High-T_C Superconducting Receiving Coils for Nuclear Magnetic Resonance Imaging

Hsu-Lei Lee, In-Tsang Lin, Jyh-Horng Chen, Herng-Er Horng, and Hong-Chang Yang

***Abstract*—Nuclear magnetic resonance (NMR) microscopy poses high demands on the sensitivity of the receiver coils. We have developed high-T_c superconducting (HTS) tape receiving coils for nuclear magnetic resonance imaging. The surface receiver coil is constructed from high-T_c $Bi_2Sr_2Ca_2Cu_3O_y$ tape coil and cooled in liquid nitrogen temperature. The desired receiver surface coil is numerically simulated and optimized to have high value of the unloaded quality factor. With this HTS receiver coil we have obtained significant improvement in the unloaded Q-value, loaded Q-value and substantial gain in signal-to-noise ratio (SNR). The SNR improvement of 2.4 was achieved in the kiwi imaging and improvement of 2.7 in the braining imaging of rat at 300 K. The MRI microscopy is tested and compared the results with copper receiver.**

***Index Terms*—HTS RF surface coil, magnetic resonance imaging, signal-to-noise ratio.**

I. INTRODUCTION

IN THE CASE of small-volume and high resolution imaging, the noise of the receiver coil, and/or the preamplifier noise set the system noise floor and hence the MRI performance, the sample noise no longer dominates the SNR. Thus, it is desirable to reduce coil noise to improve the image resolution and reduce the acquisition time. Cooling the temperature of the receiving coil [1] or using high-T_c superconducting (HTS) coils [2]–[7] can improve the SNR. Even in high-field MRI, when the coil and the corresponding region of interest are reduced in size, there is a cross over point where the receiver noise becomes the dominant source of noises, which must be reduced to enhance the SNR. Several demonstrations have shown that for low field and high resolution applications HTS coils perform significantly better than copper coils. Okada *et al.* [2] used $Bi_2Sr_2Ca_2Cu_3O_y$ tape coil to build a low field superconducting receiving coil resonating at 2.74 MHz with a better SNR. Ma *et al.* [3] show the application of HTS thin film coil to image human subject with improved SNR compared with copper coil. Cheng *et al.* [4] developed $Bi_2Sr_2Ca_2Cu_3O_y$ HTS tape coil, which showed a gain of 3 in the SNR over the copper coil in a 0.21 T magnetic resonance imaging (MRI) machine. Wosik *et al.* [5], [6] have shown that the images acquired with superconducting probe show a great improvement over copper coil in SNR and reduction of imaging time.

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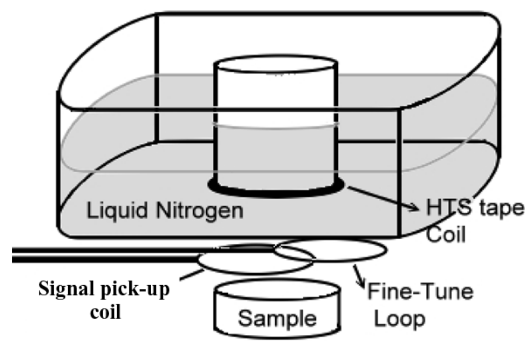


Fig. 1. Configuration of the signal pick-up coil, fine-tune loop coil and the superconducting tape coil with high Q capacitor connected in series in the imaging system.

In this work we studied unloaded and loaded Q-values of the HTS $Bi_2Sr_2Ca_2Cu_3O_y$ tape receiving coils in high field MRI system in which the samples and coils were varied in sizes. The images were taken to investigate the SNR gain. A comparison of images obtained from superconducting and copper coils is shown.

