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Electronics for a High Temperature Superconducting Receiver System for Magnetic Resonance Microimaging

R. D. Black, P. B. Roemer, and O. M. Mueller

***Abstract*—We describe an MRI (magnetic resonance imaging) receiver system that incorporates a high temperature superconducting (HTS) resonator as a surface coil. Techniques for measuring the Q of the HTS resonator in a 7 Tesla field are discussed. A method for coupling a room temperature copper resonant circuit to the HTS element is covered, and it is shown that such a coupling scheme preserves the signal-to-noise (SNR) gain afforded by the HTS coil. A preamplifier with a noise figure (NF) of <0.15 dB at 300 MHz is described.**

I. INTRODUCTION

In high field, clinical whole-body magnetic resonance imaging (MRI), it is the patient who is the dominant noise source [1]. Current commercial receiver systems at 0.5 and 1.5 Tesla have noise figures that are sufficiently low that they do not limit the SNR of the experiment. This is not necessarily the case at lower fields. Also, at high fields, as the size of the sample to be imaged and the receiving coil are reduced together, there is a crossover point beyond which the Johnson (thermal) noise in the coil starts to dominate. In this situation (i.e., for the imaging of small samples) the SNR can be improved by reducing the Johnson noise in the coil; we have done this through the use of HTS (high temperature superconducting) films [2], [3]. Ensuring that the SNR gains that an HTS coil can provide are maintained throughout the receiver chain requires a careful examination of the noise contributions up to and through the preamplifier.

Johnson noise results from the fluctuations in resistance that are caused by the random thermal motions of electrons in materials with a finite conductivity [4]. The noise power per unit bandwidth is proportional to RT, where R is resistance and T is absolute temperature. Clearly, a superconductor operated in a cryogenic environment will give rise to a reduction in Johnson noise. There are certain properties of superconductors that must be addressed, however, when considering their use in an MRI experiment. The first is that the critical field, i.e., the field at which superconductivity is quenched, must not be exceeded. The second is that the critical temperature of the material cannot be exceeded. This requirement must be balanced against the need to maintain biological samples at a temperature above the freezing point of water. Finally, the critical current value must be sufficiently high that the currents induced in the coil will not alter the performance of the coil. This is not an issue during receive, when SNR is important, but it does give rise to a nonlinear transmit characteristic in our system that must be calibrated out. The HTS material $Y_1Ba_2Cu_3O_7$ (YBCO) works well in this application and is used exclusively in the probe that is described herein [5].

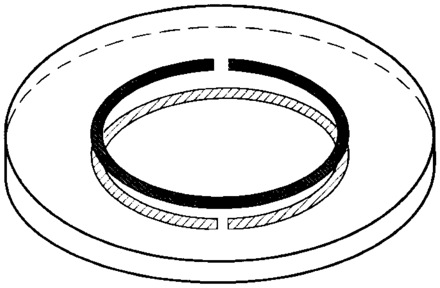

Fig. 1. The geometry of the YBCO resonators. There is a split ring on the top and on the bottom of the $LaAlO_3$ substrate. The outer ring diameter is 18 mm.

YBCO resonators were made out of 0.6 μm single crystal films that were deposited on $LaAlO_3$ substrates [6]. The films were patterned photolithographically to such a size that a resonant frequency of 300 MHz (the Larmor frequency of protons in a 7 T field) was obtained. The form of the LC (inductive/capacitive) resonator is shown in Fig. 1. The two C-shaped rings of YBCO are inductively and capacitively coupled, and the RF magnetic field pattern is that of a single loop. It is the axial component of the field that is of interest for the excitation and reception of the NMR signal. The axial field value at a point along the coil axis is simply

$$B_z = \frac{\mu_0 a^2 I}{4(a^2 + z^2)^{3/2}} \tag{1}$$

where a is the loop radius, I is the current, and z is the distance along the loop axis. (There is an extra factor of 2 in the denominator to account for the rotating magnetic field.) For a given distance z, then, B_z/I is a maximum when $a = 2^{1/2}z$. We should note that (1) is not precisely valid in this situation due to the finite widths of the rings and the small (0.5 mm) separation between the rings. However, one obtains qualitatively useful results. The variability of B_z/I as a function of loop radius for a distance z = 6 mm is shown in Fig. 2.

The Q's of the YBCO resonators were measured with an HP 8568A spectrum analyzer and a sweep generator. The measurements were performed in a Janis 8DT Supervaritemp dewar with a Cryomagnetics variable (0–9 T) field superconducting magnet. A quartz microscope slide was used to hold the YBCO resonator near to a transmit/receive antenna pair (the receive antenna was connected to the spectrum analyzer). The two antennas were overlapped slightly to eliminate their mutual inductance. A grounded copper tab was placed behind the antennas and was mounted in such a way that it could be pivoted via a stick that protruded out through the top of the dewar. This tab allowed for finely controlling nulling of the mutual inductance of the antennas. The symmetry of the resonance peak was highly

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The authors are with the General Electric Corporate Research and Development Center, Schenectady, NY 12301.

