metals. In many cases, the applications require superconducting devices to operate under non-optimum conditions, such as external magnetic fields and/or high microwave power. However, under such conditions, high-T_c superconductors may show nonlinearities in the surface impedance and thus significantly limit the application of high-T_c superconductors in both passive and active devices [Shen 1994]. To overcome these limitations, the microwave response of high-T_c superconductors in magnetic fields should be well clarified.

It is the objective of this thesis to study the magnetic field-dependent microwave surface impedance of high-T_c superconducting thin films. The focus of the present study is on the so called “anomalous microwave response” — a novel experimental observation of magnetic field-induced reduction in surface resistance and/or surface reactance in small magnetic fields.

It is generally accepted that Z_s of superconductors increases as a function of applied magnetic field *H*, viz., $\partial Z_s / \partial H > 0$. This can be easily deduced from the leading theories of microwave losses in superconductors such as Ginzberg-Landau theory [Gittleman *et al* 1964], BCS theory [Sherman 1973], the weakly coupled-grain model [Hylton *et al* 1988; Attanasio *et al* 1991; Nguyen *et al* 1993; Portis *et al* 1991] and Coffey-Clem model [Coffey and Clem 1991], as will be discussed later. This is also consistent with most of the experimental observations. However, since 1997 an anomalous field dependence of Z_s, namely $\partial Z_s / \partial H < 0$, has been observed in high-T_c superconducting thin films [Choudhury *et al* 1997; Hein *et al* 1997; Kharel *et al* 1998; 1999; Rao *et al* 1999]. An attractive feature of this anomalous effect is a large decrease of R_s, which can be even larger than 40% of its zero-field value, at very low magnetic field of just several to tens of Oersteds (Oe). Practically, this feature would be very promising for many applications such as magnetically tunable microwave devices and magnetic sensors. Till now, however, the experimental results on the anomalous microwave response are very limited and strongly sample-dependent. The variability in the experimental observations is still poorly understood and this makes it difficult to study the underlying mechanisms responsible for the anomalous microwave response.

It is the purpose of this study to understand the magnetic field-induced anomalous microwave effect from an experimentalist's point of view. This thesis offers a new body of valuable experimental evidence advancing the understanding of the anomalous microwave response of superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films. The focus is on qualitative aspects and experimental measurements rather than on detailed theoretical considerations.

1.2 Superconductivity

In 1908 H. Kamerlingh Onnes succeeded in liquefying helium gas at 4.2 Kelvin (K). Using liquid helium as a coolant, Kamerlingh Onnes was able to obtain temperature down to about 1 K. Three years later, while attempting routine electrical resistance measurements, he observed that pure mercury suddenly lost all resistance slightly above 4 K [Onnes 1911]. With this observation, the study of superconductivity was born.

For the following 22 years the scientific community believed that Kamerlingh Onnes had discovered "perfect conducting" state. Inside a perfect conductor the electrical field must be zero. From the Maxwell equation, $\nabla \times \vec{E} = -\partial \vec{B} / \partial t$, if $\vec{E} = 0$ then $\partial \vec{B} / \partial t = 0$. It means that the magnetic flux density in a perfect conductor cannot change with respect to time and thus the magnetic flux lines will be trapped inside the perfect conductor if it is cooled in magnetic fields. But in 1933, W. Meissner and R.

Ochsenfeld demonstrated exactly the opposite [Meissner and Ochsenfeld 1933]. When cooled below their transition temperature, instead of trapping magnetic flux, the so-called superconductors actually expelled magnetic flux. This revealed the other distinctive property for superconductors — perfect diamagnetism, along with perfect conductivity.

In order to include the two distinctive properties of superconductors into one theoretical frame, F. London and his brother H. London proposed two new equations to describe the electrodynamics of the superconducting state [London and London 1935]. The most notable success of London theory is the prediction of the penetration depth λ, which is a characteristic length of penetration of the static magnetic flux into a superconductor. While the interior of a superconductor expels the magnetic flux, the static flux persists within a sheath of depth λ at the surface of the sample; its magnitude decreases exponentially towards the core of the superconductor.

