

Evaluation of superconducting pickup coils with high Q for 700 MHz NMR

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Abstract. In this study, we propose a helmholtz-type coil using a high-temperature superconductor (HTS) for 700 MHz NMR pickup coils with a high quality factor (Q). We analyzed the coil microwave resonant properties of the helmholtz-type one turn coil made using an HTS (DyBa₂Cu₃O_{7-δ}: DyBCO coil) and the same type of coil made from normal metal (Cu coil) through electromagnetic simulations. The Q of the DyBCO coil at 77 K and the Cu coil at 77 K were 3295 and 482 in the simulations. The one turn coils were fabricated using 200-nm-thick DyBCO thin film deposited on an r-sapphire substrate and 3-μm-thick Cu thin film on an r-sapphire substrate. The Q of the DyBCO coil was 2920 at 77 K, and that of the Cu coil was 423 at 77 K. These experimental results indicate that the DyBCO coils are more advantageous than the Cu coils for high-sensitivity NMR measurements.

1. Introduction

Nuclear Magnetic Resonance (NMR) spectroscopy is useful for studies in organic chemistry and biology, for example protein structure analysis and new drug development. However, NMR has its drawbacks: it has low sensitivity and requires a long time for conducting measurements. The signal to noise ratio (S/N) of NMR depends on the filling factor of the pickup coil system, the quality factor of the pickup coil, and the noise temperature of the pickup coil and pre-amplifier as shown in the following equation: $S/N \propto \sqrt{\eta Q / (T_c + T_a)}$. η is the filling factor of the pickup coil system, Q is the quality factor of the pickup coil, T_c is the noise temperature of the pickup coil and T_a is the noise temperature of the pre-amplifier. To increase the sensitivity of NMR spectroscopy it is necessary to increase Q. Thus, superconductors are a promising material for NMR pickup coils. The low surface resistance (R_s) can significantly improve the Q and contribute to the enhancement of the S/N. Recently, high sensitivity pickup coils for NMR have been investigated by using superconductors [1-4]. However, NMR with superconducting NMR pickup coils is still not widely utilized. This is because superconducting NMR pickup coils with a Q higher than 10,000 are rarely reported, tuning of higher Q pickup coils is difficult, and a high RF field homogeneity is difficult to obtain. The final goal of this study is to demonstrate higher sensitivity in NMR spectrometers by using high-temperature superconductor (HTS) pickup coils. The immediate objective is to realize the



advantages of HTS pickup coils for the enhancement of Q and establish high precision simulations. In this study, we investigated the Q of NMR pickup coils by applying HTS thin film (DyBCO) to the coils. HTS thin films have low R_s in a dc magnetic field [5, 6]. In this paper, the simulation, fabrication, and characterization of one turn HTS (DyBCO) coils are described. The DyBCO coil fabricated for this study was evaluated at 77 K, and it was compared with that of a normal metal coil (Cu coil).

2. Simulation

We analyzed the microwave resonant properties of the DyBCO and Cu helmholtz-type one turn coils through electromagnetic simulations using Sonnet-EM software. Fig.1 shows the simulation and three dimensional models of the one turn coils. For the substrate, we used r-sapphire (25 mm×25 mm) with a dielectric constant (ϵ_r) of 10.9 and a dielectric loss tangent of 10^{-7} . For the one turn coils, we used half wavelength resonators with a line width of 0.5 mm. We used the dielectric resonator method to obtain the R_s value of the DyBCO thin film for the initial simulation [5]. We adopted a contactless power feeding method by using a feeding loop antenna made of Cu. Matching was obtained by adjusting the distance between the one turn coils and the feeding loop antenna from 0.01 mm to 9.5 mm. Self resonant frequency of the one turn coils was set to 750-850 MHz. This is because the resonant frequency of the one turn coils shifts, when using a loaded sample tube and tuning with a dielectric plate. For the simulated results, we obtained an unloaded quality factor (Q_u) of 102 for the Cu coil at room temperature, 482 for Cu coil at 77 K and 3295 for the DyBCO coil at 77 K.

