A new optical magnetometer for MCG measurements in a low-cost shielding room

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Abstract. In the past years we were able to show that room temperature optical magnetometers based on magnetic resonance in atomic vapors can be used to measure magnetocardiographic (MCG) signals of healthy adults. The objective of our ongoing work is to demonstrate that multichannel arrangements of affordable and maintenance-free optical magnetometers can be operated in clinical settings. On the way to that goal we studied a new optical magnetometry scheme using linearly polarized light. We also investigated the possibility to operate such magnetometers in inexpensive magnetic shielding rooms based on aluminum.

Keywords: Magnetocardiography; MCG; Optical magnetometer; OPM; Magnetic resonance; Magnetically shielded room; Gradiometer

1. Introduction

Optical magnetometers are an interesting alternative to superconducting quantum interference devices (SQUIDs) for biomagnetic measurements since they eliminate the need for cryogenic cooling. The basic principle of such magnetometers which use light to create a macroscopic spin polarization (optical pumping magnetometer, OPM) is known since the 1960s [1] and has received increased attention in the past years. Our group in Fribourg could demonstrate cardiomagnetic measurements (MCG) with OPMs [2–5] while other groups have developed an optical magnetometer for the measurement of magnetic fields [6,7] from the brain. In our work we concentrate on MCG in which the relatively strong cardiac signals allow for a wider choice of optical magnetometer technologies. We chose the optically detected

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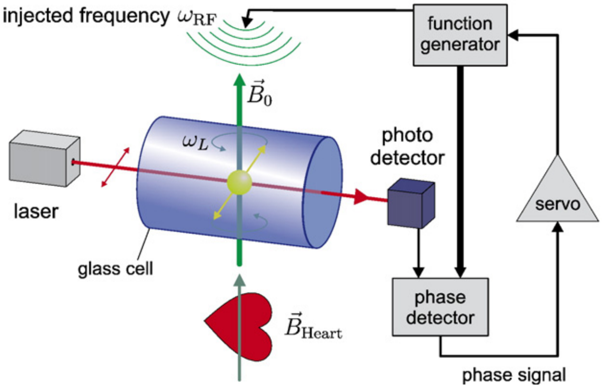

Fig. 1. Sketch of the operation principle of DRAM magnetometers. Linearly polarized light generated by the laser transmitted through a glass cell containing an atomic vapor (Cs). The frequency of the light is resonant with the first absorption line of Cs. The light optically pumps the atoms thereby creating a spin alignment in the atomic medium. This alignment processes in the static magnetic field B_0 with a frequency proportional to the modulus of B_0 (Larmor frequency, $\omega_{\mathrm{L}}=\gamma|B_0|$). This precession is coherently driven by an oscillating magnetic field (frequency ω_{RF}), which leads to a modulation of the medium's index of absorption. The detector measures this modulation by monitoring the transmitted intensity. The phase difference between the detector signal and the oscillating magnetic field is measured by a phase detector. A specific value of the phase signal is achieved under the magnetic resonance condition ($\omega_{\mathrm{RF}} = \omega_{\mathrm{L}}$). A servo loop maintains this condition by controlling the function generator that supplies ω_{RF}.

magnetic resonance scheme, since the individual modules are affordable, operate at room temperature, and do not need strong shielding from ambient magnetic fields.

2. Methods

Magnetometers that use optically detected magnetic resonance can be realized in many different ways. We have developed a novel kind of such magnetometers based on atomic alignment [8,9] produced by linearly polarized light (double resonance alignment magnetometer, DRAM). In comparison to classical OPMs that use circularly polarized light, the DRAM technique (see Fig. 1) can be implemented in smaller sensor modules. Those modules currently have dimensions of 40 mm × 26 mm × 60 mm and can be mounted

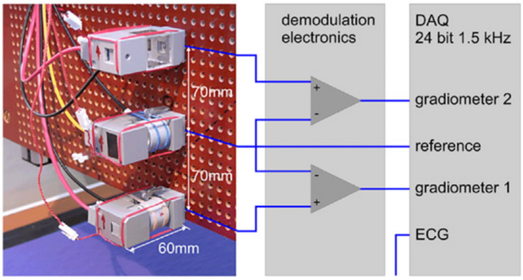

Fig. 2. Photograph of the sensor module arrangement in the new setup. Three modules are configured as two axial gradiometers. The data acquisition records both gradiometer signals, the magnetometer signal of the central sensor and the ECG. A second-order gradiometer signal can be calculated by software.

on a nonmagnetic board at arbitrary locations. The spatial range in which the sensors can be mounted is only limited by the homogeneity of the offset magnetic field B_0. In order to study larger (30×30 cm^2) multichannel arrangements of such sensor modules, we carefully designed large coils to compensate offset fields when we installed a new lab two years ago. The main coils for the vertical field component are a Helmholtz-like configuration of two quadratic coils with a size of $4.5 \times 4.5 \times 2.5$ m^3.

