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Towards an MPI-MRI-MEG fused neuroimaging system: Acquisition of MR images at 300 kHz with a newly developed compact OPM

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Abstract

Optically pumped magnetometer (OPM) is a promising magnetic sensor alternative to SQUID that enables the measurement of very small magnetic signals. In addition, OPMs have the intrinsic advantage of not requiring cryogenic cooling. We have been developing a compact and portable OPM module with a pump-probe arrangement. Since sensitivity of OPM does not depend on frequency, it is suitable to be used as a receiving sensor for magnetic particle imaging (MPI) and ultra-low-field (ULF) MRI systems. In a previous study, we demonstrated the possibility of remotely detecting magnetic fields generated from super-paramagnetic iron oxide nanoparticles using an OPM with a flux transformer. Here, we introduce our newly developed miniaturized OPM module having its noise floor less than 20 $fT/Hz^{1/2}$ as well as the first magnetic shieldless OPM-based ULF-MRI scanner with an OPM operating at a Larmor frequency of 300 kHz.

I. Introduction

Optically pumped magnetometer (OPM) is a sensor based on electron-spin polarization of alkali-metal atoms [1, 2, 3]. Over the past two decades, it was demonstrated that OPMs operating under spin-exchange relaxation-free (SERF) condition as well as high-density SERF-like condition have reached sensitivities comparable to and even surpassing those (less than several $fT/Hz^{1/2}$) of superconducting quantum interference devices (SQUIDs). OPMs have the intrinsic advantage of not requiring cryogenic cooling and expected to overtake SQUIDs, and the possibilities for magnetoencephalogram (MEG) measurements and MRI have been demonstrated.

Towards advancements in neuroscience and improvement of clinical diagnosis of neuropsychiatric disorders, we have been developing the SERF and high-density SERF-like OPMs with pump-probe arrangement as joint research projects with several Japanese companies since 2006. Since sensitivity of OPMs does not depend on frequency, OPMs are suitable to be used as receiving sensors for not only MEG but also MPI and MRI systems. In 2017, we succeeded to reconstruct the first MR images obtained at a Larmor frequency of 5 kHz by using a prototype of ULF-MRI with a pump-probe-type OPM [4]. Here, the Larmor frequencies of proton and alkali-metal atoms used in OPM are different under the same static magnetic (B0) fields. To address this issue, we used a flux transformer (FT) to detect NMR signals remotely.

Magnetic particle imaging (MPI) can determine high-speed hemodynamic imaging employed as a new method to measure biological functions. In MPI, an induction coil detects magnetic signals generated via the magnetization of magnetic nanoparticles (MNPs), characterized by nonlinear magnetization. This results in high-speed and high spatial resolution imaging. However, considering the specific absorption rate and time-varying magnetic field (dB/dt), which are limited to minimize risks in human health, magnetic signals should be measured in a low-frequency range to obtain in vivo MPI measurements. OPMs used as a detector instead of an induction coil are expected to be capable of operating MPI scanners at a relatively low excitation or driving frequency because of their tunable sensitive frequency. This is an important advantage in fabricating clinical human-sized MPI scanners.

In a previous study [1], we demonstrated the possibility of remotely detecting magnetic fields 2 to 20 kHz generated from super-paramagnetic iron oxide nanoparticles (SPIONs) using the same OPM module used for the ULF-MRI, indicating that OPM is a promising sensor for MPI. Here, we introduce our newly developed pump-probe-type compact OPM module and the first OPM-based ULF-MRI scanner operated at 7.05 mT [5] towards an MPI-MRI-MEG fused innovative neuroimaging system.

II. Material and methods

II.I. Principles of pump-prove-type OPM

In the pump-probe-type OPM with alkali-metal atoms, a circularly polarized pump beam and a linearly polarized probe beam crossed orthogonally in the center of the glass cell including vaporized atoms such as K and Rb [1, 5]. The wavelength of a pump beam was tuned to D1 line of atoms. Electron spins of alkali-metal atoms were polarized by the pump beam along its direction.