II. EXPERIMENTAL DETAILS

The HTS $Bi_2Sr_2Ca_2Cu_3O_y$ tape coils of different sizes were wounded into a circular shape and connected in series with a high-Q capacitor (about 1000 at 125 MHz, American Technical Ceramics, Hungtington Station, NY, USA) to form an LC resonating circuit. The capacitors are chosen to have much higher Q to minimize their effect on the measurements of coil's Q values. Fig. 1 shows the configuration of the HTS tape coil with capacitor connected in series, the signal pick-up coil, the fine tune loop coil used in the MRI system (3 T Bruker MRI system). The fine tune coil and the signal pick-up coil were placed under the HTS tape coil. The signal pick coils are the transmitting/receiving coils. The tuning was accomplished by adjusting the relative position of the inductively coupled HTS tape coil, the signal pick-up loop and the fine-tune coil. Before imaging the coils were tuned to the resonant frequency of 125.3 MHz and matched to the standard preamplifier. The HTS tape coil was the silver-sheathed $Bi_2Sr_2Ca_2Cu_3O_y$ tape supplied by the Innova superconductor technology Co, Ltd. The wires with multi-filamentary structure show critical temperature of 110 K and the engineering critical current density greater than 9000 A/cm^2. The width of the tape is 4.1 ± 0.1 mm. The thickness of the tape is 0.230 ± 0.01 mm. The coils were cooled to 77.4 K with liquid nitrogen in a polystyrene container which can hold liquid nitrogen for about 1 hour.

For LC resonant loop (surface coil), the resonant frequency $f_o = 1/2[\pi(\mathrm{LC})^{1/2}]$ and its Q value, $\mathrm{Q} = 1/(2\pi f_o \mathrm{CR})$, in which R is the total resistance of the coil and the equivalent resistance of the loaded sample. The Q value of the HTS tape coil can be written as [7]

$$\mathrm{Q} = \left(\frac{A}{\mu_o}\right)\omega^{\frac{1}{2}}\left[\frac{a^2(K-k)N^2}{b}\right]\left(\frac{p}{l\rho^{\frac{1}{2}}}\right), \tag{1}$$

where A is a constant related to the tape configuration, μ_o is the permeability in free space, a is the radius of the coil, b is the width of the tape, N is the number of turns of the coil, ρ is the resistivity at 77.4 K, l and p is the length and cross section of the solder, K is a function of the $b/2a$, k is a function of $c/2a$ and c/b, and c is the thickness of the tape. Considering a single turn of the coil with uniform soldier joints, the Q value can be simplified to

$$\mathrm{Q} \propto \frac{a^2(K-k)\omega^{\frac{1}{2}}}{b} \tag{2}$$

The SNR for superconducting coil $\mathrm{S}^{\mathrm{supercon}}$ and the copper coil $\mathrm{S}^{\mathrm{copper}}$ can be written as [5]:

$$\mathrm{S}^{\mathrm{supercon}} \propto \frac{1}{(\mathrm{R}_\mathrm{c}^{\mathrm{supercon}}\mathrm{T}_\mathrm{c} + \mathrm{R}_{\mathrm{sample}}\mathrm{T}_{\mathrm{sample}})^{\frac{1}{2}}}, \tag{3}$$

$$\mathrm{S}^{\mathrm{copper}} \propto \frac{1}{(\mathrm{R}_\mathrm{c}^{\mathrm{copper}}\mathrm{T}_\mathrm{c} + \mathrm{R}_{\mathrm{sample}}\mathrm{T}_{\mathrm{sample}})^{\frac{1}{2}}}, \tag{4}$$

where $\mathrm{R}_\mathrm{c}^{\mathrm{supercon}}$ and $\mathrm{R}_\mathrm{c}^{\mathrm{copper}}$ is the radio frequency (rf) resistance of the HTS tape coil and the copper coil respectively; $\mathrm{R}_{\mathrm{sample}}$ is the sample resistance; $\mathrm{T}_{\mathrm{sample}}$ is the sample temperature. Therefore, we obtain a gain G in the SNR if the copper coil is replaced by the superconducting surface coil given by the following equation:

$$\mathrm{G} = \frac{(\alpha\mathrm{R}_{\mathrm{coil}}^{\mathrm{copper}} + \mathrm{R}_{\mathrm{sample}})^{\frac{1}{2}}}{(\alpha\mathrm{R}_{\mathrm{coil}}^{\mathrm{supercon}} + \mathrm{R}_{\mathrm{sample}})^{\frac{1}{2}}}, \tag{5}$$

where $\alpha = \mathrm{T}_{\mathrm{coil}}/\mathrm{T}_{\mathrm{sample}} = 0.263$, $\kappa = \mathrm{Q}_{\mathrm{loaded}}/\mathrm{Q}_{\mathrm{unloaded}}$, where $\mathrm{Q}_{\mathrm{loaded}}$ and $\mathrm{Q}_{\mathrm{unloaded}}$ are the loaded and the unloaded quality factor, respectively. Since superconducting coil has a much lower rf resistance compared to that of the copper coils, a better SNR can be obtained if one uses the receiver with a configuration involving the superconducting coils.

