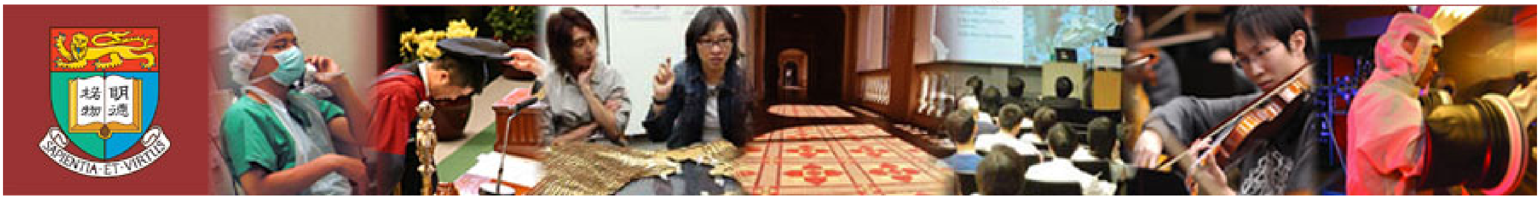

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Design of Superconducting MRI Surface Coil by Using Method of Moment

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***Abstract*—A method of moment with an enhanced model to design high-temperature superconductor (HTS) RF surface coils for magnetic resonant image (MRI) is presented. The resonant frequency and quality factor (Q) of HTS RF spiral coils are simulated using this method. The agreements of resonant frequencies and Qs between the simulation and measurement are excellent with differences less than 1% and 3%, respectively. The 0.2-μ m-thick YBaCuO (YBCO) thin films are deposited onto single side of 0.508-mm-thick LaAlO$_3$ (LAO) and sapphire substrate and patterned into a spiral shape. To accurately analyze the resonant frequency and Q of a coil, an enhanced two-fluid model is employed. HTS RF coils with diameter of 65 mm for 0.2T and 1.5T MRI systems are designed and fabricated with the measured Q of 19 K and 23 K, respectively. In addition, the shift of resonant frequency due to the mutual coupling between two HTS spiral coils is predicted by this method, which is important for design of HTS coil arrays in an MRI system.**

***Index Terms*—MoM, MRI, mutual coupling, RF coil.**

I. INTRODUCTION

IN MAGNETIC resonant images (MRI), there are two major noise sources in an RF receiving signal: sample noise and RF coil noise. Normally, the RF coil noise is dominated in low field MRI [1]; it is also dominated in magnetic resonance microscopy (MRM) when the sample is very small, e.g., 50 μm^3 [2]. In these two cases, reducing RF coil noise becomes essential to improve the signal-to-noise ratio (SNR) for higher MRI quality [3].

High-temperature superconductor (HTS) material at liquid-nitrogen temperature (77 K) provides extremely low resistive loss compared to copper, a commonly used material for RF coil design. Recent research [4]–[6] has shown significant improvement of MRI image quality with SNR approximately improved by a factor of three due to the use of HTS RF coils; therefore, it is believed that HTS RF coils can offer potential applications in the area of MRI.

However, HTS films are generally expensive, and therefore it requires delicate design and precise fabrication in order to get high-Q HTS coils which can operate at a desired resonant frequency. Design of the coils with expected resonant frequency and Q becomes the most critical process. In the past, HTS RF coils were fabricated through iterative experimental trials, which in turn significantly increase the fabrication cost and time. Adjusting the resonant frequency through the fabrication process is an alternative to solve the problem, but it is not favorable since it leads to Q degradation. In this paper, we have developed a numerical method with the use of an enhanced two-fluid model [7], [8] to simulate the design of the HTS RF coil, such that the RF conductivity and surface impedance of HTS material can be fully analyzed.

