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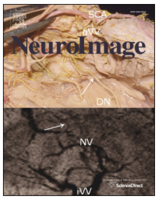

Multi-channel atomic magnetometer for magnetoencephalography: A configuration study

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ABSTRACT

Atomic magnetometers are emerging as an alternative to SQUID magnetometers for detection of biological magnetic fields. They have been used to measure both the magnetocardiography (MCG) and magnetoencephalography (MEG) signals. One of the virtues of the atomic magnetometers is their ability to operate as a multi-channel detector while using many common elements. Here we study two configurations of such a multi-channel atomic magnetometer optimized for MEG detection. We describe measurements of auditory evoked fields (AEF) from a human brain as well as localization of dipolar phantoms and auditory evoked fields. A clear N100m peak in AEF was observed with a signal-to-noise ratio of higher than 10 after averaging of 250 stimuli. Currently the intrinsic magnetic noise level is 4 $\mathrm{fTHz}^{-1/2}$ at 10 Hz. We compare the performance of the two systems in regards to current source localization and discuss future development of atomic MEG systems.

Introduction

One of the most successful applications of the superconducting quantum interference device (SQUID) is in the field of biomagnetism. Especially, high sensitivity of a low-Tc SQUID magnetometer enabled the measurement of neuromagnetic fields from a human brain and opened the field of magnetoencephalography (MEG) (Cohen, 1972). Since the SQUID MEG system was developed, numerous successful investigations in various fields have been conducted with MEG. At present, MEG is one of the most useful modalities for studies of brain functions together with the functional magnetic resonance imaging (fMRI) and positron emission tomography (PET). Specifically, due to its high temporal resolution, MEG has a unique position in the field of the cognitive science (Kwon et al., 2005; Tarkiainen et al., 2003). Although MEG is a powerful tool for functional brain imaging in both basic brain research (Darvas et al., 2003; Kakigi et al., 1995) and clinical diagnoses (Cheyne et al., 2007; Colon et al., 2009), existing SQUID systems have a number of technical limitations that hinder more widespread use of this technique. Among them are a high rate of liquid helium consumption, fixed sensor configuration, frequent requirement for cryogenic maintenance, high cost and the need for large shielded rooms.

Atomic magnetometer (AM) which optically detects polarization change of alkali metal vapor under external magnetic field is emerging as a promising alternative to existing MEG sensors. The sensitivity of a spin-exchange relaxation free (SERF) magnetometer is sufficient for measuring an MEG signal (Kominis et al., 2003). In addition to the absence of cryogenics, atomic magnetometers can operate in a multi-channel configuration at a relatively low cost by utilizing many common detector elements. They can also operate with a smaller magnetic shield since there is no need to place a bulky liquid helium dewar inside the shielded room. However, the geometrical constraints and other technical features of the AM system are substantially different from SQUID systems and require careful consideration for maximum utilization of the available sensitivity and for being practically useful in routine MEG studies.

The aim of this research is to show the ability of potassium AM as a detector of weak evoked brain signals. In this study, we compare specific features of two multi-channel AM MEG configurations and introduce AM specific data analysis methods such as localization of effective sensor positions by application of gradients, noise reduction technique for mode hopping elimination (MHE), and response time correction. The first system uses a transmitted probe beam, similar to the arrangement reported in Xia et al. (2006). In the second system we use a retro-reflected probe beam and several new technical features. We show measurements of auditory evoked fields (AEF) with both AM systems and demonstrate the source localization with dipolar phantoms and AEF signals.

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In addition to our approach using a single alkali-metal cell for multichannel recording, it is also possible to use an array of individual fiber-coupled atomic sensors. Fiber-coupled sensors with small alkali-metal cells have reached sensitivity below $10 \mathrm{fT/Hz}^{1/2}$ (Shah and Romalis, 2009) and have been used for recording of magnetoencephalography signals (Johnson et al., 2010, 2013; Sander et al., 2012).

Material and methods

Transmitted probe atomic MEG system

Generals

The detailed description of this setup was reported previously (Xia et al., 2006). By absorbing circularly polarized pumping photons, potassium atoms in a glass cell are spin-polarized, creating local magnetization. The magnetization is rotated in the presence of an external magnetic field. The tipped component of magnetization rotates the polarization of linearly polarized probe light. We optically measure the distribution of B_y field components in the y–z plane by using a 16 × 16-channel photodetector array, with geometry shown in Fig. 1(a).

