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Imaging of Microwave and Radio-Frequency Fields Using Nitrogen-Vacancy Centers in Diamond

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Abstract

Nitrogen-vacancy (NV) centers in diamond constitute platforms for quantum information processing and quantum sensing. Here we report on high spatial resolution imaging of microwave (MW) and radio-frequency (RF) fields utilizing Rabi oscillations and spin-locking. We have found a 22 times enhancement of the microwave amplitude near a resonator with a tapered wire structure.

1. Introduction

Coherent manipulation of spins for quantum information processing and quantum sensing [1] requires a precise spatial control of the MW and RF field-distributions. Numerical simulations such as finite-difference time-domain methods are used for this purpose. Small difference in the shape and the size of MW or RF components may result in a large difference in the performance of the devices. However, few methods are available to image the MW and RF fields in μm resolution. Therefore, it is desirable to develop methods to measure the MW and RF field-distributions at spatial resolution to meet this requirement.

NV centers in diamond offer a unique method to measure AC fields with high sensitivity and high stability. The spin states of the electrons in the NV centers is directly read out by the photoluminescence. As a result, a standard optical microscope may be used for the measurement of spatial distribution of the spin states. Combined with the microwave pulse sequences for the Rabi nutation or the spin-locking, the MW and RF fields are detected at high sensitivities through the photoluminescence. In this paper, we report on high spatial resolution imaging of MW [2] and RF fields by coherently controlling the spins in the NV centers.

2. Experimental

Figure 1 (a) shows schematics of setup for the imaging of the MW and RF fields using NV centers in diamond. A MW resonator prepared by patterning of a Ti/Au film by photolithography was placed below a diamond chip. NV centers were located at about 10 nm below the surface of the diamond chip formed by ion-implantation of $^{15}N_2^+$ followed by heat treatment. Spatially homogeneous MW field in the field of view of the microscope image was applied by a MW planar ring antenna placed above the diamond chip. A photolithography defined MW resonator as shown in Fig. 1 (b) was placed below the diamond chip. The RF field was applied using a metal wire in the MW resonator. The NV centers were excited by green laser pulses, and the photoluminescence from the NV centers was collected by an objective lens and imaged on a cooled scientific CMOS camera. A static magnetic field was applied to the diamond chip parallel to the [111] direction by a pair of permanent magnets. Details of the experiment can be found in Refs. [2,3].

3. Results and discussions

Microwave field imaging

The Rabi frequency Ω is proportional to the microwave field projected to the plane perpendicular to the symmetry axis of the NV centers, B_1. At a detuning of Δ, the generalized Rabi frequency is given by $\Omega' = \sqrt{\Omega^2 + \Delta^2}$. At $\Omega' \gg \Delta$, the observed Rabi frequency is proportional to B_1 in a good approximation. This enables us to measure microwave field strength quantitatively from the Rabi oscillations.

A pulsed-optically detected magnetic resonance spectrum of $^{15}N_2^+$ implanted NV centers are split in two as shown in Fig. 2(a). The splitting of the spectrum is associated with the hyper fine interaction of ^{15}N nuclear spins of $A_{\parallel} = 3.03$ MHz.

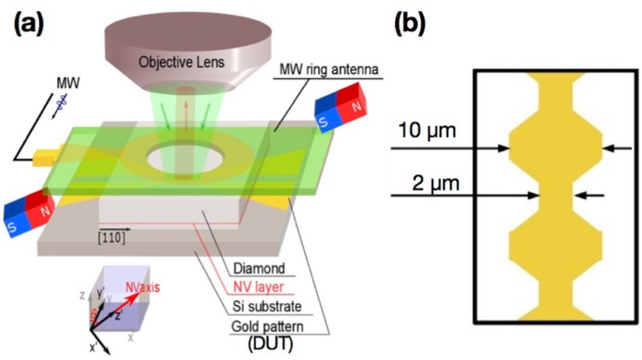

Fig. 1 (a) Schematics of setup for the imaging of the MW and RF fields using NV centers in diamond under MW excitation by MW ring antenna and MW resonator. (b) Schematic structure of a MW resonator with a tapered Ti/Au wire.

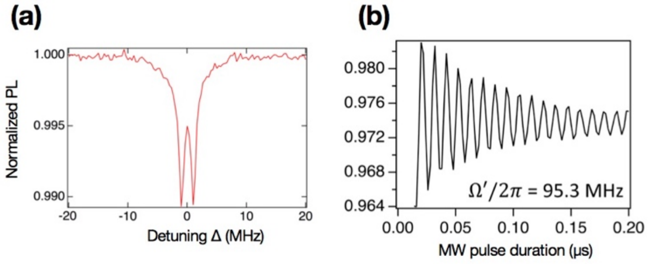

Fig. 2 (a) A pulsed optically detected magneto-resonance spectrum from the PL of NV centers with the symmetry axis parallel to the [111] direction located above a MW resonator. The duration of the MW pulses was 1.5 µs. (b) A Rabi oscillation of the normalized PL intensity of NV centers located above a MW resonator.

