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SUMMARY

An anomalous microwave effect in high-temperature superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films has been observed and studied systematically using high sensitive microwave resonator techniques. The so-called anomalous microwave effect is characterized by a dc magnetic field-induced reduction in microwave surface impedance Z_s (= R_s + jX_s), especially in microwave surface resistance R_s. While the main focus of this study was on understanding the anomalous microwave effect from an experimentalist's point of view, a lot of efforts have also been necessarily put into some related topics, including the deposition and characterization of YBCO thin films, the design, fabrication and packaging of microwave resonators, the set-up of the microwave measurement system and the improvement of microwave measurement methods.

The first report of the anomalous microwave effect in high-temperature superconducting thin films was in 1997. The observation of field-induced reduction in Z_s was surprisingly contradictory with the prediction of the prevailing theories, which highlighted the theoretical importance of the anomalous microwave effect. And then, the potential application of this anomalous effect was also realized. However, due to some difficulties, very few experimental results on this anomalous effect have been obtained since then. The shortage of experimental data limited the theoretical attempts on the anomalous effect and retarded the understanding of the underlying mechanisms.

The primary motivation of this work was therefore to offer a new body of valuable experimental data on the anomalous microwave effect to advance our understanding of this effect, both theoretical and practical.

In this thesis, some basic but important features of the anomalous microwave effect, such as its dependencies on field alignment, frequency, temperature and microwave power, have been revealed through carrying out measurements of the anomalous effect under certain conditions. Most of the experimental results achieved in this work were reported for the first time in the literature. With a carefully designed experiment, the hysteretic properties of $Z_s(H_{dc})$ have also been examined in dc magnetic fields with different strengths. The results directly confirmed that the anomalous microwave effect happens in a Meissner state where the dc magnetic field is not strong enough to form vortex inside the superconducting thin films. A comparative study of different samples demonstrated that there is a strong correlation between the anomalous effect and the microstructure of the superconducting thin film samples. It was suggested that the grain boundaries, especially the *a*/*c* type grain boundaries, in the thin films play important roles in the anomalous effect. A phenomenological model, which combines the conventional weak link model with an anomalous weak link, was therefore proposed to describe the experimental data on the anomalous effect. The simulation results fitted well with the experimental data within some extents.

Several existing theories and models that can predict a magnetic field-induced reduction in Z_s have been reviewed and compared with the experimental observations. Unfortunately, none of them can give a satisfactory explanation for the anomalous microwave effect observed in the high-temperature superconducting thin films.

Though it is still impossible to elucidate the origin of the anomalous microwave effect clearly, the experimental data gathered in this work have greatly developed the understanding of the anomalous microwave effect, which no doubt will be very helpful in determining the underlying physical mechanisms.

LIST OF PUBLICATIONS

"DC magnetic field-induced anomalous microwave response in YBCO thin films: temperature dependence",
C. K. Ong and X. S. Rao, *Physica* **C** 362, 169 (2001).

"An anomalous weak link model for microwave surface impedance of $YBa_2Cu_3O_{7-\delta}$ films in a weak dc magnetic field",
B. B. Jin, C. K. Ong, X. S. Rao, and C. Y. Tan, *Superconductor Science and Technology* **14**, 1 (2001).

"Magnetic-field-induced anomalous microwave response in superconducting $YBa_2Cu_3O_{7-\delta}$ thin films",
X. S. Rao, C. K. Ong, and Y. P. Feng, *Applied Physics Letters* **77**, 2897 (2000).

"Hysteresis measurement of anomalous microwave surface resistance in superconducting thin films",
X. S. Rao, C. K. Ong, B. B. Jin, and Y. P. Feng, *Physica* **C 341**, 2747 (2000).

"Q-factor measurement of nonlinear superconducting resonator",
X. S. Rao, C. K. Ong, and Y. P. Feng, *Electronics Letters* **36**, 271 (2000).

"The anomalous unloaded quality factor behavior of high-T_c superconducting microstrip resonator in weak DC magnetic field",
B. B. Jin, X. S. Rao, C. Y. Tan, and C. K. Ong, *Journal of Superconductivity* **13**, 85 (2000).

"DC magnetic field-induced decrease of microwave surface impedance in superconducting thin films",
X. S. Rao, C. K. Ong, B. B. Jin, C. Y. Tan, and Y. P. Feng, *Singapore Journal of Physics* **15**, 123 (1999).

"Anomalous microwave response of high-temperature superconducting thin-film microstrip resonator in weak dc magnetic field",
X. S. Rao, C. K. Ong, B. B. Jin, C. Y. Tan, S. Y. Xu, P. Chen, J. Li, and Y. P. Feng, *Physica* **C 328**, 60 (1999).

"Experimental observation and simulation of unusual microwave response for the superconducting microstrip resonator at small dc magnetic field",
C. K. Ong, X. S. Rao, and B. B. Jin, *Superconductor Science and Technology* **12**, 827 (1999).

"Nonlinear properties of superconducting $YBa_2Cu_3O_{7-\delta}$ microstrip filter in a dc magnetic field",
W. F. Lee, X. S. Rao, C. K. Ong, and S. Uysal, *Microwave and Optical Technology Letters* **22**, 192 (1999)

"Modified resonant perturbation method for the study of microwave surface resistance of superconducting thin films",
C. K. Ong, L. F. Chen, J. Lu, S. Y. Xu, X. S. Rao, and B. T. G. Tan, *Reviews of Scientific Instruments* **70**, 3092 (1999).

"A phenomenological description for unusual surface impedance behaviors of high-T_c thin film in weak DC magnetic field",
B. B. Jin, X. S. Rao, C. Y. Tan, and C. K. Ong, *Physica* **C 316**, 224 (1999).

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