In 1950 V. Ginzberg and L. Landau proposed a thermodynamic, phenomenological theory of superconductivity based on Landau's general theory of second order phase transitions [Ginzberg and Landau 1950]. Their approach turned out to be surprisingly successful and gave deep insight into the characteristic properties of most interesting superconducting materials. Ginzberg-Landau theory introduced another characteristic length, coherence length ξ, of superconductors. Depending on the ratio of the two characteristic lengths, $\kappa = \lambda / \xi$, superconductors can be divided into two groups: type-I ($\kappa < 1/\sqrt{2}$) and type-II ($\kappa > 1/\sqrt{2}$) superconductors [Abrikosov 1957]. While the former expels magnetic flux completely from their interior, the latter does it completely only at small fields, but partially in higher external fields.

While great success was achieved in understanding the macroscopic properties of superconductors by intuitive, phenomenological London theory and Ginzberg-Landau theory, little progress was made in developing a fundamental theory of superconductivity until the publication in 1957 of the microscopic theory, or BCS theory, by John Bardeen, Leon N. Cooper, and J. Robert Schrieffer [Bardeen *et al* 1957], for which they were awarded the Nobel Prize in Physics in 1972. The BCS theory describes superconductivity in low-temperature metals, such as mercury and lead, and is based on an attractive interaction between electrons that results from their coupling to phonons.

Along with the developments in theory of superconductivity, a lot of efforts were spent on the search for new materials with high superconducting transition temperatures (T_c). In 1973, the highest known T_c was 23.3 K for Nb_3Ge and a higher T_c was not discovered until 1986. From 1911 until 1986, T_c only increased by ~19 K. This naturally led one to think that there was probably an upper limit for T_c. One theory based on the phonon mechanism for superconductivity even predicted that the maximum T_c could not exceed 40 K [Ginzberg and Kirzhnits 1982]. By 1986, most researchers had even given up searching for higher temperature superconductors.

Bednorz and Müller's discovery of high-critical temperature superconductivity above 30K in ternary perovskite-related cuprate structure in 1986 [Bednorz and Müller 1986] has revitalized the research interest in the field of superconductivity. The maximum T_c had been fixed at 23 K for the previous 14 years. Shortly after this breakthrough, C. W. Chu and his colleagues discovered superconductivity above 90 K in $YBa_2Cu_3O_7$, a layered copper oxide with complicated unit cells [Wu *et al* 1987; Zhao *et al* 1987]. Since then, many other new superconductors have been found with even higher critical temperatures, such as the thallium family of compounds with a maximum T_c up to 125 K [Sheng and Herman 1988] and the mercury compounds with a maximum T_c up to 150 K [Schilling *et al* 1993; Chu *et al* 1993; Nunez-Regueiro *et al* 1993]. Some of the high-T_c superconductors are listed in Table 1.1.

Prior to the discovery of the so-called "high-temperature superconductors (HTS)", all known superconductors required liquid helium as a refrigerant. Liquid helium, which evaporates at 4.2 K, is rare, expensive, hard to handle, and even somewhat dangerous. As a result, the technological applications of superconductivity have always been severely limited. Liquid nitrogen, which evaporates at 77 K, is plentiful, inexpensive, and relatively easy to work with. The discovery of superconductivity above 77 K, the boiling temperature of nitrogen, generated enormous excitement and research challenges that are still at the forefront of physics, chemistry, material science and engineering.

After the discovery of high-T_c superconductivity, many efforts have been made to develop microscopic theories to understand the new phenomena. It has soon been realized that the high-T_c superconductivity cannot be fully explained in the framework of the BCS theory that has proven successful in understanding the conventional low-T_c superconductivity in metals and alloys. It is known that a two-electron pairing is still involved, but the nature of the pairing, *s*-wave vs. *d*-wave, remains controversial, although very recent experiments seem to favor *d*-wave pairing [Shen *et al* 1993; Kelley *et al* 1994; Ding *et al* 1995a; 1995b]. Besides, many new concepts, such as spin and charge inhomogeneities ("stripes") [Lee PA 1999] and pseudogap [Shen and Desau 1995; Campuzano *et al* 1998], have also been introduced to understand the high-T_c superconductivity and related materials. Despite a lot of achievements have been made in these theoretical attempts, the basic physical mechanisms responsible for the high T_c are not yet clear.