In most MRI clinical applications, the operating frequency of RF coils is low, ranging from a several megaHertz to 100 MHz. In order to obtain such a low resonant frequency, the coil should have enough inductance and capacitance. The commercial availability of HTS materials is, however, limited to HTS thin film with a maximum diameter of 100 mm; hence, it further restricts the flexibility in HTS coil design. Planar spiral design is a good approach for such a device as it offers high inductance and capacitance; moreover, its planar geometry is suitable for HTS thin film, in addition to its simplicity in design and fabrication.

Several papers have been published for the calculation of the distributed capacitance and inductance of spiral resonators. Jiang calculated the capacitance of a spiral coil [9]. The inductance in that method was derived from a standard formula [10] which led to a 30% to 100% disagreement with the measurement. Although Hejazi improved Jiang's method [11], his method is too complicated and difficult to use. Another method called the Lumped-Element model [12] for the analysis of rectangular spiral inductance was also suggested; however, this model did not consider the loss of signal into the substrate and only concerned the weak coupling between perpendicular strips. Method of moment (MoM) is widely used for integral equations, especially for the analysis of multilayer structure for thin layers or strips because it shows better performance than the finite-element method (FEM). It calculates the distributed capacitance and inductance of HTS spiral resonators. MoM also takes the HTS superconductivity characteristic into account while conductivity is ignored in other methods. It is, therefore, suggested in this paper.

The MoM presented here is based on electromagnetic field mixed potential integral equation. The enhanced two-fluid model is used to simulate the conductivity of HTS material. The HTS RF coils are designed as a type of planar multilayer structure. The Momentum 2-D EM software [13] is used to simulate the S-parameter, resonant frequency, and Q of the

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coil. The simulation of HTS RF coils for both 0.2T and 1.5T MRI systems are demonstrated using this method. In addition, the mutual coupling between two closely parallel HTS spiral coils is also investigated. The shift of resonant frequency with the different mutual coupling between two coils is studied.

II. THEORY

A. MoM

To simulate planar structure with arbitrary metallic patterns on each of the layers of the structure, a mixed potential integral equation is used in order to obtain the current on the metal pattern of device as

$$\iint_S -j\omega G^A(\rho, z, z') \cdot \vec{J}(\vec{r}\,') + \frac{1}{j\omega} \nabla \cdot \left[G^V(\rho, z, z') \nabla' \cdot \vec{J}(\vec{r}\,') \right] dS + \vec{E}^{in}(\vec{r}) = Z_S \cdot \vec{J}(\vec{r}\,') \quad (1)$$

where G^A and G^V are the Green's magnetic and electric potential functions for multilayered medium [13], z is the field point and z' the source point, $\vec{J}(\vec{r})$ is the unknown surface current on the metal pattern excited by the electric field $\vec{E}^{in}$, and Z_s is the surface impedance of metal material.

To solve the integral equations, the Galerkin MoM is used such that the linear system becomes

$$\sum_{n-1}^{N} Z_{mn} \cdot I_n = V_m \qquad m = 1, \ldots, N \quad (2)$$

where $I_1, I_2, \ldots I_N$ are the unknown surface currents of metal pattern, $V_1, V_2, \ldots V_N$ are the excitation voltages, and Z_{mn} is the impedance reaction between the mth and nth test functions. By (2) the current on the metal pattern and also the scattering (S) parameters of the device can be obtained.

B. Enhanced Two-Fluid Model

The enhanced two-fluid model for the calculation of the conductivity of HTS material improves the accuracy of HTS coil design. In this model, the superconducting carrier scattering and loss are described by an effective relaxation time constant τ_s, which is not concerned in the conventional two-fluid model [7], [8]. With an enhanced two-fluid model, the conductivity of HTS is modeled as

$$\sigma_1 = \sigma_n f(T) + \frac{\sigma_2}{\omega \tau_s} \quad (3)$$

$$\sigma_2 \approx \frac{1}{\omega \mu_0 \lambda^2(T)} \quad (4)$$

where $f(T)$ is the temperature function, σ_n is the normal-state conductivity of the HTS material at $T = T_c$, T_c is critical temperature, and T is operating temperature. Normal loss mechanisms and other effects, such as grain boundary losses and residual losses, are included in σ_n. λ is the effective penetration depth and depends on the London penetration depth λ_L as defined in conventional two-fluid model. They are given as

$$\lambda = \lambda_L \sqrt{1 + 1/(\omega \tau_s)^2} \quad (5a)$$

$$\lambda_L = \frac{\lambda_0}{\sqrt{1 - (T/T_c)^2}} \qquad \text{for } T < T_c. \quad (5b)$$