In order to avoid beats in the Rabi oscillations, the MW frequency was set at the center of the two dips. A typical Rabi oscillation of the normalized PL intensity of NV centers is shown in Fig. 2(b).

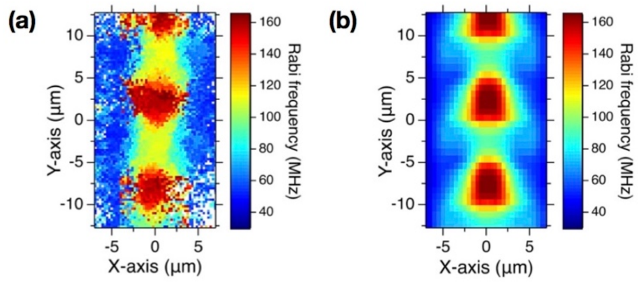

Fig. 3 (a) Microwave imaging at a frequency of 2.730 GHz. (b) Simulated result by finite-difference time-domain (FDTD) analysis.

Rabi oscillation measurements around the MW resonator reveals that the Rabi frequency depends strongly on the position. To clarify the position dependence of the Rabi frequency, we obtained the Rabi frequency at each pixel by fast Fourier transform (FFT) transform of the Rabi oscillations [2]. Figure 3(a) shows the obtained Rabi frequency distribution in the vicinity of a tapered wire as shown in Fig. 1(b). The measured Rabi frequency distribution agrees well with the simulated result by finite-difference time-domain (FDTD) analysis as shown in Fig. 3(b). The obtained Rabi frequency distribution around the tapered wire shows that the MW intensity is controlled as a function of the wire width, more intense on the narrower part of the wire. The maximum Rabi frequency was about 165 MHz in the narrowest part of the tapered wire. This is compared with a bulk Rabi frequency in the presence of only the microwave planar ring antenna without the resonator, we have found that 22-fold enhancement of the Rabi oscillation frequency (440-fold enhancement of microwave power) was achieved.

The observed enhancement of the MW field is understood in terms of the local enhancement of the electromagnetic field by the resonator. The MW planar ring antenna produces spatially homogeneous MW field around the MW resonator, which induces an oscillating current in the wire. The induced current re-emits MW field around the wire. The re-emitted MW field in the vicinity of the wire increases proportional to $1/r^2$ in the near field regime in the dipole approximation, which explains our observation in Fig. 3(a).

The MW imaging was performed at MW frequency of around 2.7 GHz in this study. A resonance frequency of NVs around 115 GHz at 4.2 T was reported in Ref. [4]. Our method of the MW imaging should be applicable to MW frequency range ~ 100 GHz.

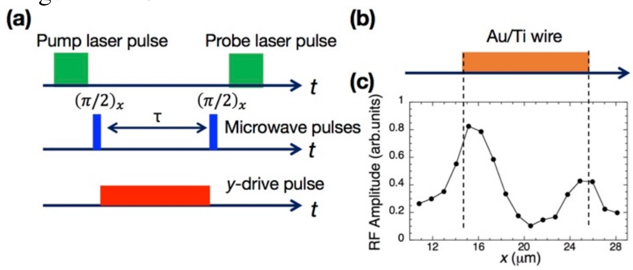

Fig. 4 (a) A pulse sequence for a spin locking measurement. (b) Schematics of a cross sectional view of a Au/Ti wire. (c) Spin-locking signal as a function of lateral position (x).

RF field imaging

A high sensitivity detection of AC fields in the MHz regime is provided by a spin-locking measurement, performed by a pulse sequence as shown in Fig. 4(a). After initializing the spins in the $|0\rangle$ state by a pump laser pulse and applying a $(\pi/2)_x$ MW pulse, a driving MW field is applied in the y-direction in the rotating frame. This creates an energy gap Ω_2 between the dressed states $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and $|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$, where Ω_2 is the Rabi frequency of the y-driving field. RF field on resonant to Ω_2 is detected. MW field amplitude can be calibrated by the method described previously. RF field at a frequency of 27.75 MHz was fed to a Ti/Au wire (Fig. 4(b)). Figure 4(c) shows spin locking signal as a function of the lateral position. RF field projected to the [111] direction was found to have peaks in the vicinity the edges of the wire.

4. Conclusions

In this paper, we demonstrate that our wide-field microscopy provides a strong tool for imaging of MW and RF fields. Our method enables us to drive NV spins at high local peak MW power with low average power, avoiding heat generated in the diamond chip. Our method may contribute to local control of quantum spins, and evaluation of MW and RF devices.

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