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Wide-field Imaging of Magnetic Field With Nitrogen-vacancy Centers in Diamond by Frequency Modulation of Microwaves

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Abstract

We report on our newly developed wide-field magnetic field microscope utilizing a frequency modulation of the microwave based on optically detected magnetic resonance of NV ensembles in diamond. We demonstrate that our approach is a promising method to obtain magnetic field image within short measurement time.

1. Introduction

Negatively charged nitrogen-vacancy (NV) color centers in diamond have been attracting much interest as a promising method to image magnetic field distribution [1]. The unique electronic properties of NV centers enable us to measure magnetic field by monitoring photoluminescence (PL) intensity near electron spin resonance condition in a microwave field. Whereas superconducting quantum interference devices (SQUIDs) have highest flux sensitivity to date, SQUIDs have to be operated at low temperatures. High resolution imaging has been performed using a SQUID [2,3], but long measurement time is typically required to obtain an image because magnetic flux is measured sequentially by scanning the position of a SQUID probe.

Magnetic field imaging using NV centers has wide applications, for example, in biological imaging and material science. High sensitivity magnetic field measurement may be performed from room temperature to low temperature. Furthermore, measurement time to obtain an image may be significantly reduced by monitoring PL from large number of NV centers by wide-field imaging using a multichannel photodetector. Consequently, magnetic field imaging using NV centers is expected to find wide applications where SQUIDs are difficult to be applied. A wide temperature range for operation is also advantageous to image magnetic properties and current densities in solid state materials, in particular, topological insulators and superconductors. In this paper, we present on wide-field imaging of magnetic field distribution with NV ensembles utilizing a frequency modulation of the microwave.

2. Experimental

We used a (100) IIa type chemical vapor deposition (CVD) chip with a size of 3.0x3.0x0.3 mm^3 with native nitrogen impurities (Element 6) and (100) CVD electronic grade chips with a size of 2.0 x 2.0 x 0.5 mm^3 (Element 6) implanted with 10 keV $^{15}N_2^+$ ions at doses between 1x10^{12} and 1x10^{13} cm^{-3}, annealed at 800 °C and treated by acid. Figure 1 shows a schematic diagram of a set-up for magnetic field imaging. A single turn coil with a diameter of 1 mm was prepared by a photolithography and was used to apply the microwave with the power of 17 dBm to NV centers in diamond. For optical excitation, we used either Millennia Pro 6 W or a 520 nm semiconductor laser diode. A liquid crystal laser amplitude stabilizer was used to reduce the noise in the laser light from Millennia Pro 6 W. We used microscope objectives 10x, NA 0.25 and 100x, NA 0.78. The excitation laser light was focused to the back aperture of the microscope objective. After passing through a low pass optical filter with a cut-off wavelength of 650 nm, photoluminescence from negatively charged NV centers was detected either using an sCMOS camera or a photodiode with a lock-in amplifier. The microwave signal generator, the sCMOS camera, and the lock-in amplifier were controlled by a computer. External magnetic field was applied parallel to [001] direction using $Nd_2Fe_{14}B$ permanent magnets.

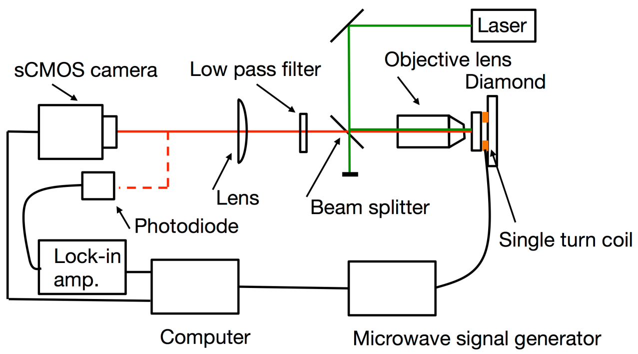

Fig. 1 Schematic diagram of a set-up for magnetic field imaging. Either an sCMOS camera or a photodiode is used.