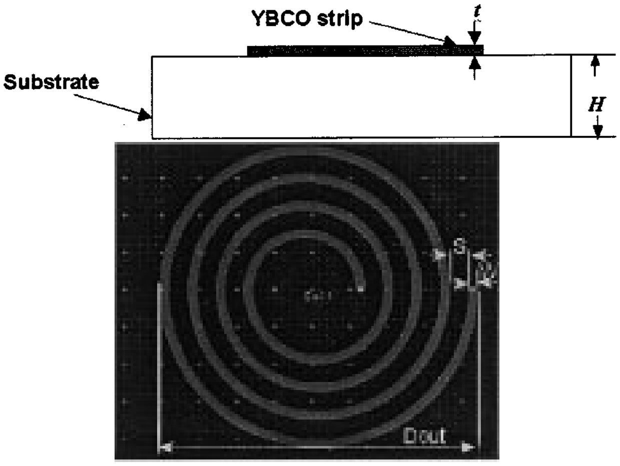


Fig. 1. HTS spiral coil geometry: (a) cross sectional view and (b) bird's eye view.

TABLE I
DESIGN PARAMETERS OF HTS THIN FILM WITH LAO AND SAPPHIRE SUBSTRATES

Substrate	Substrate thickness	Loss tangent	Dielectric constant	HTS thickness	HTS Conductivity(s/m)
LAO	0.508mm	10^{-5}	23	200nm	$9\times10^{11} - j3\times10^{9}$
Sapphire	0.508mm	10^{-6}	9.4	200nm	$9\times10^{11} - j3\times10^{9}$

In this relation, λ_0 is the value of the penetration depth at $T = 0$ K; τ_s is a parameter related to superconducting carrier loss and can be obtained by experimental data [7].

With the enhanced two-fluid model, the conductivity and hence the impedance of HTS material [8] can be obtained.

