Magnetoencephalography Using High Temperature rf SQUIDs

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Summary: We have developed high-critical-temperature radio-frequency Super conducting QUantum Interference Devices (SQUIDs) with step-edge grain-boundary Josephson junctions and large flux focusers. These planar devices were fabricated from epitaxial $YBa_2Cu_3O_7$ films and operated in the magnetometer and first-order gradiometer configurations while immersed in liquid nitrogen. At the temperature of 77K, we have attained a magnetic field resolution for the magnetometer better than 200 $fT/Hz^{1/2}$ down to less than 1 Hz, i.e., over the low signal frequency range important for medical diagnostics. The results to date show a high promise for biomagnetic diagnostics. For the first time, we recorded the evoked responses from human brains using a high-temperature magnetometer and a first-order electronic gradiometer channel simultaneously. These results were obtained in a magnetically shielded room. An improvement in the magnetic field resolution by another order of magnitude is possible and probable.

Key words: High-temperature superconductor; Thin-film; SQUID; Biomagnetism; Diagnostics; Magnetoencephalography; Auditory evoked fields.

Introduction

In 1987, superconductors with a high transition temperature, T_c>90K, were discovered and first high temperature superconducting quantum interference devices (SQUIDs) were demonstrated (Koch et al. 1987). High temperature superconductors (HTS) could significantly simplify the biomedical diagnostic equipment based on the use of SQUIDs and should also dramatically reduce the cost of such equipment. In the future, HTS SQUID-based measurements may replace much of today's routine electrophysiology. The driving force for such a development originates from the ease of handling due to the lack of electrodes and the non invasive character of a biomagnetic measurement as well as the simplification of SQUID cooling. Of course, low-cost high-T_c SQUIDs operating in liquid nitrogen and having a sufficiently high magnetic field spectral resolution need to be available first. This high resolution is equivalent to a sufficiently low value of detectable magnetic field intensity per root of frequency, B_N.

Present diagnostic systems, which use low-temperature-superconductor (LTS) direct current (dc) SQUIDs cooled with liquid helium, typically attain B_N values of the order of 5-10 $fT/Hz^{1/2}$. This resolution, limited by the white and low frequency 1/f excess noise of the system, is sufficient for real-time magnetoencephalography (MEG). In the case of HTS SQUIDs, the level of the white thermal noise voltage will be unavoidably 4.5 times higher, since the temperature of operation of a device immersed in liquid nitrogen (T = 77K) is approximately 20 times higher. However, the main sensitivity limitation at low signal frequencies is imposed by the 1/f excess noise. This noise was very high in early HTS SQUIDs (1987-1989) which were fabricated from either polycrystalline bulk ceramics or polycrystalline films and used Josephson junctions created by natural grain boundaries. Indeed, until recently, it has not been known whether or not that noise could be reduced to levels sufficiently low for biomedical diagnostics at relevant low signal frequencies ranging from, say, 0.1 Hz to 100 Hz.

In the past two years, however, it has been shown that radio-frequency (rf) and dc SQUIDs which are fabricated

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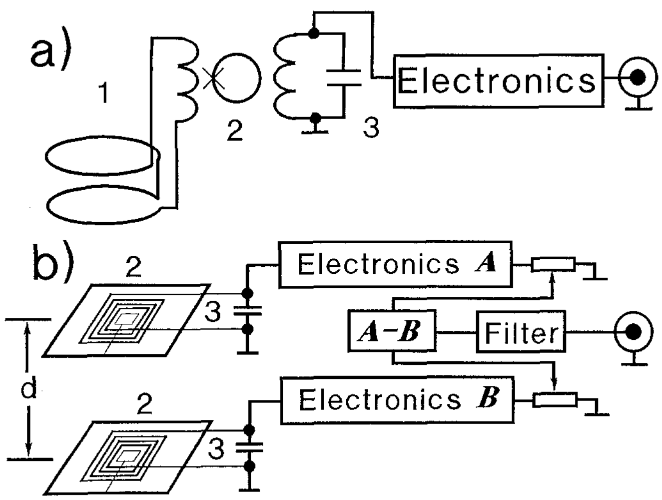