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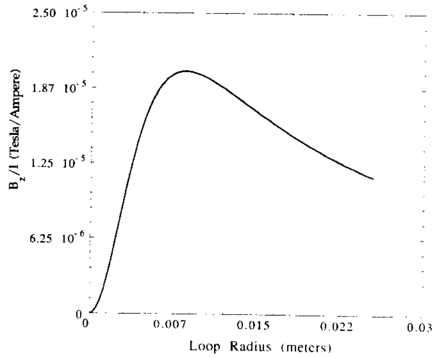

Fig. 2. Axial field per unit current for a wire loop at a distance of 6 mm along the loop axis.

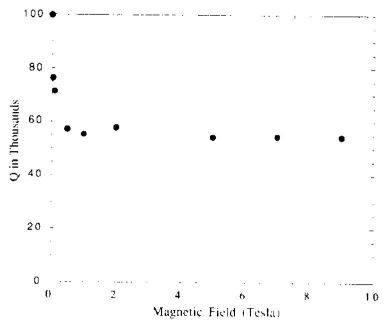

Fig. 3. Q versus magnetic field for a YBCO resonator at 4.2 K. The field was applied along the a–b plane of the superconductor.

dependent upon precise nulling, and, therefore, so were accurate Q value measurements. The antennas were far enough away to prevent loading of the resonator due to proximity effects. A copper cylinder was placed around the resonator to prevent loading from other sources. Fig. 3 shows how Q varies with magnetic field strength (field parallel to plane of the coil and to the a–b plane of the YBCO) at 4.2 K. The initial drop in Q (below 1 T) occurs, we suspect, as the first critical field, H_{c1} [7], is exceeded. There is very little field dependence beyond 1 T since the upper critical field, H_{c2}, of YBCO is very large (generally believed to be >100 T).

We now turn to a discussion of how much of an SNR gain we can expect from an HTS receiver system. Because $Q = \omega L/R$, where ω is frequency, L is inductance, and R is resistance, we note that the reduction in Johnson noise voltage, and therefore the increase in SNR, is:

$$\mathrm{SNR} \propto \sqrt{\frac{Q}{T}}. \tag{2}$$

Typical 300 MHz copper film resonators that we have made, are identical in size to the YBCO coils and have Q's ~400 at room temperature. Referring to Fig. 3 we see that the Q of the YBCO resonator is ~50,000 at 7 T, which is the field present in our MRI microimaging system. The YBCO resonator is kept at 10 K during operation (the Q value is essentially the same as it is at 4.2 K). So, the increase in SNR that will accrue to the HTS coil, as compared with a room temperature copper coil[1] of the same size, is approximately a factor of 60. In order to realize this gain, however, a coupling procedure must be developed that will not add noise to the signal received by the superconductor. We shall see that a straightforward inductive coupling approach makes this possible.

The coupling arrangement is shown in Fig. 4(a). The superconducting, or primary, resonant circuit has an inductance, a capacitance, and a residual AC resistance. (Superconductors only pass DC current without resistance [7].) The NMR signal voltage is indicated by the generator E. This primary circuit is inductively coupled to a room temperature, copper coil secondary. Solving the circuit equations for the two coupled resonant circuits leads to the equivalent circuit for the secondary shown in Fig. 4(b) [8]. At resonance, the reactive components of Z_p (impedance of the primary) cancel out, and $Z_p = R_p$, the residual AC resistance of the YBCO coil. If M, the mutual inductance, is made large enough, then the coupled impedance due to the primary will dominate the other impedances in the secondary. Again, we resonate the secondary so that it is only the real resistance of the copper coil that contributes. It turns out to be relatively easy, in fact, to make $(\omega M)^2/R_p = 50\,\Omega$. The SNR of the primary circuit alone is:

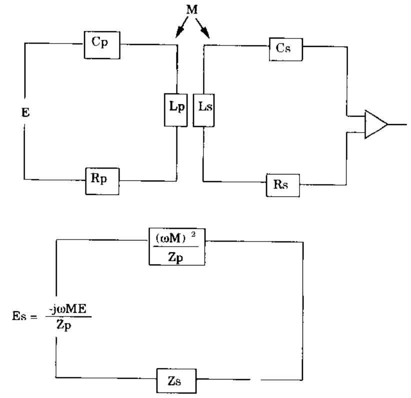

Fig. 4. (a) Circuit diagram for the inductively coupled YBCO resonator (primary) and the room temperature copper resonator (secondary). (b) The equivalent circuit for the secondary.

$$\mathrm{SNR} \propto \frac{E}{\sqrt{R_p}} \tag{3}$$

where R_p is the resistance at 10 K. The SNR for the equivalent secondary circuit in Fig. 4(b) when R_s is negligible compared to 50 Ω is:

$$\mathrm{SNR} \propto \frac{\omega ME}{R_p} \Bigg/ \sqrt{\frac{(\omega M)^2}{R_p}} = \frac{E}{\sqrt{R_p}}. \tag{4}$$

So we see that even though the net Q of the coupled circuits is lower than the Q of the superconducting resonator alone, the SNR gain is preserved as long as the coupled impedance is made large with respect to other impedance terms in the secondary. It may help to view the coupled resonators in terms of a voltage transformer. Both the signal and noise voltages are transformed up.