In comparison to SQUID systems, where the sensor positions are fixed at design state, the AM system has more flexibility. In our case the head of a subject is placed on top of the cell, as shown in Fig. 2. This feature is advantageous, for example, for baby MEG detection (Okada et al., 2006). An inherent restriction in the optical signal detection is the fact that we lose the position information along the probe beam direction; i.e. what we measure is the integral of all the magnetic fields along the probe beam path. However, to localize a neuroelectric source, we need to also get the spatial field distribution along the x axis. This can be achieved by slicing the pumping beam in multiple sections and illuminating only part of the cell at any given time (Gusarov et al., 2009). Such time division measurement is possible for repetitive measurements, such as evoked fields. In the detection of the spontaneous brain wave or epileptic spikes, one can also use magnetic field modulation techniques to measure different components of the field (Li, 2006; Seltzer and Romalis, 2004).

In our configuration, the sensor arrangement also provides a depth profile of the magnetic field (Fig. 1(c)), which can help with magnetic source multipole analysis. The depth profile measures the decrease of the magnetic field as a function of distance from the source to a sensing location. The decay of the magnetic fields depends on the order of the current multipole, hence one can analyze the source current structure, particularly for the case of multiple sources. For a SQUID sensor system, such layered configuration of pickup coils is undesirable due to the superconductive screening currents on the lower coils. Even with adoption of an external feedback SQUID scheme, distortion of the fields in the gradiometric pick-up coil configuration is unavoidable. In contrast, high buffer gas pressure in the vapor cell of the atomic

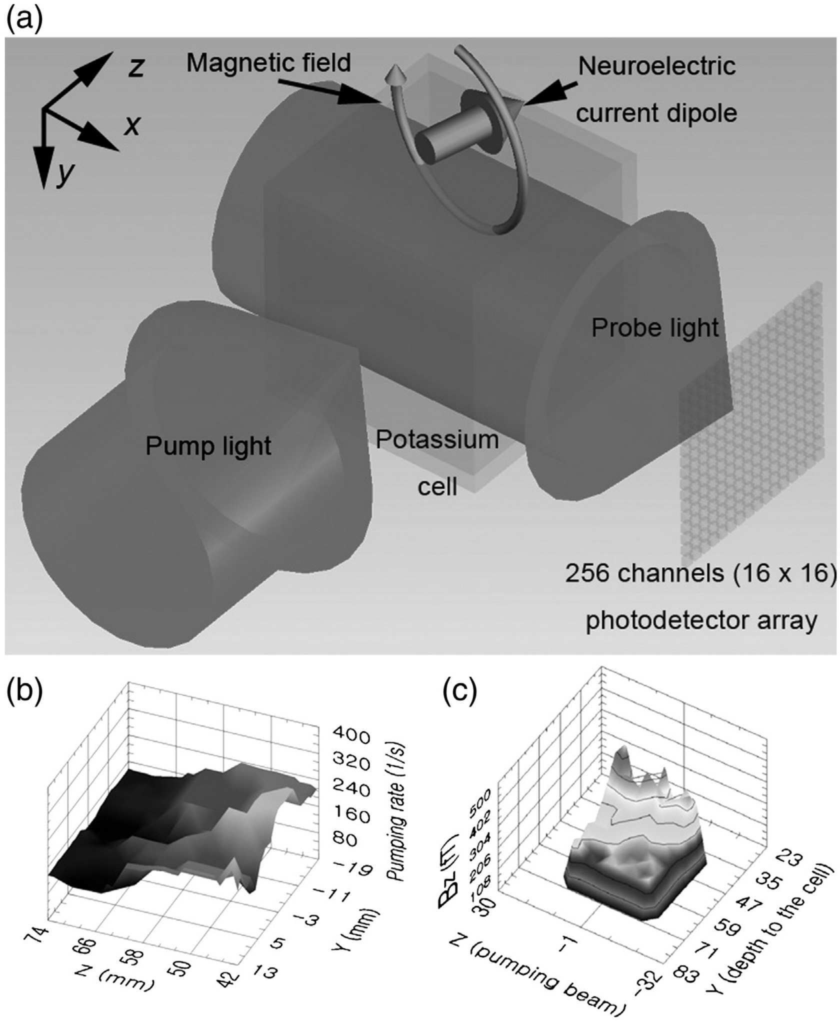

Fig. 1. Multichannel magnetic field mapping with an atomic magnetometer; the expanded probe laser beam detects the spatial distribution of B_y components on the y–z plane with a 256-channel detector array. (b) Spatial distribution of pumping rate in the vapor cell, which makes a different sensor characteristic for each sensor. (c) Map of the magnetic field map of the AEF signal measured with the magnetometer.