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Magnetoencephalography using a multilayer high-T_c DC SQUID magnetometer

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Abstract

We describe tests of the use of a multilayer high-T_c DC SQUID magnetometer for magnetoencephalography (MEG) and compare our measurements with results obtained using a low-T_c SQUID sensor. The integration of bias reversal readout electronics for high-T_c DC SQUID magnetometry into a commercial MEG data acquisition system is demonstrated. Results of measurements performed on a saline-filled head phantom are shown and the detection of an auditory evoked magnetic response of the human cortex elicited by a stimulus is illustrated. Future modifications of high-T_c DC SQUID sensors for applications in MEG, in order to reach a resolution of 1 fT/√Hz at 77.5 K over a wide frequency band, are outlined.

Keywords: High-T_c superconducting heterostructures**;** quantum interferometers; SQUID; magnetometer; magnetoencephalography

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1. Introduction

Magnetoencephalography (MEG) is a non-invasive technique that complements other functional brain imaging modalities, providing valuable information about neural dynamics of the living human brain with superb (millisecond) temporal resolution. Some of the largest magnetic fields that have been measured by MEG from brain tissue originate from evoked cortical activity and have typical amplitudes in the range of

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a few hundred femtotesla [1-3]. MEG is a technique that is complementary to electroencephalography, in the sense that the two techniques have different sensitivities to different orientations of neuronal currents.

MEG measurement systems presently rely on low-T_c direct current superconducting quantum interference devices (low-T_c DC SQUIDs) that are based on Nb films, operate at 4.2 K and are cooled by liquid helium. Generally, SQUIDs demonstrate superior sensitivity for measuring the vector components and spatial gradients of magnetic fields, as well as an ability to resolve small changes in large signals. However, the cost of liquid helium and the inconvenience of its use for cooling the sensors are significant obstacles that prevent general acceptance of MEG systems in clinical practice. In addition, world reserves of helium are running out and prices for helium are expected to increase after 2015 by up to a factor of 30 [4]. These issues highlight the need to develop magnetic field sensors that provide an alternative to the helium-cooled low-T_c DC SQUIDs that are used exclusively in MEG systems. Sensors for MEG applications should have a magnetic field resolution of better than 10 fT/√Hz and a size for the sensor's pickup coil of below 20 mm. Direct coupled high-T_c SQUIDs [5, 6] with an intrinsic white noise that greatly exceeds 10 fT/√Hz at 77.5 K have previously been tested for the recording of MEG signals. As observed in [6], about 2000 epochs were required to achieve a signal-to-noise ratio of 3 in the measurement of an evoked MEG signal. The resulting times for MEG measurements with such sensors were unacceptably long.

High-T_c DC SQUID multilayer magnetometers with 16-mm pickup coils and 12-turn input coils of high-T_c superconducting thin-film flux transformers have demonstrated magnetic field resolutions down to 4 fT/√Hz at 77.5 K [7]. Such sensors offer great potential to serve as replacements for low-T_c SQUIDs in MEG systems. Such an upgrade using high-T_c SQUIDs would make MEG systems independent of helium, more user-friendly and would save about 100,000 Euros/year in the operating cost of each system. In this paper, we report on a test of the applicability of multilayer high-T_c DC SQUID magnetometers for MEG measurements in the form of a direct comparison with low-T_c DC SQUIDs.

2. Experimental results

A high-T_c DC SQUID magnetometer for MEG measurements was prepared using high oxygen pressure magnetron sputtering and deep-UV (200 nm) photolithography. The sensor consisted of a DC SQUID and a 16-mm multilayer flux transformer made on a separate substrate that were combined together in a flip-chip configuration [8, 9]. A bicrystal (100) $SrTiO_3$ (STO) substrate with a symmetric 24° in-plane misorientation angle was used for preparation of the DC SQUID. The flux transformer was prepared using $YBa_2Cu_3O_{7-x}$ (YBCO), $PrBa_2Cu_3O_{7-x}$ (PrBCO) and STO films on a single crystal ∅ 30 mm STO wafer. The multifunctional computer program "IRTECON" [10] was used for automatic measurements of the electron transport properties of the high-T_c films, Josephson junctions and DC SQUIDs. The high-T_c magnetometer was encapsulated in vacuum-tight sealed fiber-glass epoxy capsulation together with a modulation coil and a Pt heater. AC-bias SQUID control electronics and a 1.5 liter LN_2 cryostat, both from Cryoton Ltd, were used for operation of the high-T_c magnetometer. Both high-T_c and low-T_c SQUID systems had magnetic field resolutions of 5 fT/√Hz when operating at 77.5 K and 4.2 K, respectively. Operation of the DC SQUID control electronics in bias reversal mode led to an approximately 3-fold reduction in the intrinsic low-frequency noise originating from fluctuations of the critical currents of the Josephson junctions in the high-Tc DC SQUIDs. The spectral density of the background signal of the high-T_c system measured at 77.5 K with the high-T_c DC SQUID magnetometer placed in a superconducting shield is shown in Fig.1a. The distance between the pickup coil of the signal magnetometer and the bottom of the cryostat was 19 mm in the low-T_c system and 15 mm in the high-T_c system.

