Cryogenic Varactor-Tuned 4-element Array and Cryostat for μ-MRI of Trabecular Bone in the Distal Tibia

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Introduction

Non-invasive quantitative assessment of systemic bone diseases such as osteoporosis is possible by 3D μ-MRI of trabecular bone micro-architecture [1]. While MR images at resolutions < 200 μm can hit severe SNR limits, these can be compensated by site-specific optimization of the rf receive coil, such as by use of a closely-coupled multi-element array and cryogenic electronics. For example when thermal noise of the rf coil dominates system noise, significant SNR improvement can be achieved by cooling a normal metal coil or by using superconductors (HTS) [2]. Furthermore, arrays of cryogenically cooled coils have potential for additional SNR enhancement, increasing with the number of array elements. For design purposes, it is important to consider the relative SNR gain achievable using cold copper versus HTS material, since the challenge of implementing an HTS array is exacerbated by the required low-loss electronic circuits for tuning/matching and mutual inductance cancellation. We have developed cryogenic copper and HTS arrays for μ-MRI of trabecular bone microstructure in the distal tibia, together with novel varactor-based cryogenic control circuitry, and we here report preliminary results of a clinically practical cryogenic 4-element array and cryostat assembly, sufficiently robust for studies on a 3 T whole-body MRI scanner.

Methods and Results

Each element of the array is designed as a double-sided structure, consisting of two split rings, the gaps in each quasi-ring rotated 180° from each other (Fig. 1). Such structures have been referred to as twin horse-shoe (H-S) resonators [3]. Such a double-sided structure has not only distributed capacitance, but also reduced capacitive loss by concentrating the electric field within the substrate. Both copper and HTS array elements were designed with equivalent dimensions. HTS elements were fabricated of 0.5 μm thick $YBa_2Cu_3O_{7-x}$ thin films deposited on both sides of $LaAlO_3$ substrates. The ring gaps are evident in Fig. 1. The only difference between the copper and HTS array layouts was the necessity of adding built-in coupling capacitors for the HTS elements [4]. The size of a single element was 35 mm diameter, selected to keep the coil/body resistance ratio (R_c/R_b) large enough for the SNR gain to be about 100% at 123 MHz. Unloaded Q of a copper element at room temperature (RT) and 77 K was 300 and 900, respectively, while loaded Q (on the tibia) was 250 and 600 at RT and 77 K, respectively. Unloaded Q of an HTS element at 77 K was ~19,500, while loaded Q of an HTS element was ~1050.

We designed a four-element receive-only copper array using a varactor tuning/matching/ decoupling circuit as shown in Fig. 2 (RFC = rf choke). A capacitive decoupling network of 8 varactors was used for isolation of elements. The circuit of Fig. 2, integrated with the cryogenic array, was designed to work at 77 K and is based on GaAs varactor diodes (Metelics). The array and electronics were designed for integration with a custom-built G-10 plastic cryostat, shaped to fit the human distal tibia (Fig. 3). This G-10 cryostat was used to cool the array and the associated electronics to 77 K in a static bath of liquid nitrogen. The distance from the array to the outside surface is about 5 mm, with the minimum distance achievable being about 3 mm. This system required only 30 minutes of cooling to be fully operational and stable at 77 K for many hours. The integrated array-cryostat system was fully bench-tested using an HP8712 network analyzer to measure inter-element isolation and loaded/unloaded Q ratios under RT and cryogenic conditions.

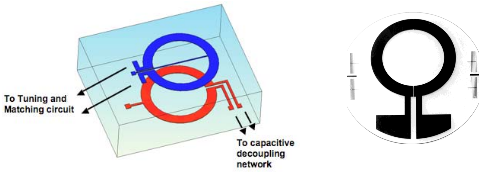


Fig. 1. Sketch of a single element design (left), and photo of a single HTS element (right), where large pads form the coupling capacitors.

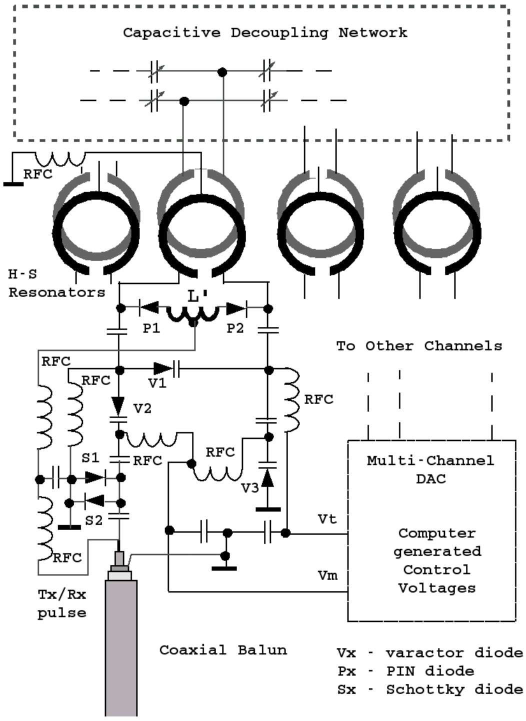
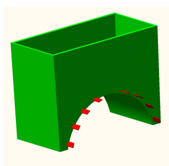


Fig. 2. Four-element array circuitry using GaAs varactors for tuning/ matching, and GaAs PIN diodes for detuning during rf transmit. Cryogenic coaxial λ/4-baluns connect each channel to its preamp.


(a)

Fig. 3. Liquid nitrogen plastic cryostat placed on distal tibia (a). Cryostat insert (green) has sapphire plates (red) as cold fingers in thermal contact with the rf array (b). Photo of a 4-element copper array (without electronics), mounted inside the cryostat (c).


(b)


(c)

Preliminary testing of key design concepts resulted in demonstration of basic performance of both HTS resonant elements (Fig. 4a) and mutual element isolation (Fig. 4b). The MR images shown in Fig. 4 are taken from initial tests that give evidence for successful functioning of the varactor-based circuitry for tuning/matching, element isolation, and transmit decoupling.

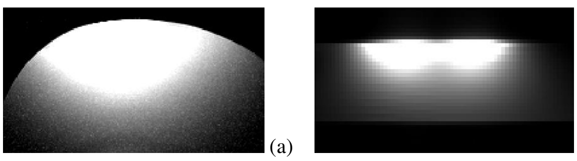

(a) (b)

Fig. 4. Gradient echo MR images acquired on a 3T whole-body scanner, using the circuitry of Fig. 2 connected to a single-element HTS coil at 77 K (a), and a 2-element copper array at RT (b).

Discussion and Conclusions

The cryogenic array set-up presented here was successfully fabricated and relatively low-loss electronic circuitry for high-Q elements was developed (electronic Q at 77 K is ~3000). The array is currently being tested on a 3 T whole-body scanner. Cryogenic SNR gain for in vivo μ-MRI of trabecular bone will be determined from ratios of ROI's drawn on trabecular bone and on the image background. Previous SNR measurements we have made at 1.5 T for a copper twin horse-shoe coil (44 mm effective diameter) at RT and at 77 K have demonstrated a 100% SNR gain. To obtain the same gain at 3 T (same R_c/R_b ratio), we have therefore constructed a copper array consisting of 35 mm diameter elements. Preliminary results thus are promising for such a two-fold SNR gain for a 4-element copper array operating at 3 T compared to the RT performance of the same array, while the expectation for a 4-element HTS array is even greater. Initial imaging results using one and two channels carried out at 123 MHz support our SNR predictions.

Acknowledgements

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