On the other hand, in spite of the drawback of unclear mechanisms, the discovery of high-T_c superconductors has opened the way to a broader range of practical applications than for the conventional superconductors because cooling by liquid helium is not required. Through the steady efforts in improving the material quality of the high-T_c superconductors, which are in the forms of single crystals, thin films, bulks and wires, the feasibility of these applications has been further improved. Due to their very low surface resistance, the high-T_c superconducting thin films have practical applications in making a large portion of microwave devices, such as filters, delay lines and antenna. The reduced surface resistance means microwave elements will have a lower attenuation per unit length, and thus higher Q resonators can be made. A higher Q resonator leads to the possibility of making very narrow band filters with very small size. YBCO microstrip filters are already being fabricated commercially and exhibit good properties and much reduced insertion losses compared to identical normal metal filters.

1.3 $YBa_2Cu_3O_{7-\delta}$

The material studied in this thesis is focused on $YBa_2Cu_3O_{7-\delta}$, the most commonly used superconductors. $YBa_2Cu_3O_{7-\delta}$ (sometimes called 1-2-3 compound) has a transition temperature in the neighborhood of 90 K, well above 77 K attainable with liquid nitrogen. It is a member of the family of ceramics called perovskites, but it is actually a "defective" perovskite. Attempts to fabricate the 1-2-3 compound usually result in a stoichiometry ranging from $YBa_2Cu_3O_6$ (non-superconducting) to $YBa_2Cu_3O_7$ (superconducting). For this reason the material is often referred to as $YBa_2Cu_3O_{7-\delta}$, where $0 < \delta < 1$. For δ greater than about 0.7, the unit cell is tetragonal and the material is antiferromagnetic, with the Néel temperature decreasing as the oxygen is further reduced. For δ less than about 0.7, the unit cell is orthorhombic and the material is no longer antiferromagnetic, but it becomes superconducting, with the superconducting transition temperature increasing to slightly above 90 K as δ is reduced toward the optimum value of approximately 0.1. Shown in Figure 1.1 are the unit cells for tetragonal $YBa_2Cu_3O_6$ and orthorhombic $YBa_2Cu_3O_7$.

Like other high-T_c superconductors, YBCO is a highly anisotropic material. The conductivity, the critical field H_c, and the critical current J_c along *ab*-plane are different from those parameters along the *c*-axis. Other characteristics like the superconducting coherence length ξ and the magnetic penetration depth λ are anisotropic as well. One finds ξ_{ab} = 12-16 Å, ξ_c = 1.5-3 Å and $\lambda_{ab}(0)$ = 1400 Å, $\lambda_c(0)$ ~ 7000 Å. Superconducting energy gap, $\Delta(0)$, for the high-T_c oxides are high compared to the low-T_c materials. Typical parameters for YBCO is $v_F = 1.1 \times 10^7$ cm/s and $2\Delta(0)/k_BT$ = 5-8. The coherence length, ξ, is extremely short compared to low-T_c superconductors.

That YBCO becomes the most important superconductor in applications is mainly due to the success in fabrication high quality YBCO thin films. The electronics applications of superconductivity depend entirely on the synthesis and utilization of thin films of superconductors. YBCO can be easily deposited on a ceramic substrate by a variety of deposition techniques such as pulsed laser ablation, molecular beam epitaxy, chemical vapor deposition, magnetron sputtering, and focused ion beam sputtering. Optimum quasi-epitaxial YBCO thin films, typically 100-500 nm thick, exhibit $T_c = 90$ K (a bit lower than for bulk YBCO) and dc critical currents with $J_c \sim 10^{10}$ A/m^2 at 77 K and much more at lower temperatures. Furthermore, typical high-frequency properties include a surface resistance of ~ 1 mΩ at 10 GHz and 77 K, orders of magnitude below that of a normal metal such as copper or aluminum.