Both test measurements with a saline-filled head phantom and MEG measurements were performed in a magnetically shielded room using both a one-channel high-T_c DC SQUID measurement system and a commercial 248-channel MEG system (9-mm magnetometers; “Magnes© 3600 WH” 4D-Neuroimaging). The analog output of the high-T_c system was connected to a 16-bit analog-to-digital converter port available on the low-T_c system and processed together with the signals from the low-T_c magnetometers. A photograph taken during the test measurement on the head phantom using the high-T_c system is shown in Fig. 1b.

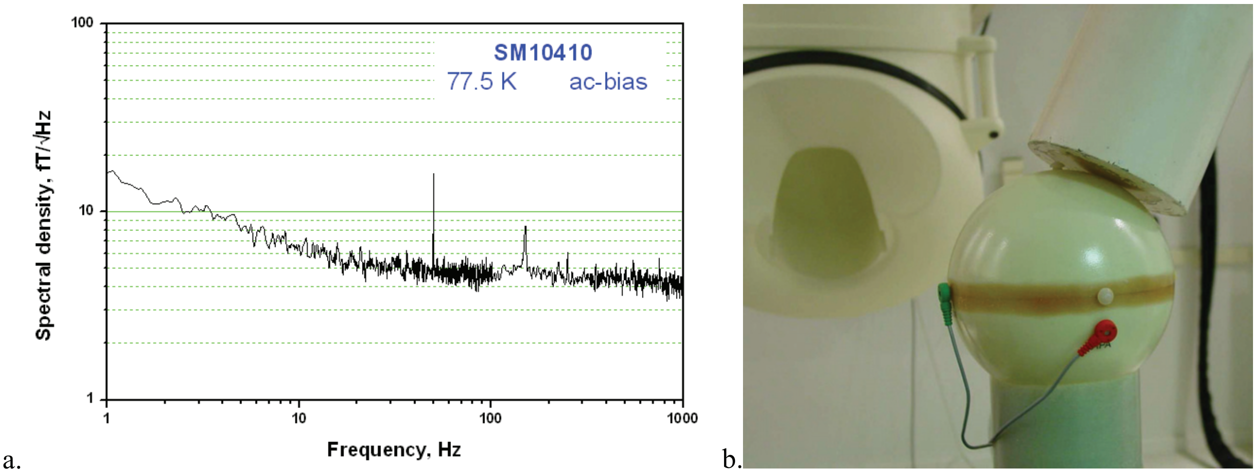

Fig. 1. (a) Noise spectral density of the 16-mm high-T_c magnetometer; (b) photograph taken during the test measurement on the head phantom using the high-T_c system.

In Fig. 2a, blue lines show the results of measurements obtained from the head phantom from one channel of the low-T_c measurement system, while the red lines in Fig. 2b show data from the high-T_c system measured at the same point above the head phantom surface.

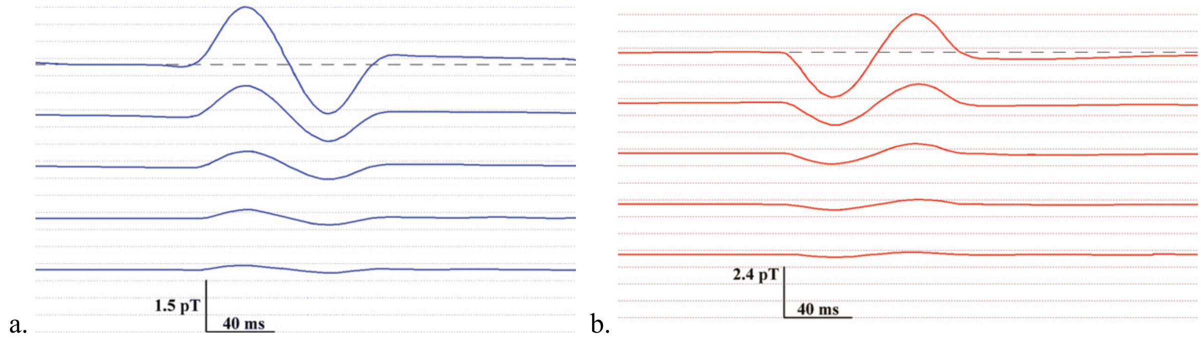

Fig. 2. Measurements of fields obtained from a saline-filled head phantom using: (a) a low-T_c SQUID and (b) a high-T_c SQUID.

