High- T_c superconducting surface coils for improving the image quality on a 3 T imager

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2007 Supercond. Sci. Technol. 20 777

(<http://iopscience.iop.org/0953-2048/20/8/009>)

[The Table of Contents](#) and [more related content](#) is available

Download details:

IP Address: 140.112.113.225

The article was downloaded on 04/03/2009 at 04:46

Please note that [terms and conditions apply](#).

High- T_c superconducting surface coils for improving the image quality on a 3 T imager

Hong-Chang Yang^{1,2,5}, Kuen-Lin Tsai², Ji-Cheng Chen¹,
Chiu-Hsien Wu¹, Herng-Er Horng^{2,3}, Jyh-Horng Chen⁴ and
Li-Wei Kuo⁴

¹ Department of Physics, National Taiwan University, Taipei 106, Taiwan

² Institute of Electro-Optical Science and Technology, National Normal Taiwan University, Taipei 116, Taiwan

³ Department of Physics, National Normal Taiwan University, Taipei 116, Taiwan

⁴ Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan

E-mail: hcyang@phys.ntu.edu.tw

Received 21 April 2007, in final form 21 May 2007

Published 21 June 2007

Online at stacks.iop.org/SUST/20/777

Abstract

A surface coil composed of a miniature spiral YBa₂Cu₃O_y (YBCO) thin film resonator and a Bi₂Sr₂Ca₂Cu₂O₃ (BSCCO) tape resonator were designed. The spiral YBCO resonator was fabricated onto one side of a 2×2 cm² LaAlO₃ substrate, which was then coupled to the receiver via a tank circuit and a fine-tuning copper coil to image small samples. Additionally, a BSCCO tape resonator of 20 cm in diameter was coupled to a receiver coil and a fine-tuning coil to image large samples. An improvement of the signal-to-noise ratio for high- T_c resonators over a conventional copper resonator is demonstrated.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

There has been a great amount of interest in increasing image quality in nuclear magnetic resonance (NMR) imaging. The utilization of scanners with higher magnetic fields is one of the techniques currently used to increase equipment sensitivity. This method functions to increase sensitivity because of the proportionality between the signal, V , and the square of the resonating frequency, ω , in NMR imaging; the signal increases as the strength of the magnetic field is increased. Another method used to increase the sensitivity has been to replace the conventional copper receiver coil with either a high- T_c superconducting thin film resonator [1, 2], high- T_c tape coil [3] or a cryogenic probe [4]. For instance, Wosik *et al* [5] reported on the design of a 63.8 MHz (1.5 T) probe consisting of patterned copper with YBCO films deposited on both sides of a 5 cm LaAlO₃ substrate. The YBCO thin film probe achieved a SNR gain of 3 and 2 for the room-temperature-cooled and

liquid-nitrogen-cooled copper coil, respectively. Ma *et al* [6] constructed coils from a 7.6 cm YBCO thin film on LaAlO₃ substrates on a 0.2 T scanner. A SNR gain of 2.8-fold and 1.4-fold were observed in images of phantoms over that of a room-temperature-cooled and liquid-nitrogen-cooled copper coil, respectively. Higher image quality can be obtained *in vivo* with high- T_c coils as compared to those obtained with copper coils at 300 K.

The total root mean square voltage noise seen by the receiver can be expressed as a sum of the uncorrelated contributions from the preamplifier, coil and sample. Assuming the preamp noise voltages are negligible compared to that of the coil and sample, the signal-to-noise ratio (SNR) of a NMR receiver coil can be expressed as

$$\text{SNR} \propto 1/[\langle V^2 \rangle_{\text{Preamp}} + \langle V^2 \rangle_{\text{C}} + \langle V^2 \rangle_{\text{S}}] \quad (1)$$

where $\langle V^2 \rangle_{\text{C}}$ is the coil noise and $\langle V^2 \rangle_{\text{S}}$ is the sample noise. The Johnson noise is given by the equation: $\langle V^2 \rangle_{\text{Johnson}} = (4kTR\Delta f)$, where T is the temperature, R is the resistance and Δf is the frequency bandwidth of the measurement.

⁵ Author to whom any correspondence should be addressed.