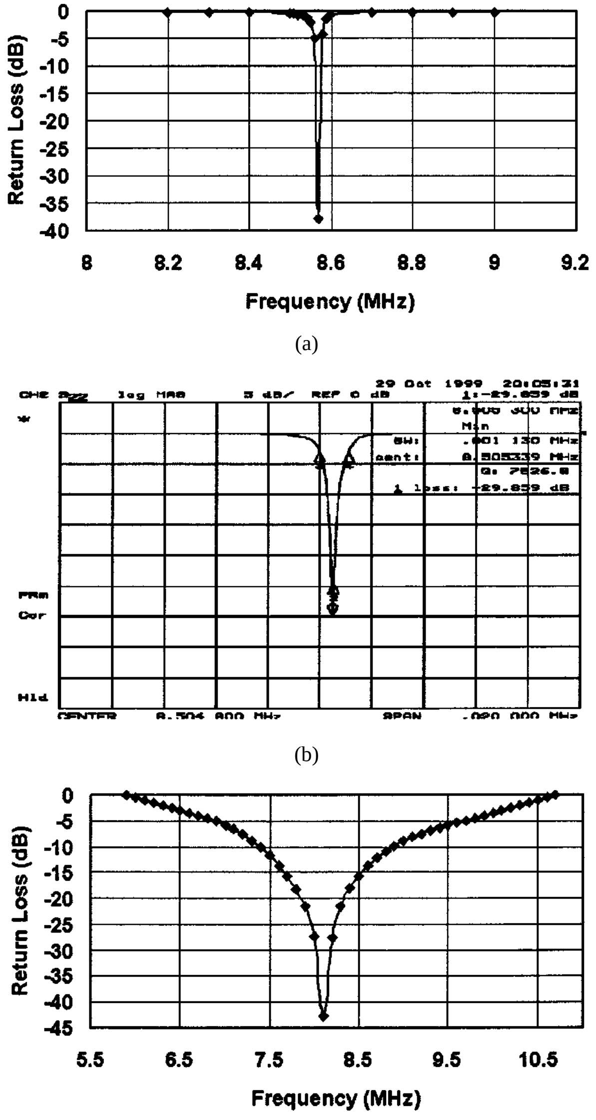
III. SIMULATION AND MEASUREMENT

A. Simulation

The geometrical structure of the HTS spiral coil is shown in Fig. 1. The coil consists of two layers: conductor layer [YBaCuO (YBCO)] and substrate layer [$LaAlO_3$(LAO)] with dielectric constant 23 or Sapphire with dielectric constant 9.4). Z_s of HTS material is obtained by the enhanced two-fluid model. The HTS spiral coil design was simulated by Momentum EM simulation software with the parameters given in Table I. Here the size of the mesh cell was chosen as 1/30 of the mesh wavelength.

B. Measurement

In order to demonstrate the efficiency of the method, we have compared the simulation and measurement results. The influence from liquid nitrogen was small and was neglected in the experiments. HTS spiral coils were fabricated using thin film for both 0.2T and 1.5T MRI systems, in which YBCO with a thickness of 200 nm was deposited on LAO and sapphire substrates with a thickness of 0.508 mm, respectively. The width and space of the coils were set to 60 μm and 50 μm, respectively. For 0.2T system, 13 turns were used with LAO while 21 turns were used with sapphire. For the 1.5T system, only one coil with six turns was designed with LAO substrate. They were fabricated in a clean room using conventional photolithographic



(a)

(b)

(c)

Fig. 2. Simulation and measurement results of resonant frequency and Q: (a) enhanced two-fluid model, (b) measurement, and (c) conventional two-fluid model.

techniques. The HTS coils were then immersed into liquid nitrogen (LN) and the return losses, S_{11}, of the coils at 77 K were recorded using an HP Network Analyzer (HP 8753E).

IV. RESULTS AND DISCUSSIONS

A. *Simulation and Measurement Results*

The plots of the simulation result with enhanced two-fluid model, the simulation result with conventional two-fluid model, and the measurement result are shown in Fig. 2. The difference between the simulated resonant frequency by using MoM with an enhanced two-fluid model in Fig. 2(a) and the measurement result was less than 1%. The difference between the conventional two-fluid model in Fig. 2(c) and the measurement was more than 4%. The measured Q was 7862, and the simulated Q with enhanced two-fluid model in the simulation was 7982; however, the simulated Q with conventional two-fluid model was only 892. The results indicate that both the simulated resonant frequency and Q with MoM simulation using the enhanced two-fluid model agree with the measurement much better than that using the conventional model.

TABLE II
COMPARISON OF RESONANT FREQUENCIES AND QS BETWEEN SIMULATED RESULTS AND MEASUREMENTS

System	substrate	Simulation		Measurement		
		frequency (MHz)	Q	frequency (MHz)	Q	
			0dBm		0dBm	-15dBm
0.2T	LAO	8.58	7982	8.508	7826	15000
0.2T	Sapphire	8.24	11800	8.260	12000	19000
1.5T	LAO	58.2	18000	57.7	18500	23000

The simulation and measurement results are shown in Table II to demonstrate the efficiency of our method. The simulated resonant frequency was in good agreement with the measured result, and their difference was less than 1%; meanwhile the Q from the simulation also agreed well with the measurement under input power of 0 dBm, with a difference within 3%. The human images acquired with the designed HTS coils at the 0.2T system are shown in Fig. 3. They have been compared with images acquired with spiral copper coil. The imaging acquisition parameters used in a GE 0.2T signal profile system were 256 × 256, 2 NEX. There was an SNR gain of about 3 using the HTS spiral coil compared with copper spiral coil.