In Fig. 2, the excitations of the head phantom current dipole were the same for the measurements made with both systems and reduced by a factor of 2 at each step from top to bottom. The peak-to-peak magnetic fields measured by the low-T_c SQUID were 3.2 pT, 1.6 pT, 800 fT, 400 fT and 200 fT, respectively. In order to obtain comparable results, no noise compensation (weights or reference channels) were applied to the data obtained using the low-T_c and high-T_c systems. Both the high-T_c and the low-T_c data are therefore purely magnetometer data. Both data sets show averages over 100 epochs and were band-pass filtered from 3 to 30 Hz.

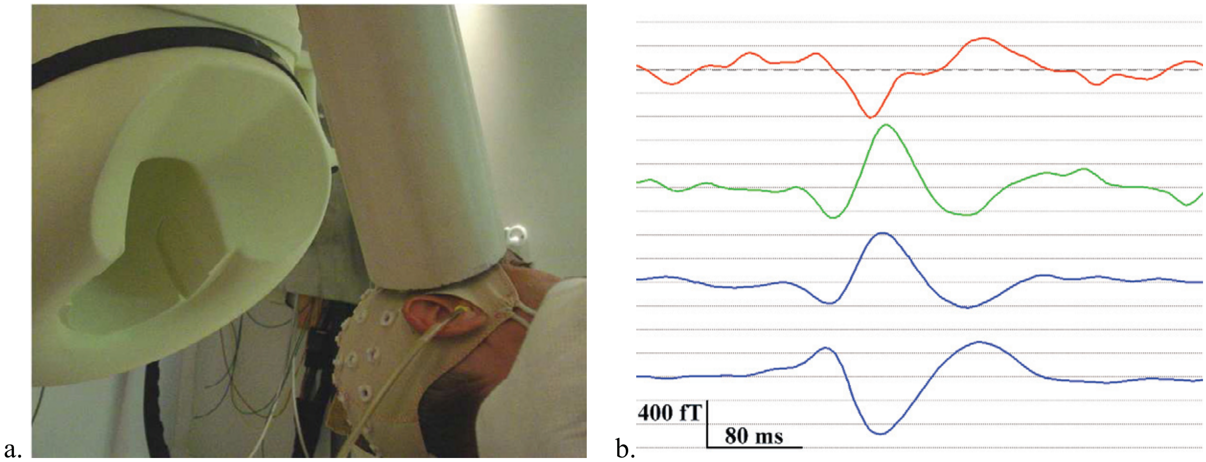

Fig. 3. (a) Photograph taken during the measurement of an auditory evoked field; (b) Results of measurements of an auditory evoked field obtained using a high-T_c SQUID sensor (red and green curves) and low-T_c SQUID sensors (blue curves).

A photograph taken during the measurement of an auditory evoked response using the high-T_c measurement system is shown in Fig. 3a. Fig. 3b shows a comparison of data acquired on the same day using the high-T_c SQUID (red and green curves) and two of the low-T_c channels (blue curves). The red curve shows a high-T_c curve measurement recorded at the first position of the SQUID. The green curve shows a result obtained after moving the recording position by a few centimeters, near to the position of the low-T_c sensor during the measurement of the upper blue curve. All of the data sets were acquired with a sampling rate of 678 Hz and a bandwidth 200 Hz and averaged over 300 epochs.

3. Discussion

The measurements shown in Fig. 2 and Fig. 3 demonstrate sufficient sensitivity of the 16-mm high-T_c magnetometers operating at 77.5 K for MEG measurement of auditory evoked magnetic fields with a relatively small number of epochs and a short acquisition time. The high-T_c magnetometers are significantly smaller than the 21-mm magnetometers used in commercial low-T_c (4.2 K) MEG systems from Elekta Neuromag©, while achieving [7] magnetic field resolution similar to that of the low-T_c system. The use of fewer radiation shields in LN_2 cryostats result in less magnetic field noise, which is often dominant over the intrinsic noise of low-T_c SQUID sensors [11]. The thermal noise of a magnetically shielded room [11] can also increase the background noise in the measuring systems, reducing the difference between their magnetic field resolutions. Thinner thermal insulation in LN_2 cryostats allows high-T_c sensors to be placed closer to the object, further increasing the signal-to-noise ratio of the MEG measurements. Nevertheless, it is desirable to improve the magnetic field resolution of high-T_c sensors further without significant degradation of their spatial resolution and cross-talk of the sensors in multichannel systems. The magnetic field resolution of an inductively coupled magnetometer with a multiturn input coil can be estimated from the following expression:

$$B_N = \frac{L_{pu} + L_i}{kA_{pu}\sqrt{L_i L_S}} S_\Phi^{1/2} \quad , \qquad (1)$$

