HIGH SENSITIVITY ATOMIC MAGNETOMETER AND METHODS FOR USING SAME

RELATED APPLICATION

This application claims the benefit of priority of provisional application U.S. Ser. No. 60/418,696, filed Oct. 16, 2002.

GOVERNMENT RIGHTS

The present invention was made with Government support and the Government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates to a highly sensitive magnetometer having the ability to detect very low magnetic field intensities, and to methods of measuring such low intensity magnetic fields. More particularly, the invention relates to atomic magnetometers that rely on polarizing alkali metal vapor, and probing the state of magnetization of the polarized metal atoms. The invention further relates to measuring characteristics of a magnetic field originating from a variety of sources, including organs of the human body.

BACKGROUND OF THE INVENTION

Over the past several decades ultra-sensitive magnetometers have found a wide range of applications, from condensed matter experiments (Tsuei, C. C. et al., *Phys. Rev. Lett.* 85, 182–185 (2000)) and gravitational wave detection (Harry, G. M. et al., *Appl. Phys. Lett.* 76, 1446–1448 (2000)), to detection of nuclear magnetic resonance (NMR) signals (Greenberg, Ya. S., *Rev. Mod. Phys.* 70, 175–222 (1998); McDermott, R. et al., *Science* 295, 2247–2249 (2002)), studies of paleomagnetism (Kirschvink, J. L. et al., *Science* 275, 1629–1633 (1997)), non-destructive testing (Tralshawala, N. et al., *Appl. Phys. Lett.* 71, 1573–1575 (1997)), and ordinance detection (Clem, T. R., *Nav. Eng. J* 110, 139–149 (1998)). For the last 30 years superconducting quantum interference devices (SQUIDs) operating at 4K have been unchallenged as ultra-high-sensitivity magnetic field detectors (*SQUID Sensors: Fundamentals, Fabrication and Applications*, Ed. Weinstock, H., Kluwer Academic (1996)) with a sensitivity reaching down to 1 fT/Hz^{12} (where fT designates femtotesla, or 10^{-15} tesla).

The most notable application of magnetic field sensors has emerged in the measurement of biomagnetism (Hämäläinen M. et al., *Rev. Mod. Phys.* 65, 413–497 (1993); Rodriguez, E. et al., *Nature* 397, 430–433 (1999)), i.e. the detection of the weak magnetic fields produced by the human brain, heart, and other organs. These instruments have enabled, among other applications, mapping of the magnetic fields produced by the brain and localization of the underlying electrical activity (magnetoencephalography, MEG). For example, measurements of the magnetic field produced by the brain have been used to diagnose epilepsy and to study neural responses to auditory and visual stimuli. Low temperature SQUID sensors (Zimmerman, J. E. et al., *J. Appl. Phys.* 41, 1572–1580 (1970); Drung, D. et al., *IEEE T. Appl. Supercon.* 11, 880–883 (2001); Oukhanski, N. et al., *Physica C* 368, 166–170 (2002)), which so far have dominated all of the aforementioned applications, have attained sensitivity levels of 0.9–1.4 $fT/Hz^{1/2}$ with a pick-up coil area on the order of 1 cm^2. Their noise in the low-frequency range of interest for biomagnetic studies (<100 Hz), however, is typically somewhat higher; indeed, commercial SQUID magnetometers typically (Del Gratta C, et al., *Rep. Prog. Phys.* 64, 1759–1814 (2001)) have noise levels of about 5 $fT/Hz^{1/2}$, partly due to magnetic noise generated by electrically-conductive radiation shielding of their liquid helium dewars (Nenonen, J. et al., *Rev. Sci. Instr.* 67, 2397–2405 (1996)).

Atomic magnetometers, an important alternative to SQUID instruments, are based on detection of Larmor spin precession of optically pumped atoms. Alkali metal magnetometers have approached similar levels of sensitivity when using large measurement volumes (Aleksandrov, E. B. et al., *Optics and Spectr.* 78, 292–298 (1995); Budker, D. et al., *Phys. Rev. A* 62, 043403 (2000)), but have much lower sensitivity in more compact designs suitable for magnetic imaging applications (Affolderbach, C. et al., *Appl Phys B* 75, 605–612 (2002)).

Spin exchange in alkali metal vapors has been discussed in Happer W. et al. (Phys. Rev. Lett. 31, 273 (1973) and in Happer W. et al. (Phys. Rev. A 16 1877 (1977)), which report experimental and theoretical aspects of observing magnetic resonance in high density alkali metal vapors in the presence of a buffer gas. U.S. Pat. No. 4,005,355 to Happer. et al. discloses a high-density alkali vapor optically pumped to produce a narrow magnetic resonance line with a frequency proportional to a magnetic field.

Bison et al. (a) (Appl. Phys. B. 76, 325 (2003) and Bison et al. (b) (Opt. Expr. 11, 908 (2003)) disclose an optically pumped cesium atom magnetometer for use in dynamic cardiac magnetic imaging. Observed magnetic noise levels in Bison et al. (b) appear to be on the order of 1000 $fT/Hz^{1/2}$.

Upschulte et al. (U.S. Pat. No. 6,472,869) discloses a diode laser-pumped alkali magnetometer. In Upschulte et al., response radiation includes photons that indicate one unit of angular momentum indicative of the torque due to the magnetic field, and a photodiode and scope that act as a means for measuring the response radiation. Upschulte et al. disclose a projected sensitivity of less than 6 $pT/Hz^{1/2}$ (pT=picotesla or 10^{-12} tesla).

In view of the disadvantages of relatively poor sensitivity, and drawbacks such as large bulk and use of cryogenic systems summarized above, there remains a need for a magnetometer that can operate in the absence of expensive liquid helium dewars needed to maintain superconducting conditions, and also to avoid the need for other liquefied gas dewars used with higher temperature superconducting devices. In addition there remains a need for the development of advantageous atomic magnetometers with high sensitivity. There further is a need for a compact magnetometer that is relatively inexpensive to assemble and operate. Additionally there is a need for carrying out biomagnetic measurements with high spatial resolution in order to observe localized areas within a living subject. The present invention addresses these and related unmet needs.

SUMMARY OF THE INVENTION

In a first aspect, the present invention provides a high sensitivity atomic magnetometer that includes

a) a sensing cell containing a mixture including an alkali metal vapor and a buffer gas, wherein the sensing cell is exposed to a background magnetic field lower than a first predetermined value;