The quality factor, Q , of the resonant circuit is defined as $Q = \omega L/R$, where ω is the resonant frequency, L is the inductance and R is the resistance. Assuming that the preamp noise voltages are negligible as compared to those of the coil and the sample, the SNR gain of the HTS resonator at 77 K over the conventional copper coil at 300 K, defined as $\text{SNR}_{\text{Gain}} = (\text{SNR})_{77 \text{ K, HTS}} / (\text{SNR})_{300 \text{ K, Cu}}$, can be expressed as

$$\text{SNR}_{\text{Gain}} = \frac{[(300 \times Q_{\text{unloaded, 300 K}}^{-1} + 300 \times Q_{\text{sample}}^{-1})^{1/2}]}{[(77 \times Q_{\text{unloaded, 77 K}}^{-1} + 300 \times Q_{\text{sample}}^{-1})^{1/2}]} \quad (2)$$

From equation (2) it was found that superconducting detecting coils can benefit from the advantages of a higher Q value and low coil impedance. Therefore one can achieve a higher SNR ratio by using the superconducting resonator.

High- T_c superconducting $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_2\text{O}_3$ (BSCCO) tape coils of 7 and 4 cm in diameter were studied [7]. A SNR gain of 1.5-fold for kiwi fruit imaging and 2-fold for a rat brain, respectively, over the conventional copper coil at 77 K were obtained. At present there is great interest in improving the MRI imaging quality for both larger and smaller samples. Using a HTS BSCCO tape coil, if one reduces the diameter of the resonator to a value smaller than 4 cm, the superconducting properties of the resonator deteriorate. Therefore a superconducting $\text{YBa}_2\text{Cu}_3\text{O}_y$ (YBCO) thin film resonator would be a good candidate for improving the image quality if a small-sized resonator is proposed for imaging small samples. An HTS thin film receiver at 77 K has been demonstrated to have a 2-fold SNR improvement for small samples in a low magnetic field at 0.064 T [8] and a 3.1-fold improvement for a mixture of 90% of D_2O and 10% of water phantom in a 7 T imager [9]. However, there is no reported data for a YBCO thin film resonator with a diameter less than 2 cm. In this study we design a new miniature YBCO spiral thin film resonator to enhance the SNR signal for small samples. On the other hand, high- T_c BSCCO surface coils with a greater diameter were studied for imaging larger samples. The width of the BSCCO tape was 4.1 mm with a thickness of 0.23 mm. The wire showed a critical current density greater than 9000 A cm^{-2} at 77 K. The spiral YBCO resonator on a miniature $2 \times 2 \text{ cm}^2$ LaAlO_3 substrate and a BSCCO tape resonator of 20 cm in diameter coupled to a 3 T receiver were investigated to improve image quality.

2. Experiments

To fabricate the spiral superconducting resonator, we first deposited a YBCO thin film onto one side of the LaAlO_3 substrate by using a radio frequency magnetron sputtering system [10]. The substrate was a 5 mm thick LaAlO_3 single crystal with a dielectric constant of 24.4 and a tangential loss of 6×10^{-5} . A YBCO film with a thickness of 500 nm deposited onto one side of the substrate showed a zero resistance at 89 K. The YBCO film was patterned to a spiral structure with the technique of photolithography shown in figure 1(a). The four-turn YBCO spiral resonating coil had an inner diameter of 16 mm, an outer diameter of 19 mm and a linewidth of 0.15 mm. Figure 1(b) depicts the seven-turn spiral copper resonator fabricated onto the printed circuit board, with the

Figure 1. Photograph of (a) a seven-turn spiral copper resonator fabricated onto a printed circuit board, (b) a four-turn high- T_c $\text{YBa}_2\text{Cu}_3\text{O}_y$ spiral resonator fabricated onto a LaAlO_3 substrate and (c) a superconducting $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_2\text{O}_y$ tape LC resonator.

spiral copper having the same linewidth as the four-turn YBCO spiral resonating coil. The seven-turn spiral copper resonator had an inner diameter of 14 cm and an outer diameter of 19 cm. The length of the spiral resonator was trimmed to fit the proton resonance frequency at 125.3 MHz in a 3 T imager. The loaded and unloaded Q values were measured. The Q values were calculated from the ratio of the resonance frequency at a 3 dB bandwidth. Figure 1(c) shows the superconducting $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_2\text{O}_y$ tape LC resonator. A study of the Q value for BSCCO-based LC resonator is reported in [11].