3. Experiment

In this study, two kinds of one turn coils were prepared using normal metal (Cu coil) and HTS (DyBCO coil). For the Cu coil, Cu thin film (3 μm) was deposited on the r-sapphire substrate by using a DC-sputtering system. Then, the film was patterned in a one turn shape by photolithography and wet etching by using aqueous ferric chloride. For the DyBCO coil, DyBCO (200 nm) thin film was deposited on the r-sapphire substrate by the thermal co-evaporation method (produced by THEVA GmbH). Then, the film was patterned in a one turn shape by photolithography and Ar ion-beam etching. Then, the fabricated one turn coils were mounted on a jig made of Cu. Fig. 2 shows a photograph of the fabricated DyBCO coil mounted on the jig. Under this setup, the frequency responses were measured by a network analyzer at 77 K. Matching for the 1 turn coils was achieved through adjusting the distance between the one turn coils and the feeding loop antenna. Based on the measurement, we estimated the Q_u of the one turn coils.

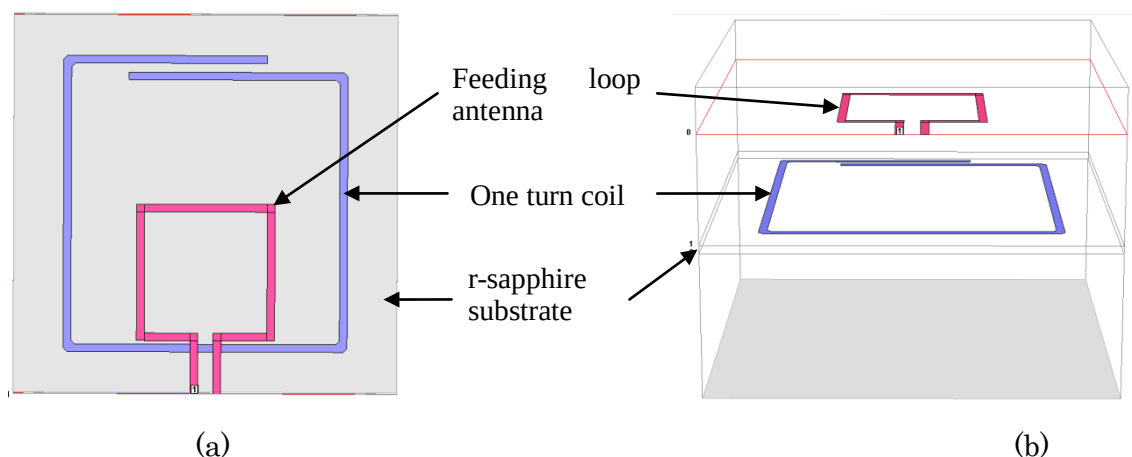


Fig.1. Simulation model for one turn coil. (a) Top view. (b) Three dimensional model.

4. Results and Discussion

4. 1. Actual value of the Q_u

In this study, one turn coils were prepared using normal metal (Cu coil) and HTS (DyBCO coil). Fig. 3 shows the frequency responses of the one turn coils for the simulation results and the experiment results. Solid lines represent the frequency characteristics obtained from the experiment and broken lines represent the simulated frequency characteristics for the one turn coils. In each resonance curve, matching for the one turn coils was achieved by adjusting the distance between a movable feeding loop antenna and the one turn coils. From the experiment, we obtained a quality factor (Q_u) of 102 for the Cu coil at room temperature, 423 for the Cu coil at 77 K and 2920 for the DyBCO coil at 77 K. The actual and simulated self resonant frequency of the one turn coils displayed approximately the same value; however, the actual Q_u was lower than the simulated Q_u . The cause of this could be that the R_s of HTS and Cu thin films deteriorated, which resulted from the thin films being patterned in a one turn shape. The actual Q_u of the DyBCO coil was 6.9 times higher than that of the Cu coil. This result indicates that DyBCO coil is more advantageous than Cu coil for high-sensitivity NMR measurements. However, since the Q_u of DyBCO coil is low, it is difficult to utilize for NMR. Q_u is defined using following equation: $1/Q_u = 1/Q_r + 1/Q_d + 1/Q_c$. Q_r (radiative Q) is the Q resulting from radiation loss, Q_d (dielectric Q) is the Q resulting from dielectric loss by using a substrate and Q_c (conductive Q) is the Q resulting from conductor loss. DyBCO coils fabricated by using r-sapphire substrates have low dielectric loss and DyBCO thin films have low conductor loss. Therefore, Q_r is thought to be a dominant factor for determining Q_u .