1.4 Microwave surface impedance

Supposing an electromagnetic plane wave is irradiated perpendicularly onto a wall made from a perfect conductor, the boundary conditions require that at the wall the ***H*** field be parallel and the ***E*** field be perpendicular to the surface. If the wall is made from normal conductors, then in addition to the transverse magnetic field $\boldsymbol{H}_t$ there will be a small transverse electrical field $\boldsymbol{E}_t$ at the surface. $\boldsymbol{H}_t$ and $\boldsymbol{E}_t$ are perpendicular with each other. The ratio of their amplitudes E_t and H_t gives the complex surface impedance Z_s

$$\frac{E_t}{H_t} = Z_s = R_s + jX_s \tag{1.1}$$

with R_s the surface resistance and X_s the surface reactance. The former determines the energy loss, and the latter determines the resonance frequency when the material forms part of a resonant circuits — the usual configuration for the valuation of R_s and X_s.

In the limit of local electrodynamics ($\xi << \lambda$), which holds true for almost all the high-T_c superconductors, the frequency dependent surface impedance $Z_s(\omega)$ can be calculated from the more fundamental parameter, the complex electrical conductivity $\sigma = \sigma_1 - j\sigma_2$, by

$$Z_s(\omega) = R_s(\omega) + jX_s(\omega) = \sqrt{\frac{j\omega\mu_0}{\sigma_1 - j\sigma_2}} \tag{1.2}$$

where μ_0 is the permeability of free space and ω is the measuring frequency. The conductivity σ can be evaluated in different theoretical models. For example, in the two-fluid model (TF), it is given by [Lancaster 1997]

$$\sigma_{1TF} = \frac{n_n e^2 \tau}{m\left(1 + \omega^2 \tau^2\right)} \tag{1.3}$$

$$\sigma_{2TF} = \frac{n_s e^2}{\omega m} + \frac{\omega n_n e^2 \tau^2}{m\left(1 + \omega^2 \tau^2\right)} \tag{1.4}$$

where n_n and n_s are the density of normal carriers and that of superconducting carriers respectively, e and m are the electron charge and mass, τ is the relaxation time of the normal carrier. For most practical situations $\omega\tau << 1$ and relaxation effects can be ignored. Hence one can see from (1.3)-(1.4) that σ_1 and σ_2 are determined by n_n and n_s respectively.

Assuming $\sigma_1 << \sigma_2$, which is a good approximation for temperatures lower than and not too close to T_c, the surface resistance and surface reactance can be derived approximately from Equation (1.2) as follows.

$$R_s(\omega) = \frac{\omega^2 \mu_0{}^2 \sigma_1 \lambda^3}{2} \tag{1.5}$$

and

$$X_s(\omega) = \mu_0 \omega \lambda \tag{1.6}$$

where

$$\lambda = (\mu_0 \omega \sigma_2)^{-1/2} \tag{1.7}$$

is the frequency-independent penetration depth. Equation (1.6) shows that there exists an effective inductance at the superconducting surface, which is frequency dependent and is given by $\mu_0\lambda$. In contrast, the surface resistance, R_s, varies as ω^2 and as λ^3, assuming other parameters remain constant.

Z_s is generally a function of some system parameters, such as frequency, temperature and applied magnetic field. It reads

$$Z_s = Z_s(\omega, T, H)\,. \tag{1.8}$$

By measuring the functional dependence of Z_s, one can obtain a lot of information both on the intrinsic properties of the superconducting states and the external material properties of the superconductors.

1.5 Magnetic field-induced anomalous microwave response

The term of "anomalous microwave response" or "anomalous microwave effect" used in this thesis refers specially to a family of experimental observations in which the surface impedance, especially the surface resistance, of HTS thin films at microwave frequency decreases with increasing magnetic fields. These observations are "anomalous" since it is generally expected that the surface impedance of HTS thin films is a monotonic increasing function of applied magnetic field.