III. Results and Discussion

Fig. 2 shows the S_{11} parameter of the frequency response of the HTS tape coils with diameters of 7 cm and 12 cm coupled to the matching and tuning coil for 3 T superconducting imaging system with the configuration in Fig. 1. The HTS tape coil has a central resonance frequency at 125.3 MHz for protons after fine tuning. The unload Q-values are of 675, 1107 and 1934 for diameters of 4 cm, 7 cm and 12 cm respectively at 77.4 K. The Q value is calculated from the formula: $\mathrm{f_o}/(\Delta\mathrm{f})_{3\ \mathrm{dB}}$, where $\mathrm{f_o}$ is the central resonance frequency, and $(\Delta\mathrm{f})_{3\ \mathrm{dB}}$ is the bandwidth at 3 dB. We measured the

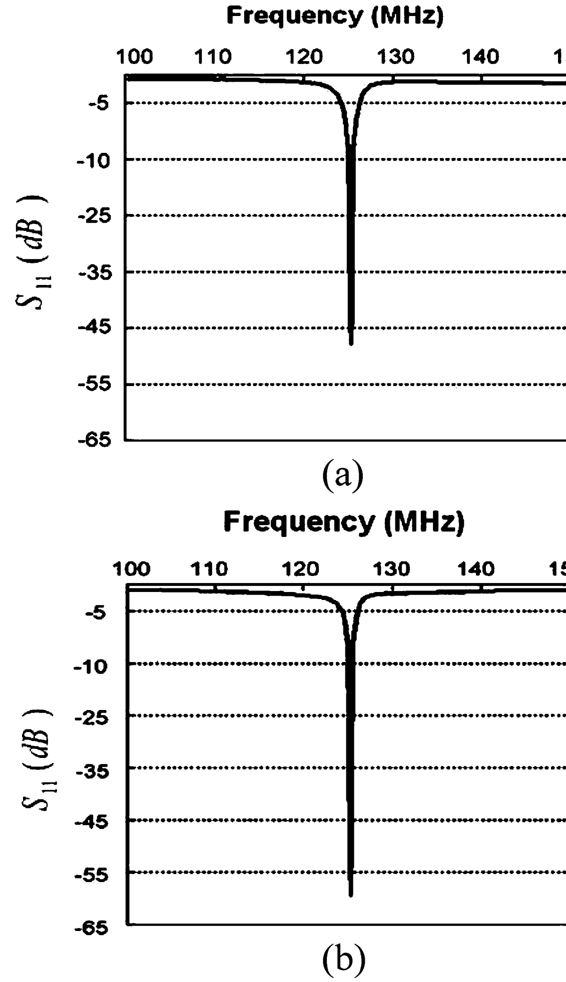
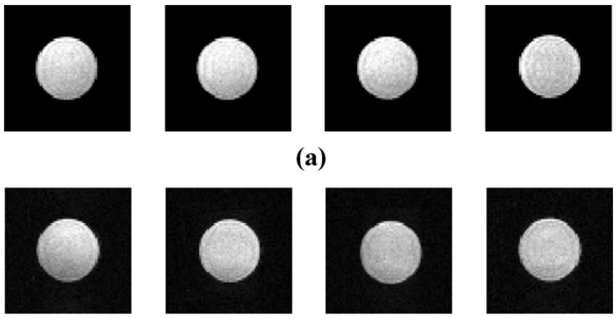


Fig. 2. The S_{11} parameter as a function of the frequency for the HTS coils with diameters of (a) 7 cm; of (b) 12 cm coupled to the tuning coil.

loaded and unloaded Q for phantoms with different conductivities with receiving coil of 7 cm in diameter at 77 K. The superconducting HTS receiving coil of 7 cm in diameter shows unloaded Q value of 1048 at 77.4 K; the loaded Q values are 673, 620 540, and 507 at 77.4 K for phantoms with conductivities of 0 S/m, 0.5 S/m, 0.9 S/m, and 1.41 S/m, respectively. The copper coil of the same diameter shows the unloaded Q values of 459 at 77.4 K; the loaded Q values are 294, 289, 264, 250 at 77.4 K for phantoms with conductivities of 0 S/m, 0.5 S/m, 0.9 S/m, and 1.41 S/m, respectively. Yuan and Shen [8] studied the quality factor of the HTS rf tape coils with larger sizes of 65 cm, in the MRI receiver. They observed unloaded quality factor of 1270 for larger HTS coil of 65 cm in diameter.