Figure 1. a) A schematic diagram of a conventional first order rf SQUID gradiometer: 1 -gradiometer pickup coil, 2 - rf SQUID loop, 3 - resonant LC "tank" circuit. b) A schematic diagram of our thin film first order YBCO gradiometer: 2 -SQUID loops in large flux focusing washers, 3 - the tank circuit.

from epitaxial HTS thin films and correspondingly incorporate one or two engineered Josephson junctions can exhibit a 1/f noise much lower than the polycrystalline SQUIDs. SQUIDs with step-edge grain-boundary junctions and superconductor-normal metal-superconductor (SNS) weak links appear to have the relatively lowest 1/f noise. Today, the energy spectral resolution at 1 Hz and 77K is the same in our HTS laboratory rf SQUIDs with step-edge junctions as in commercial LTS devices at 4.2K, i.e., about 5 x 10^{-29} J/Hz. The energy resolution at 1 Hz and 77K in the best laboratory dc SQUIDs with SNS and step-edge junctions is (1-2) x 10^{-29} J/Hz, only one order of magnitude worse than in commercial LTS devices at 4.2K (Friedl et al. 1992; DiIorio et al. 1992). This energy resolution was attained with SQUID inductances L_s = 20 pH, too low for an effective coupling to the signal. Nevertheless, the results illustrated the intrinsic device capabilities. A further improvement of the SQUID energy resolution, especially in the very high frequency rf SQUIDS, can be expected.

The very low B_N value in LTS diagnostic SQUIDs is attained through the use of a flux transformer with large diameter pickup coils, usually wound from a superconducting wire into a first-order gradiometer configuration shown in figure 1a. The wire is connected to a superconducting planar spiral input coil which is strongly coupled to the SQUID loop itself. Unfortunately, no suitable low-noise HTS wire can be fabricated at present. Planar spirals, transformers and gradiometer coils, however, can be patterned from multi layered low-noise epitaxial HTS films separated by thin insulating layers (Wellstood et al. 1990). A dc SQUID magnetometer with a separate ("flip-chip") planar flux transformer attained a sensitivity of about 2 pT/$Hz^{1/2}$ at 1 Hz and 90 fT/$Hz^{1/2}$ at 1 kHz and 77K (Miklich et al. 1991). Efforts to fabricate low 1/f noise HTS SQUIDS integrated with planar flux transformers into one multilayered device structure have not yet been entirely successful, although a remarkable progress has already been accomplished (Lee et al. 1991) and an eventual solution to the problem is in sight. Below, we describe the use of a much simpler, and presently more sensitive, temporary alternative to such an integrated device. A single-layer rf SQUID with a large planar flux focuser on the chip permitted us to attain a B_N = 170 fT/$Hz^{1/2}$ at 1Hz and 77K. A magnetometer and a first-order gradiometer using such chips made it possible to record even the relatively weak evoked response signals of human brains, as well as other biomagnetic signals.

Experimental Method

We have shown earlier that planar 1.4 x 1.4 mm^2 washer rf SQUIDs with step-edge junctions fabricated from epitaxial $YBa_2Cu_3O_7$ (YBCO) films can operate with relatively low white and 1/f noise levels when immersed in a liquid nitrogen bath within a low-noise, magnetically shielded fiberglass dewar (Zhang et al. 1992). These noise levels were additionally reduced through the use of a high tank frequency of, approximately, 150 MHz, instead of the usual 10-20 MHz. Subsequently, to increase the magnetic field gain, we increased the size of the flux-focusing YBCO washer to 8 x 8 mm^2 centered on a standard 10 x 10 mm $SrTiO_3$ substrate chip. A magnetometer with the SQUID having a loop inductance of L_s = 190 pH, attained a B_N = 170 fT/$Hz^{1/2}$ at 1 Hz and 700 fT/$Hz^{1/2}$ at 0.1 Hz. A first order electronic gradiometer, schematically shown in figure 1b, consisted of two such magnetometer channels, A and B, each with L_s = 380 pH and a B_N = 300 fT/$Hz^{1/2}$ at 1 Hz. The tank frequency was in this case 100 MHz. The amplitude-balanced summation of their opposite-phase output signals (A-B) provided the gradiometric output. The gradiometer base, i.e., the separation of two SQUID chips, was d = 60 mm. The single channel (magnetometer A) and the summation signal (A-B) could be recorded simultaneously.