Intrinsically, the application of dc and/or mw magnetic field, from Ginsberg-Landau equations [Gittleman *et al* 1964] and BCS theory [Sherman 1973], will cause dissociation of Cooper pairs into quasiparticles, thus affecting the complex conductivity and raising the surface impedance. Same prediction comes from the weakly coupled grains model [Hylton *et al* 1988] that treats the HTS thin films as a network of superconducting grains and intergrain weak links. The applied magnetic field will induce decoupling of the neighboring superconducting grains by modifying the nonlinear inductance of weak links [Attanasio *et al* 1991; Nguyen *et al* 1993; Portis *et al* 1991]. It will cause an increasing R_s and effective penetration depth. This can also be expected when vortices are involved in the HTS films. The dissipation of vortices will increase monotonically with the applied dc and mw magnetic field [Halbritter 1990; Coffey and Clem 1991; Portis and Cooke 1993; Sridhar 1994]. From these points of views, the observed decrease in Z_s is quite anomalous.

1.5.1 Experimental history

It is important to place the work of this thesis, which addresses the anomalous microwave response of HTS thin films, in proper context. To this end, a rather complete overview of the limited experiments on this anomalous effect or the similar follows.

The first observation of the anomalous microwave response of HTS superconducting thin films was reported by Choudhury *et al* in 1997 [Choudhury *et al* 1997]. The authors measured the surface resistance of patterned YBCO thin films in the presence of a small dc magnetic field. The *c*-axis oriented YBCO thin films were deposited on $LaAlO_3$ (LAO) substrates by pulsed laser deposition method. The measurements of surface resistance were made by a suspended line resonator technique with the dc magnetic field perpendicular to the surface of the YBCO thin films. With a fixed low microwave input power at −21 dBm, the microwave surface resistance R_s was observed to decrease as the dc magnetic field H_{dc} is initially raised from zero, to pass through a minimum, and then to increase monotonically. The position of the minimum was observed to occur at around 5 Gauss and the depth of the minimum was about 30% of the initial zero-field R_s value. The R_s minimum found at non-zero dc magnetic field indicated that this small field served to decrease microwave losses in the YBCO samples under test. This is really a surprise since it is contradictory with the predictions of the leading theories as we shown previously. However, the observation of R_s minimum at non-zero dc magnetic field disappeared with a higher microwave input power at −11 dBm.

To confirm the experimental result, the authors also measured the variation of R_s with applied microwave input power in a fixed H_{dc}. The observations are consistent. Furthermore, they found that the non-linearities in the sample were also suppressed at small dc magnetic fields for low microwave powers.

The unusual behavior of R_s highlighted the interesting nature of the low-field phenomena in HTS thin films. Choudhury *et al* tried to examine the experimental data in the framework of two proposed explanations for non-linear response in HTS thin films, viz., weak links and dynamics of a current-driven critical state. However, it seems that both of the models cannot explain the anomalous effect observed.

In the same year, Hein and his colleagues also reported the observation of the anomalous effects in a series of *c*-axis oriented YBCO thin films on LAO substrates fabricated by different thin film deposition methods [Hein *et al* 1997]. Two microwave resonators, a sapphire dielectric resonator at 8.5 GHz and a Cu cavity resonator at 87 GHz, were employed in their experiments to study both the microwave magnetic field (H_{mw}) and the dc magnetic field dependence of the surface impedance of the un-patterned HTS thin films. They found a correlated reduction of R_s and X_s in both H_{dc} and H_{mw} of the scale of < 20 mT in their samples. The correlation of R_s and X_s can be put into the framework of the two-fluid model. The same results were observed for various, differently prepared samples even though the parameters are strongly sample-dependent. The consistent observation of reduction of R_s and X_s, similar in value in both dc and microwave fields, indicated that the time scale of the underlying mechanism can be below 50 ps if the dc and microwave fields play the same role.

The reduction in R_s and X_s was attributed to magnetic-field-induced suppression of the spin-flip scattering rate in the superconductors. This explanation is an extension of Ovchinnikov and Kresin's magnetic impurity theory [Ovchinnikov and Kresin 1996]. It declares that magnetic impurities are likely to be present in most HTS materials. The interaction between localized magnetic moments of magnetic impurities and cooper pairs that are in the singlet state destroys the pair correlation and is accompanied by spin-flip scattering. An external magnetic field would force the localized magnetic moments to align, frustrate the spin-flip scattering, and lead to a reduction of pair breaking. Qualitatively, this explanation would give a simple picture to understand the experimental data they collected.

