High sensitivity laser pumped Caesium magnetic sensor for magnetoencephalography

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Optically pumped quantum magnetic sensors provide the most sensitive up-to-date measurement of the magnetic field absolute value [1]. They are operating at room temperature and have a prominent perspective in a wide range of applications. After the pionering works by Dehmelt, and Bloom [2, 3] the electrodeless discharge lamps were used as a routine source for optical pumpinng. The last two decades made a change: diode lasers became available for pumping with unique combination of high power, narrow spectral line and flexibility of frequency control. High power provides a possibility to pump much more atoms, in comparison with lamp pumping, *i.e.* providing higher signal-to-noise ratio at the cost of accuracy. In many applications, sensitivity is more important than accuracy (long-term-stability). The medical applications, as magnetocardiography (MCG) [4] and magnetoencephalography (MEG) are such the case. These applications are traditionally the realm of superconductive quantum interferometer devices [SQUID]. Optically pumped magnetometers (OPMs) are supposed to be an alternative to SQUIDs [5–7].

Quantum sensor sensitivity depends on signal magnitude, its linewidth and principal noise. The magnetic resonance magnitude could be simply increased by total number of atoms, either the sensitive volume [5], or atomic density [7]. For small size sensors, the only choice is in increasing the density, *i.e.* vapour pressure related to the operating temperature. This solution has an apparent drawback, because the linewidth is also increased with density too, due to spin-exchange. The only exception is a magnetic sensor operating in a mode free of spin exchange (SERF mode) [8, 9], realizing high density Hanle magnetometer operating at near zero magnetic field. But such extreme conditions of homogeneous magnetic "vacuum" requires rather bulky and expensive magnetic shields or even magnetically shielded rooms, not suited for most of medical applications. Our goal is in developing a prototype of small compact and sensitive quantum sensor operating at Earth magnetic field range. Our approach utilizes the line-narrowing effect in highly polarized media firstly observed by W.Happer [10] and investigated, *e.g.* in [11].

The development of compact sensor suited for detection of magnetic field induced by brain neural activity is the field of active interest [12–14], it is a real challenge for technical physics and technology. The general trend of the technology is in development of compact sensors with reasonable loss of sensitivity, Chip-Scale Atomic Devices are the prominent examples. The magnetic sensor compactness opens a new fields of device applications. Such sensor could be placed more close to the magnetic field source, having gain in magnetometer response, since magnetic field is rapidly diminishes with distance; moreover small size means better spatial resolution in magnetic mapping task. The sensitive volume as small as 0.8 mm^3 was demonstrated [12] at the cost of reduced performance. Other important sensor features are sensitivity, dynamic range and immunity to interference and noise. Note, that the MCG/MEG magnetic signal is mostly located in a spectrum range from one to hundred Hz, so sensitivity is measured in this range.

We have developed a prototype of magnetic sensor with a volume of a part of cubic centimeter and measured its intrinsic sensitivity. The cubic cell with size of several mm was made of glass and filled with droplet of Caesium and buffer gas. The test of sensor sensitivity was performed in magnetic shield at Ioffe Institute Atomic Radio-spectroscopy Lab. Two identical cells were placed in a common thermostat heated to a temperature of about 90^{0}C. The cells were illuminated by circularly polarized light of pumping laser tuned to the one of Caesium D1-line hyperfine transition. The magnetic resonance was induced by AC-resonance field and probed by linearly polarized light of the second (probe) laser, tuned off the resonance. The optical power of the lasers, as well as their frequencies detuning, operating cell temperature, resonance driving AC-field magnitude, *etc.* were optimized to gain the best sensor sensitivity. The pumping light power was high enough to provide light narrowing effect [10,11], making extra gain in sensor sensitivity. The magnetic field is stabilized either by external Rb-vapour magnetometer, placed close to the sensors, or by one of the sensors itself.