where A_{pu} and L_{pu} are the area and inductance of pickup loop of flux transformer, k is coupling coefficient between SQUID washer and input coil in the flux transformer and S_Φ is white flux noise of the SQUID. S_Φ is determined mainly by thermal fluctuations in the Josephson junctions, by the maximum voltage response to the magnetic flux $|\partial V/\partial\Phi|$ and by the noise of the preamplifier of the control electronics $S_{Ve} \approx (0.2\ \mathrm{nV})^2$:

$$S_\Phi = S_V / \left(\frac{\partial V}{\partial \Phi}\right)^2 \approx \left\{ \frac{12k_B T}{R_N}\left[\frac{R_N^2}{2} + \frac{L_S^2}{4}\left(\frac{\partial V}{\partial \Phi}\right)^2\right] + S_{Ve} \right\} / \left(\frac{\partial V}{\partial \Phi}\right)^2 \quad , \qquad (2)$$

where R_N is the normal state resistance of the Josephson junctions and k_B is the Boltzmann constant.

The white noise of the sensors may be reduced further, for example by the implementation of serial SQUID arrays, by a factor of √N where N is the number of SQUIDs in the array. For sufficiently large values of N, the magnetic field resolution of the high-T_c DC SQUID magnetometers, using sufficiently large input coils, can potentially reach values of below 1 fT/√Hz at 77.5 K. Our estimations from equations (1) and (2) suggest a field resolution 1 fT/√Hz at 77.5 K for a serial connection of two DC SQUIDs (N = 2), with a diameter of the pickup loop of the multilayer flux transformer of 30 mm, and with coupled inductances of the DC SQUID loops from about 40 pH up to about 80 pH (see Fig. 4).

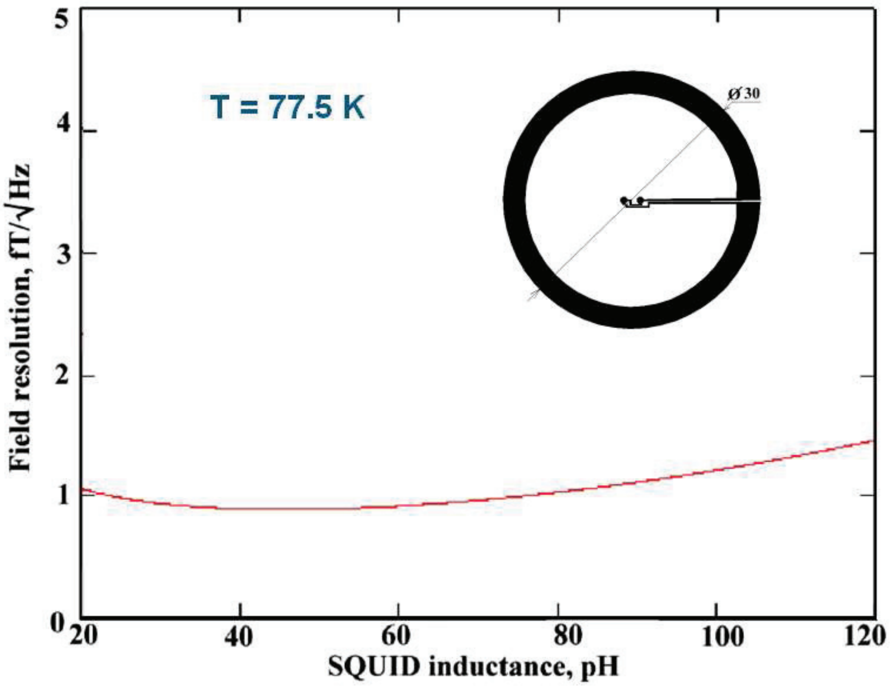

Fig. 4. Expected magnetic field resolution $B_N(L_S)$ of a high-T_c DC SQUID magnetometer consisting of a dual-SQUID inductively coupled to a 30-mm superconducting flux transformer (see insert) having two multiturn input coils.

The serial connection of two DC SQUIDs in a dual-SQUID geometry is the first step in the application of high-T_c DC SQUID arrays [12]. By testing a dual-SQUID circuit separately, we have observed a doubling of SQUID voltage swings and a reduction in noise, when compared with a single SQUID sensor used with a similar SQUID washer and similar parameters of the Josephson junctions. Two washers in the dual-SQUID system can be inductively coupled to two multiturn input coils of the large area multilayer flux transformer (see insert to Fig. 4), providing improved sensitivity of the sensor to the magnetic field to be measured [8]. We expect that the application of a modulation signal to the directly coupled loop of the dual-SQUID magnetometer will result in lower noise in the sensor and less cross-talk between the sensors, when compared to the application of the modulation signal to the pick-up coil of a multilayer flux transformer. Further experiments with multichannel high-T_c MEG systems are required to determine whether sufficiently low cross-talk between the sensors can be realized for the case of relatively large pickup loops of high-T_c DC SQUID sensors.

Acknowledgements

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