3. Results and discussions

We have performed magnetic field measurements by two methods, first by using a single channel photodiode, and second by using a multichannel sCMOS camera. In both cases we employ a frequency modulation of the microwave frequency $\nu(t)$ [4] as given by

$$\nu(t) = \nu_0 + \nu_{\mathrm{mod}}\Sigma\left[\cos\left(2\pi r_{\mathrm{mod}} t\right)\right] \qquad (1)$$

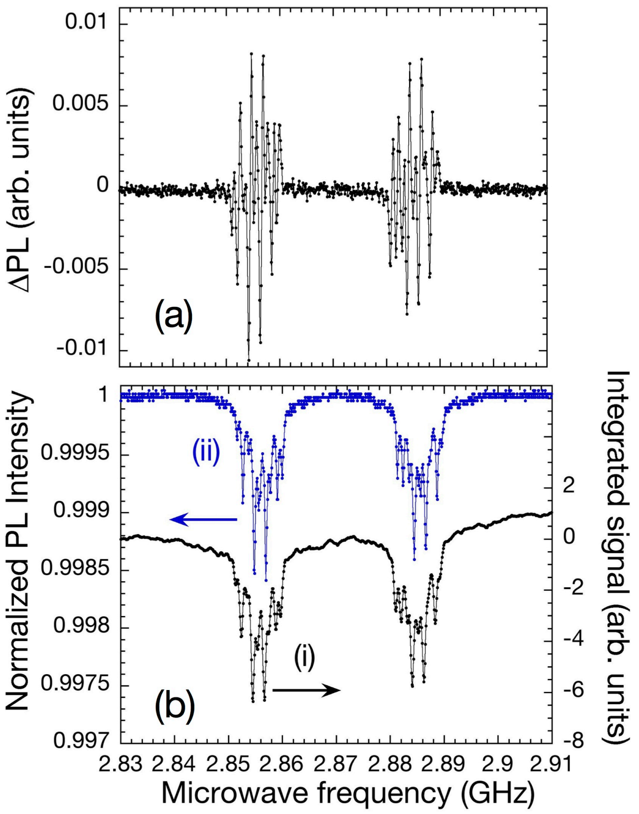

Fig. 2 (a) Frequency modulation signal obtained by a wide-field imaging using a 100x microscope objective as a function of the microwave frequency. (b) Integrated frequency modulation trace (i) and continuous-wave electron spin resonance trace (ii). Constant back-ground was corrected.

where ν_0, ν_{mod}, and r_{mod} are the center frequency, the modulation amplitude, and the modulation rate, respectively. A sinusoidal frequency modulation was applied for the case of single channel measurements with a lock-in amplifier, where Σ is set to 1 in Eq. (1). The modulation rate is limited by $1/T_2^*$. A rectangular modulation was applied for the case of multichannel measurements, where Σ is set to the sign function. The modulation rate in this case is limited by the frame rate of the sCMOS camera.

Figure 2 (a) shows a typical frequency modulation signal obtained by a wide-field imaging of a (100) type IIa CVD chip as a function of the microwave frequency ν_0. Both ^{14}N and ^{15}N were present in native nitrogen impurities in the standard grade type IIa CVD chip. The modulation amplitude was set to 0.5 MHz. The exposure time of each frame was 21 ms and 200 frames were captured at each microwave frequency. The laser power at the incident of the microscope objective was 6.5 mW at 520 nm. While signals integrated over 528x512 pixels with the field size of 3.4 x 3.3 mm^2 are shown in Fig. 2, images were also captured at each microwave frequency. Figure 2(b) shows an integrated frequency modulation trace. A continuous-wave electron resonance trace is also shown for comparison. Fluctuations in the PL intensity in the continuous-wave electron spin resonance trace are reduced in the integrated frequency modulation trace.

Acquisition of images using a photodiode has advantages in higher modulation rate ~100 kHz, but the total measurement time to acquire an image is N_{pixel} times the measurement time of single spot. In the wide-field multichannel detection method modulation rate is currently limited to several hundred Hz. Whereas the magnetic field sensitivity η_m in the wide-field multichannel detection method is degraded from the optimum case of single channel detection η_s, the total measurement time at a fixed sensitivity η is shorter if $\sqrt{N_{pixel}}$ exceeds η_m/η_s. By optimizing the microwave power, PL collection efficiency, and the control software, we expect further improvement in η_m.

4. Conclusions

We have demonstrated that wide-field magnetic field imaging utilizing a frequency modulation of the microwave is a promising method to obtain magnetic field image within short measurement time. We expect that our approach will find wide applications, for example, in biological imaging and material science.

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