The measurements of biomagnetic signals using our HTS SQUIDs have been performed at 77K inside a shielded room housing the liquid-helium-cooled 37-channel clinical gradiometer (MAGNES, BTI). The MAGNES data acquisition system was used for the HTS SQUID signal averaging. Data collected by the 37-channel LTS BTI gradiometer served as the reference information.

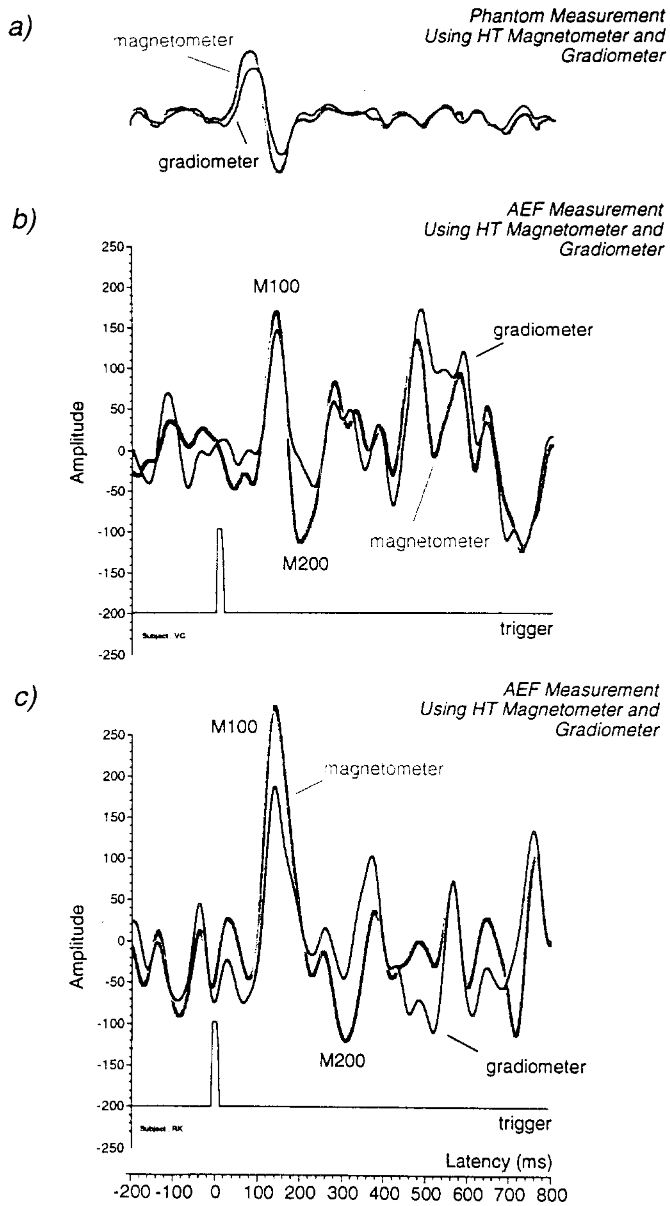

Figure 2. Evoked brain responses; trace pairs recorded simultaneously with the magnetometer (A) and gradiometer (A-B) of figure 1: a) phantom signals, b) auditory evoked responses of subject 1, c) auditory evoked responses of patient 2.