Fig.1a presents an example of in-phase and quadrature signals of the magnetic resonance, recorded by lock-in-amplifier with two cells constituting a gradiometer. Note, that both signals are almost completely coincide due to neatly balanced pumping and detection. With resonance linewidth and signal-to-noise ratio it is possible to estimate the principal sensitivity. We choose other, direct way of sensitivity measurement by applying a calibrating magnetic field and recording magnetometer response with lock-in-amplifier, as shown in Fig.1b.

Dark-noise and detecting light noise spectrum is shown in Fig.1c was recorded with the same set-up. Dark noise is well below detecting light noise. The noise spectra, were measured without applying resonance AC-field. It is worth to note, that magnetic gradient noise, not shown here, is typically is 10–30 times higher than principal sensor noise. Two beam pump-probe scheme allows us to reduce probe laser noise, due to balanced probe detection. The common magnetic field fluctuations were partly suppressed due to short base of gradiometer constituted of two sensors. The pumping light fluctuations were partly compensated by thoroughly balanced sensors pumping light level.

As a result we have demonstrated the possibility of achieving the sensitivity typical for the SERF device in a compact sensor with senivive volume less than half of cubic cm in a bias magnetic field of order 10 μT. The sensor size and its principal sensitivity opens the way to detect cortex brain activity in close proximity to the scalp, as supposed.

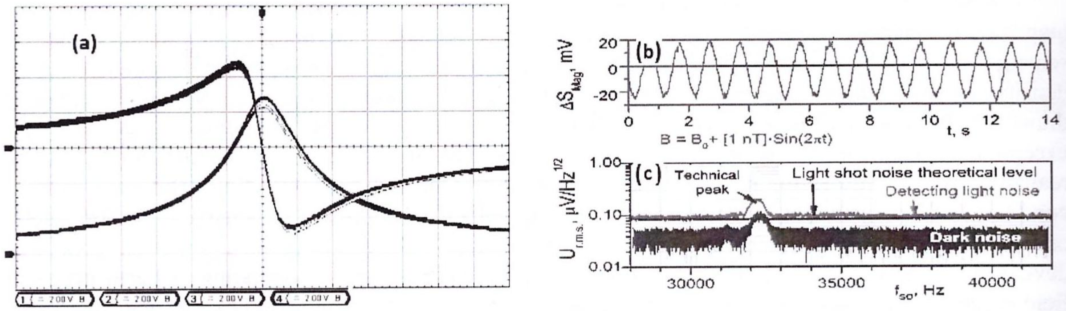

Fig. 1 Left: the measured magnetic resonance signals: vertical scale 2V/div, horizontal scale 500Hz/div. Right, a) magnetric sensor response to the 1 Hz-modulated magnetic field with amplitude 1000 pT applied to one sensor; b) spectra of dark noise and detecting light shot-noise. Resonance AC-field is not applied.

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References

[1] M. V. Romalis et al., Nature, **422**, 596 (2003).
[2] A. Bloom, Applied Optics, **1**, 61 (1962).
[3] H. G. Dehmelt, Phys. Rev. **105**, 1924 (1957).
[4] A. Weis, et al., Sensors and Actuators A: Physical, **129**, 1 (2006).
[5] E. Aleksandrov et al., Tech.Phys. Letters, **12**, 749 (in russ.)(1987).
[6] A. Weis, G. Bison and Z. Grujić, Smart Sensors, Measurement and Instrumentation, **19**, 361 (2017).
[7] I. Savukov, Smart Sensors, Measurement and Instrumentation, **19**, 451 (2017).
[8] M. Romalis, at al., Phys. Rev. Lett. **89**, 130801 (2002).
[9] W. Happer, H.Tang, Phys. Rev. Lett. **31**, 273 (1973).
[10] N. D. Bhaskar, J. Camparo, W. Happer, et al., Rev. **23**, 3048 (1981).
[11] T. Scholtes et al., Phys. Rev. A, **84**, 043416 (2011).
[12] S. Knappe et al., Biomed. Opt. Express, **3**, 981 (2012).
[13] P. D. Schwindt, Opt. Express, **24**, 15403 (2016).
[1] [14] R. Jimenez-Martinez, S, Knappe, Measurement and Instrumentation, **19**, 523 (2017).