B. *Optimization of Coil Design*

In order to optimize the performance of HTS RF coil, we have chosen different coil parameters during the simulation.

1) Width of Turns and Space Between Turns: It is shown in Table III that with a fixed width of each turn and outer spiral diameter the Q was improved with decreasing the space between turns. It is because more magnetic coupling between turns of spiral and also more distributed inductance can be generated. With a fixed space between turns and the outer spiral diameter, the Q was also improved when the width of turn was increased. It is due to the reduction of the HTS coil loss.

2) Geometry Design: The performance of the HTS RF coil with circular spiral geometry has been compared with that with rectangular spiral geometry. Fig. 4 gives the difference of Q with these two geometries. It was found that the Q was improved for more than 10% with circular spiral coil than with rectangular one.

Based on the discussion above, the circular spiral geometry and larger width-to-space ratio of spiral in our design have been preferred.

C. *Coupling Effects of Two HTS Spiral Coils*

For the design of the HTS coil array of MRI system, the mutual coupling between two HTS coils should be carefully studied because it affects the RF field homogeneity and resonant frequency. The investigation and modeling of mutual coupling between the array coils therefore become necessary. The shift of resonant frequency of the array coils with two configurations of two HTS spiral coils were examined in the simulation. The first configuration is depicted as in Fig. 5. The two HTS spiral coils were placed on the LAO substrate plane with distance d. The

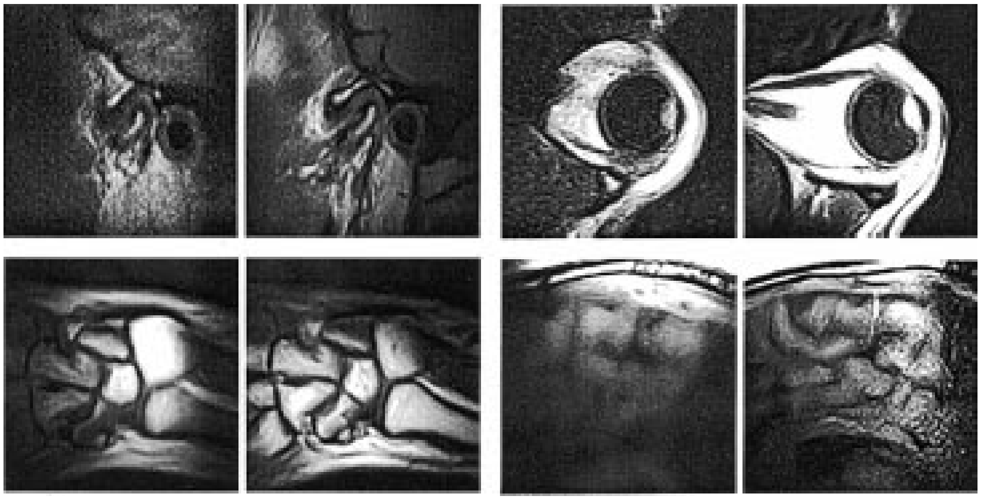


Fig. 3. Image comparisons of TMJ, orbit, wrist, and brain acquired with a copper coil (left) and an HTS coil (right) at 0.2T system with 256 × 256, 2 NEX.

TABLE III
SIMULATED Q OF HTS SPIRAL COILS WITH DIFFERENT WIDTH-TO-SPACE RATIOS

W(μm)	S(μm)	W/S	Q
30	50	0.6	6156
30	40	0.75	7136
30	30	1	8092
40	50	0.8	6144
40	40	1	6528
40	30	1.33	7434
50	50	1	6171
50	40	1.25	6528
50	30	1.67	7310