Results

We measured the evoked response of the human cortex elicited by an auditory stimulus. A series of 1 KHz, 60 dB tone bursts, each 0.5 sec in duration, was presented to a male subject's left ear. The interval between two subsequent tones was set at 4 sec. The SQUID was placed over the right temporal region, near the posterior maximum of the M100. When using the more sensitive magnetometer with L_s = 190 pH, the magnetic activity was averaged over 80 trials and was free of large amplitude artifacts. Inspection of the averaged and filtered wave form revealed the well-known components M50, M100 and M200. Furthermore, after 230 msec, a sustained field, which lasted till the offset of the stimulus, became very prominent in this subject. This sustained activity seemed to be more pronounced in the magnetometer recordings than in those taken as reference using the BTI first order gradiometer. This suggested that the sustained field is generated by a more distributed and/or a deeper source than the M100. The suggestion is also based on the earlier established fact that recordings made using a second-order LTS gradiometer gave a still weaker sustained field.

Figure 2 shows the evoked brain signal trace pairs simultaneously recorded with the electronic gradiometer and the magneto-meter channel having a $B_N \geq 300$ ft/Hz$^{1/2}$. In this case, to compensate for the higher value of B_N, the magnetic activity of the brain was averaged over 256 trials. The triggering of the evoked response was done as described above. The traces shown were filtered (1-20 Hz). The upper trace pair is the triggered signal of a brain phantom with its dipole intensity calibrated for the level of a typical brain signal. These traces illustrate the noise level. The lower trace pairs show auditory evoked fields (AEF) of two female test subjects. Again, the components M100 and M200 can be clearly identified and a sustained field becomes obvious in the magnetic recordings in figure 2b. A comparison with the phantom traces gives the assurance that the (averaged) signal level greatly exceeded the noise. The wave forms acquired for the same subjects by using the MAGNES gradiometer were consistent with the corresponding brain response of figure 2.

The results obtained demonstrate the basic feasibility of using HTS SQUIDs for magnetoencephalography, although the magnetic field sensitivity is still by over an order of magnitude too low. We may mention that the attained sensitivity was already adequate to record the magnetic activity of the heart in real-time, i.e., without any signal averaging. The electronic gradiometer recorded comparable heart signal traces with and without magnetic shielding.

Outlook

The further increase of HTS rf SQUID sensitivity up to the desired level appears to be within reach. For example, the eventual introduction of low-noise integrated flux transformers should alone reduce the B_N of our present rf SQUID by a factor of three or more. The increase in the rf SQUID tank frequency to several GHz holds a promise of low frequency spectral energy resolution lower than 1 x 10^{-29} J/Hz and superior to that of today's most energy-sensitive HTS dc SQUIDs mentioned above. Indeed, we have already demonstrated a very simple planar microwave rf SQUID operating at 3 GHz with $L_s = 125$ pH. This unoptimized device had, at a white noise level of 8×10^{-29} J/Hz, slightly higher than that of our best 150 MHz SQUID, the crossover to 1/f noise near 0.01 Hz (Zhang et al. 1992c). Naturally, the HTS dc SQUIDs with realistic inductances and well coupled integrated flux transformers may eventually attain sensitivities similar to that projected for an optimized microwave SQUID.

An additional limitation of HTS SQUID sensitivity may come from the noise caused by boiling of liquid nitrogen. While this issue requires a further study, technical solutions can be envisaged to separate the SQUIDs from this noise source.

For practical application, the HTS SQUIDs must be stable upon thermal cycling over a period of many years. Thus far, our unencapsulated devices operated over periods exceeding one year but with a slow, gradual loss of sensitivity. Preliminary tests indicate that our encapsulated devices with step-edge Josephson junctions remain stable even under most adverse conditions (e.g., a prolonged boiling in water) and should have a sufficiently long lifetime. The SQUIDs with some other types of junctions, free of grain boundaries, might be even more stable.

In conclusion, no intrinsic obstacles appear to exist for a future application of HTS SQUIDs in magnetoencephalography and other biomagnetic diagnostics.

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