In the presence of magnetic field $\boldsymbol{B}$, electron spins evolved and the magnetic field component along the probe beam rotated a linearly polarized plane of the probe beam. Since the rotation angle is proportional to the component of spin polarization along the probe beam, the strength of magnetic field can be measured. The evolution of the electron spin polarization $\boldsymbol{S}$ can be represented using the following Bloch equation.

$$\frac{d}{dt}\mathbf{S} = \gamma\mathbf{S}\times\mathbf{B} - \frac{1}{T_2}\mathbf{S} + \frac{1}{2q}\mathbf{R}_{\mathrm{OP}}$$

where γ is the gyromagnetic ratio, T_2 is the transverse spin relaxation time, q is the slowing-down factor, and $\boldsymbol{R}_{OP}$ is the pumping rate [5].

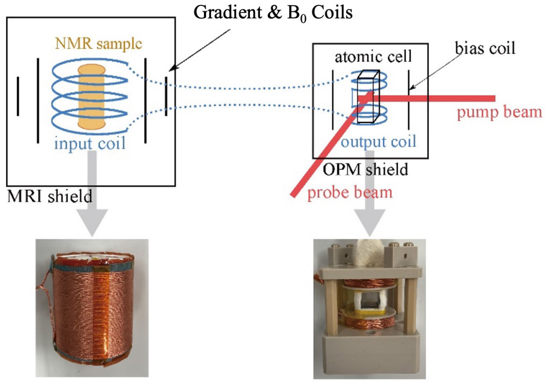

Figure 1: Hardware configuration of an ULF-MRI scanner [6]. On the MRI side, there is a phantom, the flux transformer (FT) input coil, and the static and gradient field coils; on the OPM side, there is the FT output coil and the static field coil.

II.II. Experimental setup of MRI acquisition

Our ULF-MRI system is comprised of a B0 coil, gradient coils for each of the three axes, an RF coil, an FT + OPM system, and a gradient amplifier. Our ULF-MRI apparatus is schematically illustrated in Fig. 1 [6]. While the B0 coil generates 7.05 mT (Larmor frequency: 300 kHz), the gradient coils generate a gradient magnetic field in order to encode positional information into the NMR signals and also compensate for the measurement field's nonuniformity. The RF coil produces an oscillating magnetic field that excites the magnetization.

III. Results and discussion

We reported our first compact pump-probe-type OPM module in 2012. Subsequently, we continue miniaturizing the module. Figure 2 shows our latest compact OPM module (2 x 2 x 6 cm) developed together with Hamamatsu Photonics K.K [7]. In a magnetically shielded environment, it was confirmed that the noise floor was less than 20 $fT_{rms}/Hz^{1/2}$. The pump-probe-type OPM has a wide bandwidth of several hundred Hz and is characterized by enabling to measure magnetic field not only in low frequency range necessary for MEG but also in high frequency range for MPI and ULF-MRI scanners by just changing bias DC magnetic field along the pump beam.

We developed an ultra-low-field (ULF) MRI scanner with an OPM operating at a Larmor frequency of 300 kHz and demonstrate its feasibility. 3D imaging of a phantom (Fig. 3) containing structures of the letters "K" and "H" was achieved with a resolution of 3 × 3 × 3 mm^3 after correcting frequency characteristics of the OPM to compensate its narrow frequency band [6]. By optimizing the input/output coils and resonant circuit of

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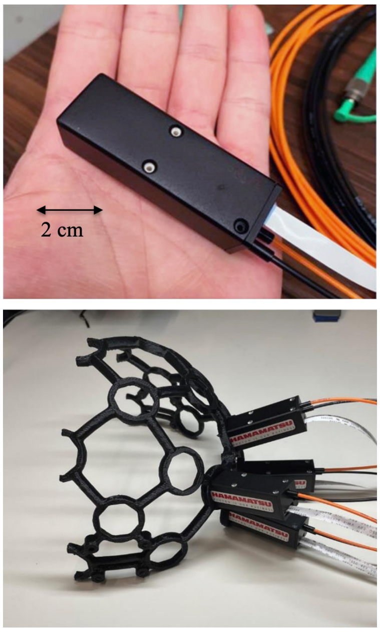

Figure 2: A newly developed compact pump-probe-type OPM module (upper) and a headcast with OPM modules for MEG measurements (lower) [7].

