4. Summary and outlook

We report on MEG measurements of healthy human subjects with a fiber-coupled chip-scale atomic magnetometer. Spontaneous and somatosensory-evoked brain fields were measured and validated with SQUID measurements. While the noise of the optical magnetometer was higher than that of the SQUID, this was partly compensated for by an increased amplitude of the physiologic signal of interest. This benefit was made possible by the small size of the CSAM and the easy handling of the devices, which enables the attachment of the sensors close to the surface of the skull, almost like conventional EEG electrodes.

The sensitivity of the CSAM sensor is currently limited by the photon-shot noise in the detected light. Since the beam diameter covers only 20% of the vapor cell area, and the detection efficiency is only 30%, the sensitivity of the CSAMs could be improved by an order of magnitude when more light is detected. More detailed numerical calculations suggest that sensitivities around 3 $fT/Hz^{1/2}$ should be achievable with the current method [29]. Higher sensitivities can be reached with larger cell sizes, but since the noise floor in most commercially-available shielded rooms is of similar sensitivity, cell sized around $(2\ mm)^3$ seem reasonable. We furthermore plan to optically heat the CSAMs, which would eliminate the fields generated at 30 kHz and allow for simultaneous measurements with SQUIDs and CSAMs [30].

While these measurements presented here can give us some ideas about the capabilities of CSAMs as inexpensive, uncooled sensors for biomedical applications, the next step would be the design of a multi-channel system to be able to localize sources and to suppress noise signals using multivariate statistics such as principal component analysis (PCA) and independent component analysis (ICA). The spatial sampling needed for brain magnetic fields was analyzed for SQUID-based sensor arrays in [31]. Those results might need minor adjustments due to the smaller distance between brain source and CSAM compared to the brain to SQUID array geometry. Newer results [32] estimating the necessary number of sensors from the degrees of freedom of brain magnetic fields indicate that 100 sensors are the absolute minimum. Therefore, the optimal number of channels in a CSAM system is not obvious at present and will be investigated in the future. Further CSAM system design improvements might include closed-loop configuration to extend the dynamic range needed for less-well shielded environments, the demonstration of gradiometers, and full vector-field measurements. These might allow at some point a fully geometrically flexible and lightweight MEG system, although the reality of this is still a long way ahead. Many small developments are needed, e.g., the projection vectors for the subtraction of background noise cannot be easily computed for a flexible geometry.

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