Using superconducting receiving coil of 7 cm in diameter, we imaged phantoms of different conductivities. The conductivities of the phantoms used are 0 S/m, 0.5 S/m, 0.9 S/m, and 1.41 S/m. Fig. 3 shows the measured SNR gain of phantoms. The SNR ratio from left to right is 69, 60.2, 54.9, and 45.3, respectively. Using the copper coil of the same diameter, we obtained SNR from left to right of 43.2, 40, 39.4, and 36.7 respectively at 77.4 K.

Fig. 4 shows is the measured SNR gain along with the data calculated from (5). Note that there is a consistency between



(a)

(b)

Fig. 3. Images of phantoms with conductivity of 0 S/m, 0.5 S/m, 0.9 S/m, and 1.41 S/m respectively from left to right with. (a) Superconducting receiving coil; (b) copper receiving coil of the same diameter at 77.4 K.

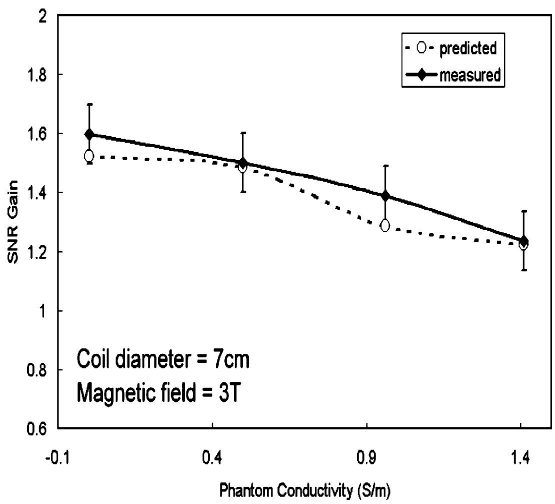
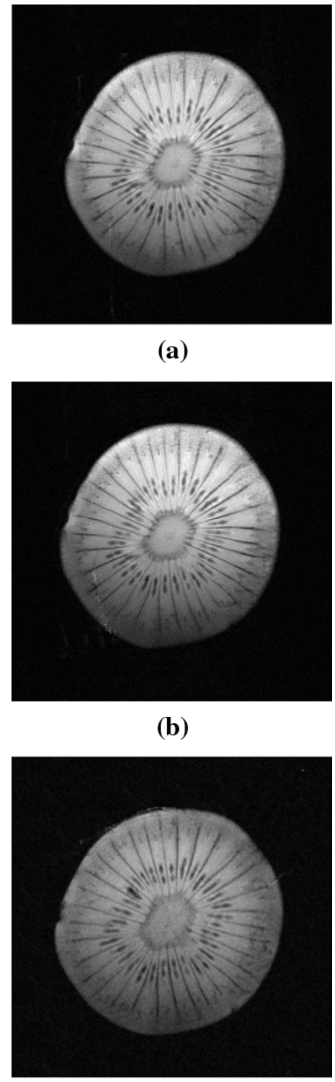


Fig. 4. The SNR gain of the HTS coil over the copper coil at 77.4 K for phantoms with different conductivities.

the calculated and the measured data. The SNR is decreased when the conductivity of the phantom is increased. The losses inherent in magnetic resonance imaging are the coil loss in the receiving coil and the sample loss in the conductive samples. In the present measurement, the rf loss is fixed for phantoms, therefore the decreased SNR is due to higher conduction loss for samples with higher conductivity.

Fig. 5 shows the images of a kiwi fruit using the HTS tape coil and the copper coil of diameter 7 cm. Using HTS coil, we obtained loaded $Q_{\mathrm{loaded}} = 511$ and $\kappa = 1.05$ at 77.4 K. Using the conventional copper coil, we obtained the loaded $Q_{\mathrm{loaded}} = 242$, $\kappa = 0.35$ at 77.4 K and $Q_{\mathrm{loaded}} = 38$ and $\kappa = 0.11$ at 300 K. The superconducting coil shows SNR gain of 1.39 and 2.56 over the conventional copper coil at 77.4 K and 300 K, respectively. In the present imaging, the distance between the imaging slice and coils are 5 cm for HTS coil and 3 cm the copper coil in the experiment. We expected to have a better SNR if we further optimize the distance between the HTS coil and samples [5].