When discussing the addition of noise power terms it is useful to use the concept of noise temperature. The noise temperature (NT) of

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[1] Even when cooled to 10 K, the thin film and bulk wire copper resonators that we have made have Q values that are more than a factor of 20 smaller than those of the YBCO resonators (in field). This is due to the inherently worse sheet resistance values of copper (see G. Muller, et al., "Survey of Microwave Surface Impedance Data of High-T_c Superconductors-Evidence for Nonpairing Charge Carriers," *J. of Superconductivity*, vol. 3, pp. 235, 1990).

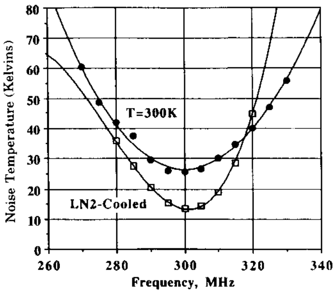

Fig. 5. Noise temperature plot for a GaAs-MESFET preamplifier at two different temperatures (LN2 = 77 K).

an element is the temperature value at which a 50-Ω load will supply a noise power equal to that supplied by the element in question. It is related to the noise figure (NF), in decibels

$$\mathrm{NT} = (10^{\mathrm{NF}/10} - 1)\,300\,\mathrm{K}. \tag{5}$$

For example, the noise temperature of the coupled impedance due to the YBCO resonator is 10 K; to this value must be added the noise temperature of the preamplifier to which the secondary circuit is connected.

Common source configuration preamplifiers, containing GaAs-MESFET's from several different manufacturers, that operate at 64 MHz [9], have been modified (by simple adjustments of the passive component values) to operate at 300 MHz. The optimum source impedance of the FET's is determined by their small gate/source capacitance values (0.3–0.5 pF) and is therefore high (1–3 kΩ). The key to the realization of low noise figures is to provide a very low-loss, high-Q input (LC) impedance transformation network. Large air-core inductors are used with low-loss variable capacitors. The preamplifier is tuned to have a noise minimum at the Larmor frequency (here, 300.5 MHz). Cooling the amplifier in liquid nitrogen results in a significant lowering of NT and it is believed that the remaining dominant noise source is Johnson noise in the input transformer. Careful design has resulted in preamplifiers that have, when cooled to 77 K, NT = 13 K (Fig. 5).

The HTS receiver system described above has been built, and initial spin echo experiments have been performed, on $CuSO_4$ phantoms and various formalin-fixed tissue samples [2]. An SNR gain of a factor of 10, as compared with a copper system of the same size that is held at room temperature, has been realized. This gain is due primarily to the increase in Q. Although the performance of the preamp described above improves when it is cooled, it tends to be unreliable when thermally cycled (it was not originally designed to be cooled), and thus we have kept the operating temperature at 300 K. Johnson noise in the impedance matching network of the preamplifier and in a warm copper RF shield, to which the YBCO coil is inductively coupled, has resulted in a high probe noise temperature. A noise temperature of less than 20 K was measured when the RF shield was cooled to 10 K, thus demonstrating that the probe noise can truly be made small. We are eliminating the matching network in the preamplifier (direct coupling from the probe to the FET) so as to eliminate the noise contribution from that source.

The enhanced SNR that this probe provides allows for a drastic reduction in image-acquisition time (time $\propto$ SNR^{-2} or for a significant increase in resolution (an image-volume element can be reduced in size by a factor equal to the SNR gain). Both of these capabilities will be used in applications of this technology to histopathologic studies.

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Estimation of Single Sweep Steady-State Visual Evoked Potentials by Adaptive Line Enhancement

Carlos E. Davila, Alireza Abaye, and Alireza Khotanzad

***Abstract*—An adaptive line enhancer (ALE) is used to obtain estimates of the single sweep steady-state visual evoked potential (SSVEP). The method is seen to enhance the estimated signal-to-noise ratio of the single sweep SSVEP by as much as 10 dB.**

I. INTRODUCTION

The sensory evoked potential (EP) is an electrical potential generated in the brain and recorded from the scalp after the presentation of a transient or periodic sensory stimulus. The steady-state visual evoked potential (SSVEP) is measured using a periodic visual stimulus to elicit the evoked response and has found numerous clinical applications [1]. The stimulus is typically a flashing strobe light or a checkerboard pattern undergoing polarity reversals. The EP is usually

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The authors are with the Department of Electrical Engineering, Southern Methodist University, Dallas, TX 75275.

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