While our study on the anomalous effect was in progress near the end of 1998, Lancaster's group reported the anomalous effect observed in their experiments [Kharel *et al* 1998; 1999]. Using a coplanar resonator technique, they measured the surface resistance and surface reactance of the YBCO thin films on polished (001)-oriented MgO single crystal substrates deposited by *e*-beam co-evaporation method. Different from the experimental results obtained by Hein *et al*, they found that there is in general no correlation between the changes in R_s and X_s in the magnetic fields. They discussed their experimental results in the framework of Hein's magnetic impurity theory and pointed out that the magnetic impurity theory is not enough to give a satisfactory explanation for their experimental data.

To be clear, all the related reports of the anomalous microwave response in HTS thin films were summarized in Table 1.2. The experiments on the anomalous microwave response in HTS thin films are very limited so far.

It should be stressed that this anomalous microwave response is not only observed in HTS, in fact, similar effects were also observed in the conventional low temperature superconductors (LTS). The first report of the similar anomalous effect can be traced back to 1950.

An unexpected decrease of surface resistance in dc magnetic fields as small as 10 Gauss was observed by Pippard when he was studying the field variation of penetration depth of superconducting tin [Pippard 1950]. The effect was noticed in all of his samples, but not at all temperatures. It does not begin until the temperature is below 3.63 K, the transition temperature being 3.73 K, but disappears again at the lowest temperature in his experiment, 1.7 K. These results were obtained with both the thicker and thinner specimens, but the effect in the thinner sample is weaker. The drop of resistance was accompanied by an increase of surface reactance.

Josephson has measured the magnetic field dependence of the surface reactance of superconducting tin at a frequency of 174 MHz and also found an unexpected behavior [Josephson 1974]. He found that in the parallel field configuration, the change of X_s with the applied dc magnetic field is quite complicated and unusual. For temperatures above about 0.93 T_c and below about 0.45 T_c the change of X_s with field is negative and cannot be expected in the theoretical consideration.

Using a superconducting microwave cavity resonator, Sridhar and Mercereau measured the small changes R_s in the 10 GHz surface resistance R_s of thin superconducting films of Sn and In, caused by a dc magnetic field-induced current J_0 [Sridhar 1983; Sridhar and Mercereau 1986]. Along with the expected increase of absorption due to thermodynamic suppression of the gap parameter by the static current, they also observed a decrease of absorption at low temperatures. They employed the formalism of a microscopic theory of the dynamic non-equilibrium quasiparticles response in the presence of a static current, which is applicable in the local electrodynamic limit and at high frequencies $\omega > 1/\tau_{in}$, where τ_{in} is the inelastic quasiparticles scattering time.

1.5.2 Importance of the present work

The data gathered on the HTS thin films has still not led to a comprehensive understanding of the full range of this anomalous microwave effect. This is partly because of the difficulty of reproducing samples with precisely known characteristics, and partly because of the serious lacking of a suitable theoretical treatment of some key aspects of the problem, such as the sample dependence. In experiments of LTS, theories have been essentially correct. However, the anomalous effect in HTS is still difficult to be studied both experimentally and theoretically since defects play important roles in the properties of HTS materials due to their ultra-short coherence length.

The work presented in this thesis addresses this lacking of experimental data of this anomalous microwave effect in HTS thin films. We systematically carried out a series of experiments to study the dependences of this effect on temperature, field direction, microwave power, frequency and sample qualities. A series of important features of this anomalous effect have been revealed by our experimental results. We have examined these results in the frameworks of several existing relevant theories and proposed a phenomenological model to describe the anomalous effect qualitatively.

Table 1.1 Progress in raising the transition temperature of cuprate superconductors at ambient pressure.