Using a smaller superconducting $\mathrm{Bi_2Sr_2Ca_2Cu_3O_y}$ tape receiving coil of 4 cm in diameter, we imaged brain of rats. The configuration of the imaging system is shown in Fig. 6. The bore diameter of the gradient coil is 7 cm. The receiving coil is a bit different from that of Fig. 1. The receiving coil is connected to a high Q capacitor so that the receiving coil can be tuned to resonance frequency of the 3 Tesla MRI system by adjusting the capacitance. The rat is placed under the liquid nitrogen contained which the liquid nitrogen can be supplied from outside.



(a)

(b)

(c)

Fig. 5. The imaging of the kiwi with a SNR of (a) 77.1 using HTS $\mathrm{Bi_2Sr_2Ca_2Cu_3O_y}$ tape coil at 77.4 K, (b) 51.3 using copper coil at 77.4 K, and (c) 30 using copper coil at 300 K.

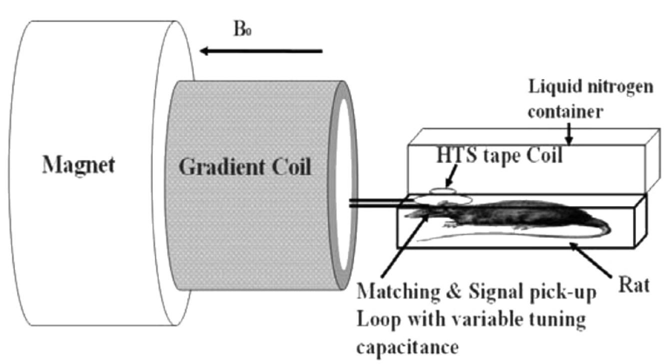
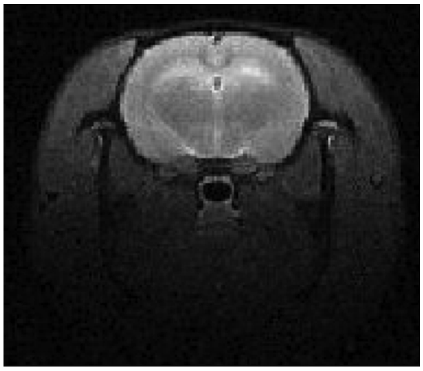
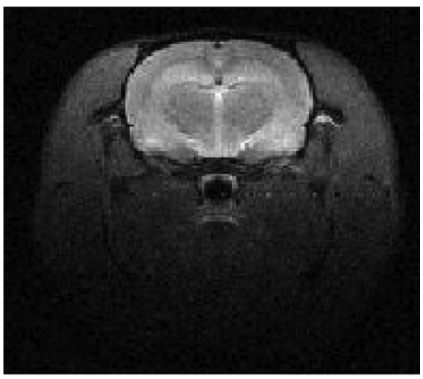


Fig. 6. Configuration of the imaging system for rats with HTS tape coil of 4 cm in diameter at 77.4 K.



(a)



(b)

Fig. 7. Images of the brain of a rat with (a) HTS coil with the SNR of 60, and (b) the copper coil with SNR of 30. The copper coil and the HTS coil are at 77.4 K.

Fig. 7 shows a comparison of the images of the brain of rat taken with HTS tape receiver coil (a) and copper receiver coil (b) of 4 cm in diameter at 77.4 K. We obtained a gain of 2 of SNR at 77.4 K. This improved SNR gain is very promising in high resolution imaging of small animals in high magnetic fields.

IV. Conclusion

In the present work $\mathrm{Bi_2Sr_2Ca_2Cu_3O_y}$ tape receiving coils were designed to image small samples. It was observed that the HTS receiver coils have much higher SNR than copper receiver coils. The better SNR improvement was achieved in the kiwi imaging and the braining imaging of rat compared with copper receiver coil. Therefore HTS coils have a great potential to provide better SNR improvement for MRI application. This is very beneficial when doing experiments that usually take a longer time, such as the diffusion imaging. This result opens new prospective for application of high-T_c coil in the diction of a weak signal of radio frequency signal in MRI.

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