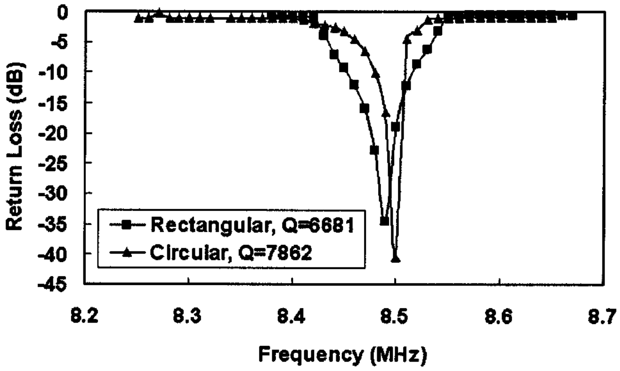


Fig. 4. The plot of simulations of circular and rectangular HTS spiral coils.

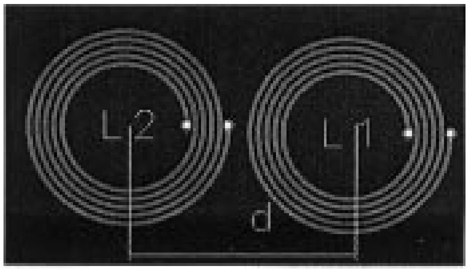


Fig. 5. The first configuration with two HTS spiral coils placed on LAO substrate plane.

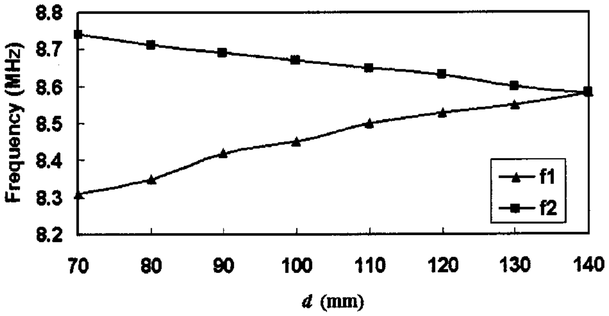


Fig. 6. The plot of frequency shift of the first configuration versus d.

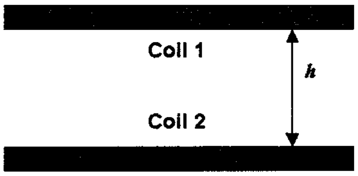


Fig. 7. The second configuration with two HTS spiral coils placed in parallel.

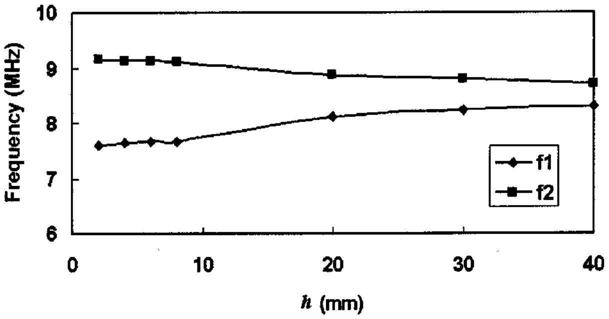


Fig. 8. The plot of frequency shift of the second configuration versus h.

plot of the frequency shift versus d is shown in Fig. 6, in which each individual spiral coil has its resonant frequency simulated as in Fig. 2. In the second configuration, two HTS spiral coils were placed in parallel with distance h as depicted in Fig. 7. The plot of the frequency shift versus h is given in Fig. 8. With the aid of the simulation, coil array design can be further implemented in which the frequency shift concern can be controlled easily.

V. CONCLUSION

The mixed potential integral equation using MoM was used to analyze the HTS RF spiral coil for MRI application. The conductivity of HTS material was simulated with the use of the enhanced two-fluid model. The presented simulation method has significantly improved the accuracy for both resonant frequency and Q in less than 1% and 3%, respectively. To optimize the HTS coil with high Q, it was found that HTS coil with a large width-to-space ratio and circular geometry has been preferred. The mutual coupling simulation between two HTS spiral coils was studied in relation to the shift of resonant frequency with different configurations, which can be used as guidance for designing HTS array coils in MRI for increasing the imaging area.

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