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Gradiometer using NV center in spatially-isolated equal-quality diamond pair for highly sensitive quantum magnetometers

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Abstract

Magnetoencephalography (MEG) requires highly sensitive magnetic sensors and a gradiometer configuration which cancels a spatially homogeneous magnetic field such as environmental magnetic field noises. Nitrogen vacancy centers (NVCs) in diamond which can be operated at room-temperature are the most promising candidate for biomagnetic sensors. However, little work has been done on gradiometers using the NVC. In this study, we construct the gradiometer which uses a pair of diamonds containing the NVC and measure a small spatially in-homogeneous magnetic field under the deliberate spatially homogeneous magnetic field by the gradiometer.

1. Introduction

Magnetoencephalography (MEG) requires highly sensitive magnetic sensors such as superconducting quantum interference devices (SQUIDs) and alkali vapor cells. Because of stronger environmental magnetic field noises than biomagnetic fields, the magnetometers need a magnetically shielded room and a gradiometer configuration which is a common way to suppress magnetic noise. In a gradiometer configuration, spatially homogeneous magnetic field such as environmental magnetic field noises can be canceled by the differential signal at two detection positions. Generally, to improve the signal-to-noise ratio (SNR), the base length, that is the distance between the two detection points, should be longer than the distance between the measuring object and sensors.

Nitrogen-vacancy centers (NVCs) consisting of a nitrogen atom and a lattice vacancy in diamond have superior physical properties and preserve the quantum coherence even at room temperature under atmospheric pressure [1-2] and energy levels are sensitive to magnetic field. Therefore, a diamond quantum sensor is one of the most promising candidate for biomagnetic sensors. Towards the application of biomagnetic measuring such as MEG, several gradiometers using NVCs [3-4] have been reported. These gradiometers use two detection points in one diamond with a short base length in micrometer order. However, centimeter order base length is needed considering MEG applications because the distance between the measuring object and sensors is centimeter order.

In this study, we demonstrated a magnetic field detection by the gradiometer using NVCs in a pair of diamonds with centimeter order base length.

2. Gradiometer configuration

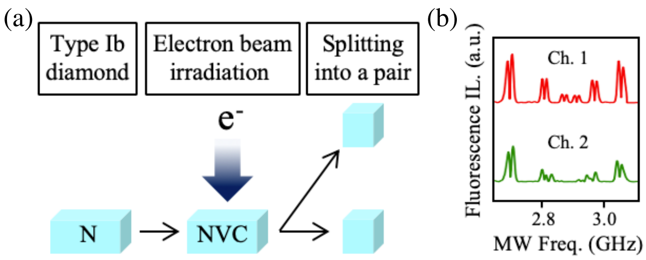

Fig. 1 (a) Fabrication process of the NVC in diamond using electron beam irradiation. (b) ODMR spectra of the spatially-isolated diamond samples of ch. 1 and ch. 2.

Our gradiometer uses the spatially-isolated equal-quality diamond pair. Figure 1 (a) shows the fabrication process of the diamond pair from the type Ib diamond which contains nitrogen concentration more than 10^{19} atoms/cm^3. To induce defects in the diamond, the type Ib diamond was exposed to electron beam irradiation of 10^{18} cm^{-2} with an energy of 2 MeV at 750℃ at a fluence rate of 1.113×10^{13} cm^{-2}/sec . Because the gradiometer configuration needs equal-quality properties, the exposed diamond split into two for two quantum diamond sensors. Optically detected magnetic resonance

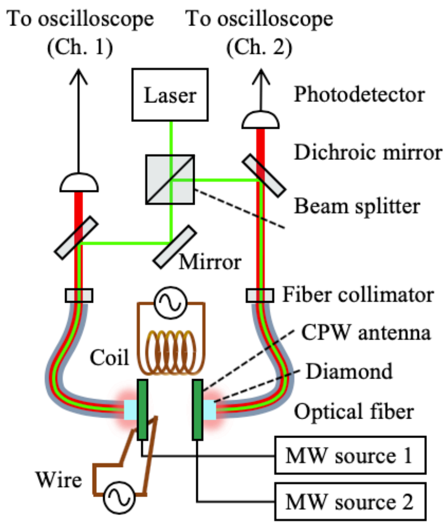

Fig. 2 A setup of the gradiometer using NVCs in a pair of diamonds.

(ODMR) spectra indicate that intensity level (IL) of fluorescence from diamonds changes responding to the magnetic field with the same ratio in two diamonds [Fig.1(b)].