After some experiments in the unshielded environment, a magnetic shielding room was mounted inside of the large coil configuration in order to reduce the ambient 50 Hz line frequency interference. With an affordable system in mind, we opted for a two layer aluminum shield that was specially designed by IMEDCO [10]. This configuration is advantageous since the shield can reduce AC magnetic field interference generated from electrical appliances and from parasitic fields generated by the offset field coils.

3. Results

In the unshielded environment the sensors could not be operated at their maximum magnetometric sensitivity. This is mostly due to 50 Hz line interference which is so large that the sensor is constantly driven in and out of the magnetic field region where its sensitivity is best. Nevertheless, we succeeded in measuring a human heartbeat under those conditions. Since the optical gradiometer was difficult to balance and since we could not realize the full potential of the magnetometers in the unshielded environment, a collaboration with IMEDCO was initiated to determine the minimal necessary shielding to operate the optical magnetometers at their optimal performance.

Relatively simple and inexpensive aluminum shielding was used to reduce the line interference by a factor of 50–100. Under these conditions the DRAM magnetometers operate essentially in the same way as in a perfectly shielded environment. First experiments prove that the sensor modules can record magnetocardiographic data without averaging. However, averaging of typically 100 heartbeats is used to further reduce remaining noise in the lightly-shielded environment. In the pilot measurements presented here, the sensitivity of the first-order gradiometers was about 1 pT/Hz$^{1/2}$. The sensitivity is currently being optimized with the goal to reach the formerly reported [5] intrinsic sensitivity of 70 fT/Hz$^{1/2}$ in the new aluminum shield.

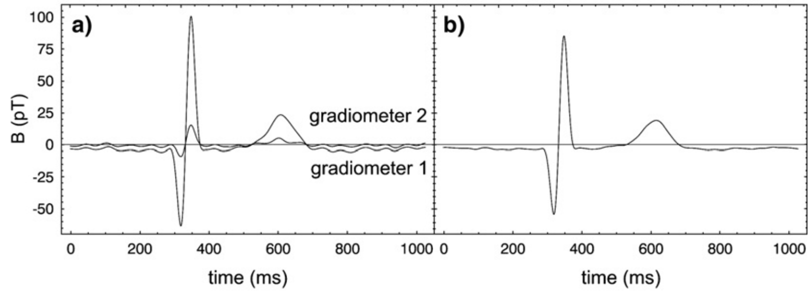

Fig. 3. a) Averaged heart beats measured with the two first-order gradiometers. Using the ECG as trigger, 110 pulses were averaged after applying a low pass filter (cutoff at 45 Hz) to the raw data. b) second-order gradiometer signal calculated from the two curves in a).

In these experiments, three sensor modules were mounted in a second-order axial gradiometer configuration with a base length of two times 70 mm (see Fig. 2). The demodulation electronics provides two first-order gradiometer signals that are, together with magnetometer data from the middle sensor and ECG data, recorded by the data acquisition system. The calculation of the second-order gradiometer data as well as low pass filtering and EGG-synchronized averaging is done by dedicated software. Fig. 3 shows averaged MCG pulses recorded with the two first-order gradiometers and the resulting second-order gradiometer data. The oscillating background, strongly suppressed by the second-order gradiometer, is a 16 2/3 Hz interference from a nearby railway line.

Currently, we study the feasibility of multichannel scaling of the described magnetometer technique which relies on more sophisticated demodulation electronics in order to exclude mutual influences of the sensors.

4. Conclusion

The DRAM technique is a very promising new approach for realizing cost-efficient multichannel optical magnetometer systems. In order to realize its full magnetometric resolution, the variation of background fields needs to be reduced to about <3 $\mathrm{nT_{pp}}$ which is possible with inexpensive aluminum shielding. We are confident that the combination of DRAM magnetometers with low-cost aluminum shielding rooms will pave the way for the use of optical heart magnetometry in clinical environments.

Acknowledgements

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