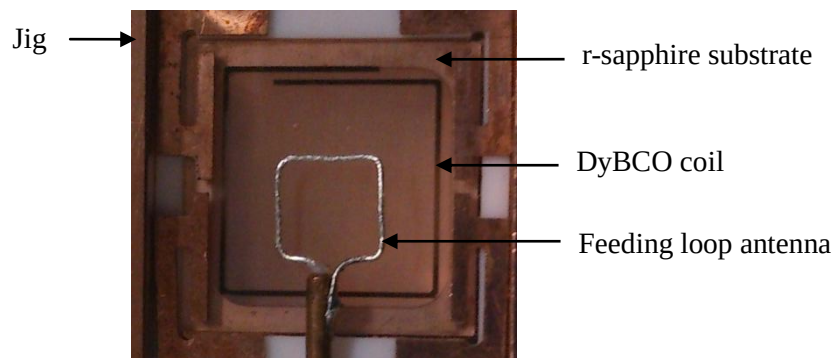


Fig.2. Photograph of fabricated DyBCO coil mounted on the jig.

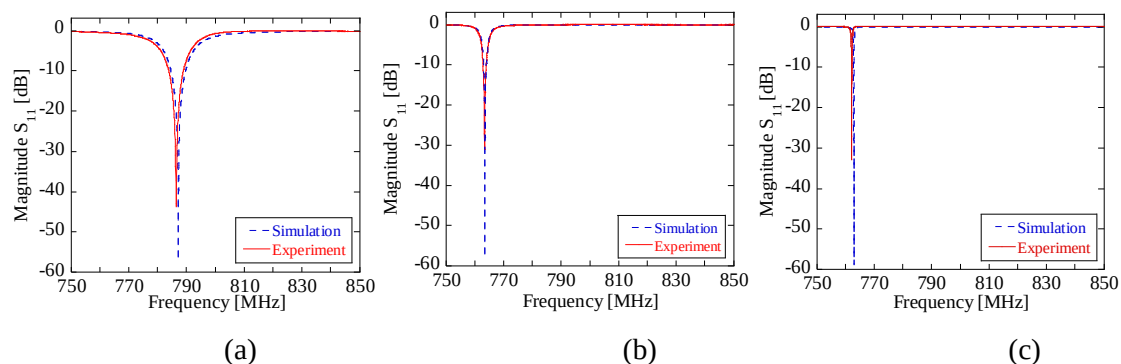


Fig.3. Frequency characteristics of one turn coils for simulated results and actual results. (a) Cu coil evaluated at room temperature. (b) Cu coil evaluated at 77 K. (c) DyBCO coil evaluated at 77 K.

4. 2. Evaluation of R_s of patterned thin films

The simulated R_s value was altered in order to obtain the same Q_u as observed in the experiment. Consequently, the R_s of the Cu thin film at resonant frequency and 77 K increased from 1.9 m Ω to 2.3 m Ω . Similarly, the R_s of the DyBCO thin film at resonant frequency and 77 K increased from 2.5 $\mu\Omega$ to 37 $\mu\Omega$. Additionally, we established a high precision simulation for measuring the R_s of patterned thin films.

5. Conclusions

In this study, one turn coils for 700 MHz NMR were designed and fabricated using DyBCO and Cu thin films and their Q_u were evaluated at 77 K. In the actual experiment, the Q_u of the DyBCO coil at 77 K was 2920, and the Q_u of the Cu coil at 77 K was 423. Therefore, the actual Q_u of DyBCO coil was 6.9 times higher than that of Cu coil. This experimental result indicates that DyBCO coil is more advantageous than Cu coil for high-sensitivity NMR measurements. For the simulation, the simulated R_s value was altered so as to obtain the same value for Q_u as in the experiment. Consequently, the R_s of the Cu thin film at resonant frequency and 77 K increased from 1.9 m Ω to 2.3 m Ω . Similarly, the R_s of the DyBCO thin film at resonant frequency and 77 K increased from 2.5 $\mu\Omega$ to 37 $\mu\Omega$. Additionally, we established a high precision simulation for measuring the R_s of patterned thin films.

Acknowledgments

This work was supported by the Strategic Promotion of Innovative Research and Development of JST (Development of the next-generation NMR technology using HTS materials). A part of this work was carried out in the clean room of Yamagata University Faculty of Engineering.

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