Material	T_c (K)	Reference
$La_{2-x}Ba_xCuO_4$ (LBCO)	30	Bednorz and Müller 1986
$YBa_2Cu_3O_{7-\delta}$ (YBCO or Y-123)	92	Wu *et al* 1987; Zhao *et al* 1987
$Bi_2Sr_2CaCu_2O_8$ (BSCCO-2212)	85	Maeda *et al* 1988
$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO-2223)	110	
$Tl_2Ba_2CaCu_2O_8$ (TBCCO-2212)	105	Sheng and Herman 1988
$Tl_2Ba_2Ca_2Cu_3O_{10}$ (TBCCO-2223)	125	
$HgBa_2Ca_2Cu_3O_8$ (HBCCO-1223)	133	Schilling *et al* 1993

Table 1.2 Related reports on the anomalous microwave response for HTS thin films.

Sample	Technique	Temperature	Findings	Reference
YBCO on LAO by PLD	Suspended line resonator	10K	Decrease of R_s in H_{dc}	Choudhury *et al* 1997
YBCO on LAO by MOCVD, PLD, sputtering and thermal evaporation	Dielectric Resonator at 8.5GHz and Cu cavity resonator at 87 GHz	4.2K and 77K	Correlated decreases of R_s and X_s in both H_{dc} and H_{mw}	Hein *et al* 1997
YBCO on MgO by *e*-beam co-evaporation	Coplanar line resonantor	15K, 35K and 75K	Correlated and uncorrelated decreases of R_s and X_s in both H_{dc} and H_{mw}	Kharel *et al* 1997; 1998

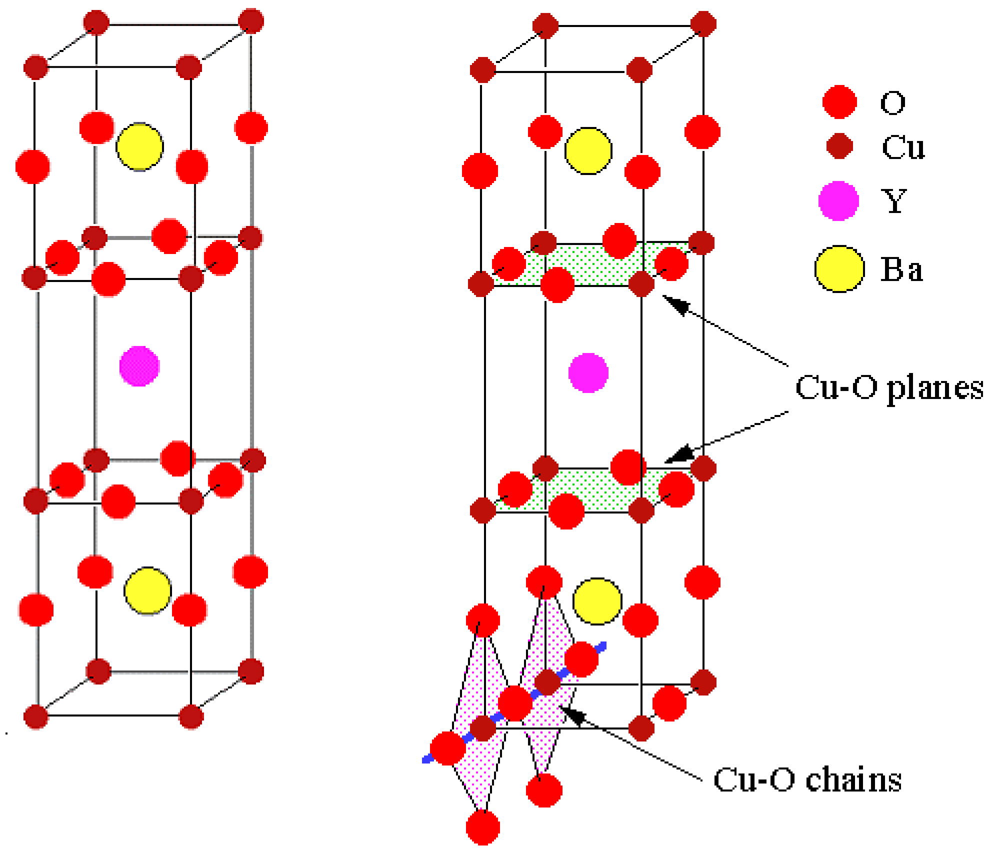

Figure 1.1 Unit cells of $YBa_2Cu_3O_6$ (left) and $YBa_2Cu_3O_7$ (right).