In order to evaluate the imaging quality of NMR imaging using the YBCO thin film spiral coil and the BSCCO resonating coil, we performed three-dimensional (3D) spin echo imaging experiments (shown in figure 2). The YBCO receiver was composed of a spiral YBCO thin film resonator on a $2 \times 2 \text{ cm}^2$ LaAlO_3 substrate which was coupled to the receiver pick-up coil (2.5 cm in diameter) through a LC fine-tuning coupling coil (2 cm in diameter), where L is the inductance and C is the capacitance. The BSCCO receiver was composed of a BSCCO LC resonating coil (20 cm in diameter), which was coupled to the pick-up coil (23 cm in diameter) and a fine-tuning coil (15 cm in diameter). A fibre glass Dewar that can hold liquid nitrogen was constructed to cool the superconducting resonator. We evaluated the image quality for the miniature YBCO spiral resonator and the BSCCO LC resonator. The image was taken with a Brüker Biospec 3 T MRI system.

3. Results and discussion

Figure 3 shows the longitude images of a calamondin with a slice thickness of 1 mm. The diameter of the calamondin was

Figure 2. Configuration of the spin echo imaging experiment using (a) a spiral YBCO resonator and (b) a superconducting $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$ tape LC resonator.

2 cm. The image was taken with a 128×128 data matrix, a field of view (FOV) of $4 \times 4 \text{ cm}^2$ and a slice thickness of 1 mm. The unloaded quality factor, Q_{UL} , was 1347 while the loaded quality factor, Q_L , was 1024 for the spiral YBCO thin film resonator at 77 K. The value of Q_{UL} and Q_L was 231 and 229, respectively, for the room-temperature spiral copper resonator. The image of the calamondin obtained from a superconducting YBCO spiral resonator shows an SNR gain of 3.46 over a conventional spiral copper coil. An obvious improvement in image quality is clearly demonstrated.

Figure 4 shows the transverse middle slices of 3D NMR images for a grapefruit of 16 cm in diameter obtained using a homemade cryostat, BSCCO resonator and silver resonator with a slice thickness of 1 mm. The image was taken with a 512×512 data matrix and a FOV of $15 \times 15 \text{ cm}^2$. For the grapefruit, the unloaded quality factor, Q_{UL} (BSCCO), was equal to 2263 and the loaded quality factor, Q_L (BSCCO), was equal to 1114.8 for the BSCCO resonator. The value of $Q_{UL}(\text{Ag})$ and $Q_L(\text{Ag})$ was 1592 and 1559, respectively, for the silver resonator at room temperature. The image shows a 2.2-fold improvement in the SNR gain over the conventional silver resonator for imaging the grapefruit. The room-temperature Ag coil had the same size and shape as the cooled coil, and therefore produced the same B_1 field, due to the unit current flow in the coil. We calculated the theoretical prediction using equation (2) and obtained an SNR

Figure 3. Images of the calamondin using (a) the spiral copper resonator and (b) the spiral high- T_c $\text{YBa}_2\text{Cu}_3\text{O}_y$ resonator, and (c) photograph of the calamondin cut into two halves.

Figure 4. Images of grapefruits using (a) the silver tape LC resonator and (b) the high- T_c $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$ tape resonator, and (c) photograph of a grapefruit cut into two halves.

gain of 3.39, which is a bit higher than in the experimentally observed data.

Odaj *et al* [9] have designed a hollow YBCO superconducting thin film resonator with a 5 mm sample tube for a 7 T MRI imager. That resonator was 5 cm in diameter and had a 13 mm diameter hole. The resonator consisted of two rings, with the rings being interrupted by two gaps on either side of the gaps. The geometry resulted in a 3.1-fold improvement in the SNR of the YBCO resonator over the conventional copper coil. In the present study we fabricated a spiral resonator onto one side of the $2 \times 2 \text{ cm}^2$ LaAlO_3 substrate for a small subject. The resonator utilized a one-sided spiral YBCO film resonator which offers the advantage of easy fabrication. A significant improvement in the imaging quality was obtained. The SNR gain was 3.46 using a miniature

YBCO spiral resonator over the copper coil. The present superconducting YBCO spiral coil is promising for imaging small samples: for instance, it shows promise for diffusion imaging of the rat brain, which requires a longer imaging time.