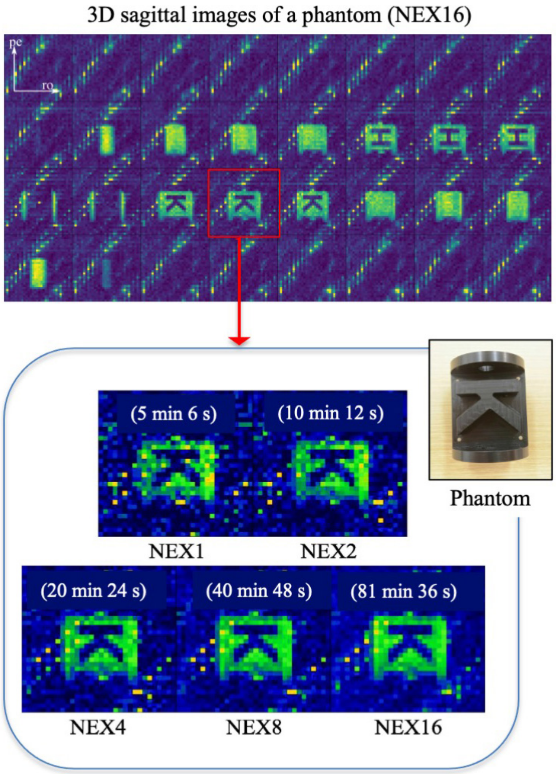

Figure 3: 3D sagittal MR images of a phantom taken at a Larmor frequency of 300 kHz [6]. The slice thickness was 3mm. The scan time shown at the top in each image was changes according to NEX (number of excitations).

the FT, we plan to make static magnetic field B0 further smaller in a future study.

In our previous study, we reported the possibility to detect neural magnetic field dependent (NMFD) changes in NMR signals as a new fMRI principle toward direct measurements of neural activities and functional connectivity as well [8]. The principle of the NMFD-fMRI might be applicable not only conventional MRI scanners but also the OPM-based ULF-MRI scanner, so that functional measurements with the OPM-based MRI scanner is an important future direction.

Meanwhile, MPI makes it possible to quickly and accurately measurements of human brain functions based on local hemodynamic responses associated with cortical neural activities, and is expected to be used to measure the brain function of individual patients in clinical settings. As described in the section I, sensitivity of OPMs does not depend on frequency, so that OPM module enables to acquire MPI signals at a relatively low excitation or driving frequency. This is an important benefit to fabricate a human-sized MPI system.

However, like MEG, which uses multiple OPMs scatted on the scalp to estimate the signal source from the neuromagnetic field, MPI also requires superimposition with brain morphology information from MRI to identify the brain activity region. Therefore, MEG, MRI, and MPI measurements in a single, affordable, and compact system using OPM as a common sensor can be expected to be a major step forward, at least in neuroimaging.

To create an MPI-MRI-MEG fused neuroimaging system, we plan to measure MEG signals directly by placing dozens to more than 100 OPMs in an array on the scalp without FT, while NMR and MPI signals are measured remotely. In the remote measurements, multiple OPMs are used separately for NMR and MPI signal detections. Input coils of FTs are placed in the vicinity of the scalp, and OPMs for MRI are tuned to the magnetic resonance frequency. On the other hand, OPMs for MPI are tuned to each harmonic frequency.

To overcome narrow bandwidth of OPM+FT, we performed MRI signal correction based on calibration of the frequency characteristics of OPM+FT [6]. In the calibration, sinusoidal magnetic fields were applied to FT input coil in 250 Hz increments from 290 kHz to 310 kHz, and the response was measured by OPM+FT. From the obtained fitting curve for the frequency responses, a correction factor was calculated. The gain within the bandwidth required for NMR signal measurement could be constant based on the correction factor, and the NMR signal was also corrected by applying the factor to the frequency domain of the NMR signal. We think the same calibration technique is useful when a single OPM treats higher harmonics of MPI signal.

In addition, we previously reported a method for directly detecting NMR signals in ULF-MRI using an OPM without FT [9]. In the direct detection, an actively

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shielded bias field tuning coil is used to locally weaken the magnetic field applied to an OPM module while maintaining the uniformity of the magnetic field near a sample. Thus, it is also expected that a more compact MPI-MRI-MEG fused system will be realized based on the direct detection of not only NMR signals but also MPI signals.

IV. Conclusions

We introduced a novel miniaturized pomp-probe-type OPM module and a prototype of OPM-based ULF-MRI scanner operated at 300 kHz without using a magnetic shielding chamber. In future work, we would like to use the same OPM module to detect magnetic fields generated from SPIONs and demonstrate the feasibility of measuring human brain function by means of MPI. We believe that an affordable OPM-based MRI-MPI-MEG fused neuroimaging system might provide important advancements in basic science and improve the clinical diagnosis and management of a variety of disorders.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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