Figure 2 shows a setup of the gradiometer using NVCs in a pair of diamonds. In each sensor, each diamond sample attached to an optical fiber is mounted on a coplanar-waveguide (CPW) antenna [5]. The base length is set to 2.7 cm, that is the distance between both diamonds. The two diamond samples are illuminated by 532 nm laser through the optical fiber to eliminate the optical noise. Each fluorescence from NVCs is collected through the optical fiber, detected using each photodiode, and digitized simultaneously. The differential signal is obtained from two signals by the computer.

Continuous-wave MW field through a coaxial cable drives NVCs at the CPW antenna homogeneously. The frequency of the MW is adjusted to the optimum point of each NVCs using each MW source. Each MW signal is frequency modulated at 400 Hz with a frequency deviation width of 8 MHz.

To evaluate the ability of the gradiometer, a solenoid-coil and wire are placed beside the sensors. The gradiometer cancels a deliberate spatially homogeneous magnetic field applied by the solenoid-coil which is a pseudo-environmental magnetic noise, while an in-homogeneous magnetic field applied by the wire remains.

3. Cancellation of a spatially homogeneous magnetic field noise

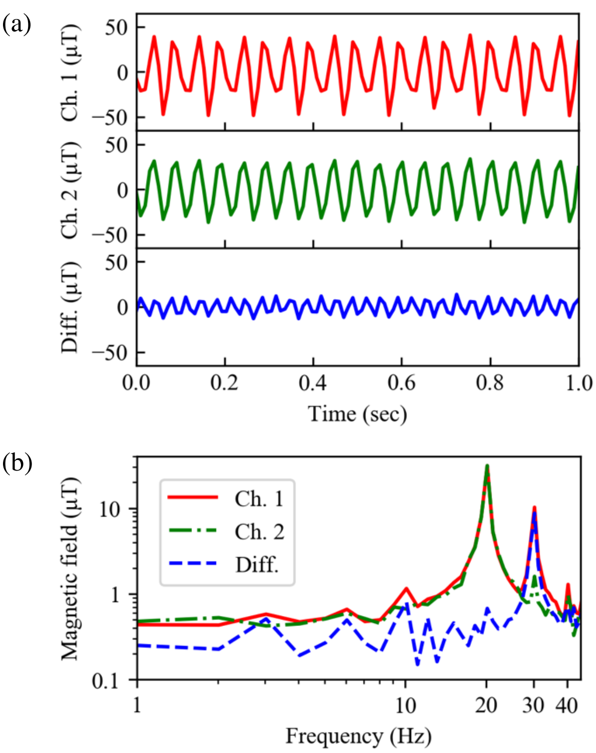

Fig. 3 Magnetic field signals at two detection positions (ch. 1 and ch. 2) and the differential signal of them. (a): Time-domain plot of signals. (b): Frequency-domain plot of signals.

We measured the magnetic field signal by the gradiometer. The spatially homogeneous AC magnetic field of 20 Hz, which corresponds to the environmental magnetic field noises, was induced by the solenoid-coil. Moreover, the in-homogeneous AC magnetic field of 30 Hz, which corresponds to the targeting signal, was induced by the wire beside the ch.1. sensor. Figure 3 shows the time-domain and the frequency-domain signals of the detected magnetic field. Each sensor, ch. 1 and ch. 2, detected the in-homogeneous AC magnetic field of 30 Hz.

One sensor (ch. 1) detected the small spatially in-homogeneous magnetic field signal which is buried under the large spatially homogeneous magnetic field signal [Fig. 3 (a), ch. 1] and the other sensor (ch. 2) detected only the large spatially homogeneous magnetic field signal [Fig. 3 (a), ch. 2]. On the other hand, the small spatially in-homogeneous magnetic field signal remains in the differential signal with cancellation of the large spatially homogeneous magnetic field signal [Fig. 3 (a), diff.].

Figure 3 (b) shows the deliberate spatially homogeneous AC magnetic field of 20 Hz is reduced to less than 1/50 in the differential signal. The gradiometer selectively detected the spatially in-homogeneous magnetic field. This result indicates that the gradiometer has a potential to cancel the spatially homogeneous magnetic field such as the environmental magnetic noise.

4. Conclusions

We constructed the gradiometer which uses a pair of diamonds containing the NVC and evaluated the ability of the gradiometer configuration. Towards MEG applications, our gradiometer has centimeter order base length because the distance between the measuring object and sensors is centimeter order. We selectively measured small spatially in-homogeneous magnetic field under the deliberate spatially homogeneous magnetic field. The deliberate spatially homogeneous magnetic field is reduced to less than 1/50 in the differential signal. This result indicates that the gradiometer has a potential to cancel the spatially homogeneous magnetic field such as the environmental magnetic noise.

Acknowledgements

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Appendix

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