Using high- T_c superconducting $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_2\text{O}_3$ (BSCCO) tape coil, Lee *et al* [7] improved the sensitivity of the imager and achieved a SNR gain of 2.4-fold for kiwi fruit imaging. The SNR gain of 2-fold was obtained when imaging a rat's brain imaging with a BSCCO tape coil over a copper coil 4 cm in diameter at 77 K. For a water phantom with a conductivity of 0.5 S m^{-1} , the SNR gain was 1.5-fold for the BSCCO tape coil over the copper coil at 77 K. Using the present BSCCO tape resonator with a larger diameter of 20 cm, we obtained an improvement in the value of SNR gain of 2.2-fold over the conventional silver resonator for imaging grapefruit using a homemade G10 fabricated fibre glass Dewar to cool the BSCCO resonator and the coupling coil. The YBCO spiral resonator fabricated onto one side of the SrTiO_3 substrate demonstrated the superior simplicity of the device fabrication. The YBCO spiral resonator showed a SNR gain of 3.46 over a conventional copper coil at 300 K for imaging small subjects such as the calamondin. Using a BSCCO LC tape resonator with a diameter of 20 cm, we obtained an improvement of 2.2-fold in SNR gain over the silver resonator for imaging grapefruit. In the present study, it was found that the YBCO spiral resonator with a smaller detection coil had a higher SNR ratio as compared with that of the BSCCO resonator with the greater diameter. The higher SNR gain as compared to the BSCCO resonator is mainly due to the size effect of the resonator.

In this study of an HTS YBCO thin film resonator for MRI at a resonating frequency of 125.3 MHz, we achieved an SNR gain of 3.46, as compared to that of copper resonators. The results suggest that higher image quality can be obtained *in vivo* with an HTS YBCO thin film coil instead of copper coil imaging. In addition, the imaging time was greatly reduced in achieving the same image quality. There may be advantages in using small coils for phase arrays. The imaging time can be significantly reduced by using parallel processing with phase array coils [12]. The potential benefits justify the continued development of practical HTS YBCO thin film receivers for imaging systems despite the considerable technical difficulties and challenges involved in cryostat and coil design.

4. Conclusion

We have designed and fabricated superconducting surface coils composed of a spiral YBCO thin film resonator or BSCCO tape resonator for the purpose of enhancing the image quality of a 3 T imager. The YBCO resonator showed an SNR gain of 3.46 over a conventional copper coil for imaging small subjects such as a calamondin. Using a BSCCO LC tape resonator, we obtained an improvement of 2.2-fold of the SNR gain over a silver resonator for imaging grapefruit. The SNR gain shows the feasibility of using HTS coils to improve image quality or reduce image time. The experimental results shows the potential benefits that may be expected in applying HTS surface coils, despite the difficulties involved in cryostat and coil design.

Acknowledgments

This work is supported by grant nos. 95-2112-M-002-010, 95-2752-M-002-016-PAE and 95-2221-E-212-054-MY3.

References

- [1] Black R D, Early T A, Roemer R B, Mueller O M, Mogro-Campero A, Turner L G and Johnson G A 1993 *Science* **259** 793
- [2] Ma Q Y 1999 *IEEE Trans. Appl. Supercond.* **9** 3565
- [3] Okada H, Hasegawa T, van Heteren J G and Kaufman L 1995 *J. Magn. Reson. B* **107** 158
- [4] Wright A C, Song H K and Wehrli F W 2000 *Magn. Reson. Med.* **43** 163
- [5] Wosik J, Xie L M, Nesteruk K, Xue L, Bankson J A and Hazle J D 2003 *IEEE Trans. Appl. Supercond.* **13** 1051
- [6] Ma Q Y *et al* 2003 *Acad. Radiol.* **10** 978
- [7] Lee H L, Lin I T, Chen J H, Chen C C, Chang Y C, Horng H E and Yang H C 2005 *IEEE Trans. Appl. Supercond.* **15** 1326
- [8] van Heteren J G, James T W and Bourne L C 1994 *Magn. Reson. Med.* **32** 396
- [9] Odoj F, Rommel E, Kienlin M V and Hasse A 1998 *Rev. Sci. Instrum.* **69** 2708
- [10] Wang L M, Yu H W, Yang H C and Horng H E 1996 *Physica C* **256** 57–63
- [11] Grasso G, Malagoli A, Guasconi P, Roncallo S and Siri A S 2000 *Supercond. Sci. Technol.* **13** L15
- [12] Wosik J, Xie L M, Nesteruk K, Xue L, Bankson J A and Hazle J D 2003 *IEEE Trans. Appl. Supercond.* **13** 1051