Superconducting Coil Array for Parallel Imaging

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Abstract

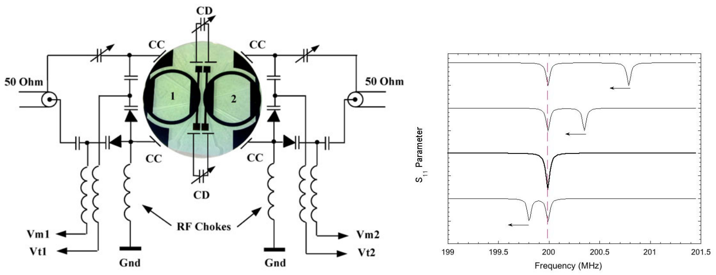
We report on the recent development and improvements of a planar 200-MHz superconducting two-coil array for parallel MRI. Two or four coils arrays, each comprised of two planar 1”-diameter superconducting ($YBa_2Cu_3O_{7-x}$) coils with built-in planar capacitors for capacitive coils coupling/matching and for mutual inductance decoupling, are fabricated by patterning multi-layered (superconductor/dielectric), double-sided thin films on sapphire substrates [1]. Here we present a design and performance of low loss matching/tuning and decoupling circuitry developed for operation with such high-Q-arrays. SNR gains of 77K copper and YBCO arrays are measured and compared with theoretical predictions and calculations.

Introduction

In recent years, the design and application of coil arrays for partial parallel acquisition (PPA) has become a subject of great interest but created significant problems with PPAs since strong decrease in overall SNR, at least by the square root of acquisition time, was a consequence of array implementation [2-3]. It has already been recognized that a significant SNR improvement can be achieved, for small size elements in the array, through cooling or by using high temperature superconductors (HTS) for coils fabrication [4-5]. SNR can be dramatically improved with the use of HTS coils when inductive coupling is used. However, for practical array designs a capacitive coupling to each elements has to be implemented. In addition, all adjustments should be done outside the cryostat and MRI magnet. It makes the practical implementation of cryogenic/HTS arrays both technologically and technically very challenging.

Method and Results.

We have designed two and four elements arrays (both copper and HTS) according to the requirements imposed by cryogenics and to the design restrictions related to the currently available superconducting technology (planar epitaxial HTS films HTS/dielectric multilayers). The HTS arrays were patterned, using lithography and wet etching, on 2” YBCO films deposited on both sides of a 0.43 mm thick sapphire substrate. Such arrays were integrated with a custom built cryo-cooler,which uses either liquid nitrogen or closed cycle pulsed tube (Cyomech). Since our previously designed matching/tuning/decoupling circuit [1] restricted the quality factor Q in the system to a few thousands, even for a relatively narrow tuning frequency range, we changed the circuit design by introducing GaAs varactor diodes (Metelics) and by custom integrating them with the array inside the cryostat (thus kept at 77K). The new system allows for all necessary frequency, matching and de-coupling adjustments to be done outside the shielded room.



(a) (b)

Figure 1. (a) A matching and tuning circuit using varicap GaAs diodes is shown. By changing the applied, $V_{m1,2}$ (matching) and $V_{t1,2}$ (tuning), voltages for the varicap diodes both 200 MHz tuning and 50 Ω rf coaxial cable matching can be achieved for both channels. The upper side of a 2” by 1” HTS array is shown [4]. CC and CD denote de-coupling and coupling capacitors, respectively. Q limitation of the circuitry is less than 6,000. **(b)** The impedance spectra of the array shown in Fig. 1a depict calculated s_{11} (reflection) at port one. It is shown for different values of decoupling capacitors (CD). Note that the decoupled frequency is equal to the lower mutual inductance split frequency. In practice, we are achieving decoupling better than -30 dB.

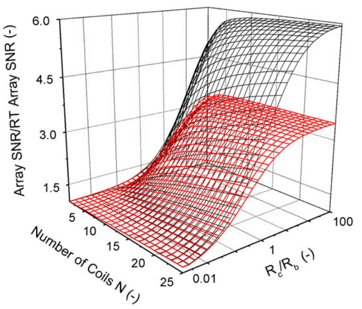


Figure 2 Calculations of the normalized SNR improvement *vs.* number of array elements and the ratio of coil (R_{Coil}) to body (R_{Body}) resistance, for 77 K copper (bottom surface plot) and HTS (upper surface plot) arrays over identical room temperature (RT) copper. The number of coils is limited to 25 and the R_c/R_b ratio changes from 0.01 to 100.

The SNR for an NxN surface coil array can be expressed as follows:

$$\mathrm{SNR} \propto \frac{S(N)}{\sqrt{\alpha\beta\left(R_{Coil}/R_{Body}(N)\right)N^2+1}} \qquad (1)$$

where N^2 is the number of elements in the array. $R_{Body}(N,R_E,\alpha)=R_b+\alpha R_E N^3$; R_b, R_E and R_{Coil} are the body, external circuits, and coil resistances, respectively. α is the ratio of coil to body temperature T_{Body} ($\alpha=T_{Coil}/T_{Body}$) and β is the coil resistance ratio at T_{Coil} and 300K. In order to estimate the SNR gain due to the use of a 77K Cu or HTS coil we used the following formula for relative SNR derived from Eq. 1 assuming that the S(N) is the same for both cases:

$$\frac{\text{Array SNR}}{\text{Array SNR}^{300K\,Cu}} = \sqrt{\frac{(R_{Coil}^{300K\,Cu}/R_{Body}(N,R_E))N^2+1}{\alpha\beta(R_{Coil}^{300K\,Cu}/R_{Body}(N,R_E))N^2+1}} \qquad (2)$$

Calculation of such SNR gain for both 77K Cu and HTS array is shown in Fig. 1. Here $R_E=0$; α = 77/300=0.25; β is equal to 1/3 and 1/10 for 77K Cu and HTS coils, respectively. Whereas copper resistance at 77 K is 1.8 mΩ and at 300K is 5 mΩ, the effective resistance of a superconductor as calculated from the coil Q is 0.5 mΩ but is limited by loss of the dielectric layer deposited on the film surface

Discussion and conclusions.

The arrays were tested for coil decoupling, tuning and matching, both at room (Cu) and liquid nitrogen temperatures (Cu and superconductor). Presented matching/tuning and de-coupling circuitry, increased an upper Q limit to 6,000. Obtained SNR gain of cooled Cu and HTS two-element array over room temperature Cu, tested on both phantoms and a mouse model at 200 MHz (Bruker), were 2 and 2.8, respectively. It matches simulations from Fig. 2 for 77K Cu, however, for HTS array it is less than expected. This gain for HTS array was limited by dielectric loss of one of build-in capacitors, not by electronics. Tests of array for PPA is underway.

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