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Detection of radio-frequency field with a single spin in diamond

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Abstract Detection of a.c. magnetic field is consequential for many developments in physical and biological sciences, and various designs of magnetometer have been proposed recently. However, the large size of sensor and the extreme measurement conditions required strongly limit their application. It remains a challenge to reconstruct the vector of a.c. field with nanoscale spatial resolution using a single spin under ambient conditions. In this work, we choose the radio-frequency (RF) field as a typical case and realize the measurement of RF field based on a nitrogen-vacancy (NV) center in diamond. We build a solid sensor through measuring the effect of RF field on NV electron spin energy levels and the transition between them. Both of the phase and amplitude (including the transverse and longitudinal components) are measured by this new approach.

Keywords Magnetometer · Nitrogen-vacancy center · Quantum metrology · Radio-frequency field

1 Introduction

Detecting the radio-frequency (RF) field is essential for many developments in physical and biological sciences [1–5]. In the past few decades, copious magnetic sensors have been proposed, such as superconducting quantum interference devices [2, 3, 6] which utilizing the phenomena of superconducting quantum interference, and semiconductors [4] which making use of the Hall effect. Exploration in cold atoms [7, 8] and coplanar-waveguide-type probe [9–12] have also been realized.

Our method for RF field detection is based on a single quantum system, which is a nitrogen-vacancy (NV) center in diamond. As depicted in Fig. 1b, the NV center consists of a substitutional nitrogen atom and an adjacent vacancy. The NV center systems are convenient to initialize and read out [13–15], have long coherence times [16] and can be manipulated by alternating field [17–20] with high precision at room temperature. In addition, the NV sensor can reach a sub-nanometer resolution. Owing to these good properties, the NV center has been demonstrated to be a perfect magnetometer with sub-nano resolution and high sensitivity at room temperature [21–30].

2 Materials and methods

Our setup is based on a home-built confocal microscope and the experiments are carried out on the electron of the NV center. The NV center exists in two forms: neutral charged state NV^0 and negatively charged state NV^-. In this work, we only consider the NV^- (simplified with NV hereinafter). The electronic ground state of the NV center forms a spin triplet, and it can be polarized by a 532 nm laser pulse. The hyperfine structure formed by NV electron spin and ^{14}N nuclear spin is shown in Fig. 1d, where energy levels of the electron with $m_S = 0, -1$, and $+1$ are labeled by $|0\rangle_e$, $|-1\rangle_e$, and $|+1\rangle_e$, and the energy levels of the nucleus with $m_I = 0, -1$, and $+1$ are labled by $|0\rangle_n$, $|-1\rangle_n$, and $|+1\rangle_n$. These spin states can be manipulated by alternating fields.

In this work, we apply an RF field as the source to be detected and a microwave (MW) field as the auxiliary field to manipulate NV electron spin. The transverse amplitude

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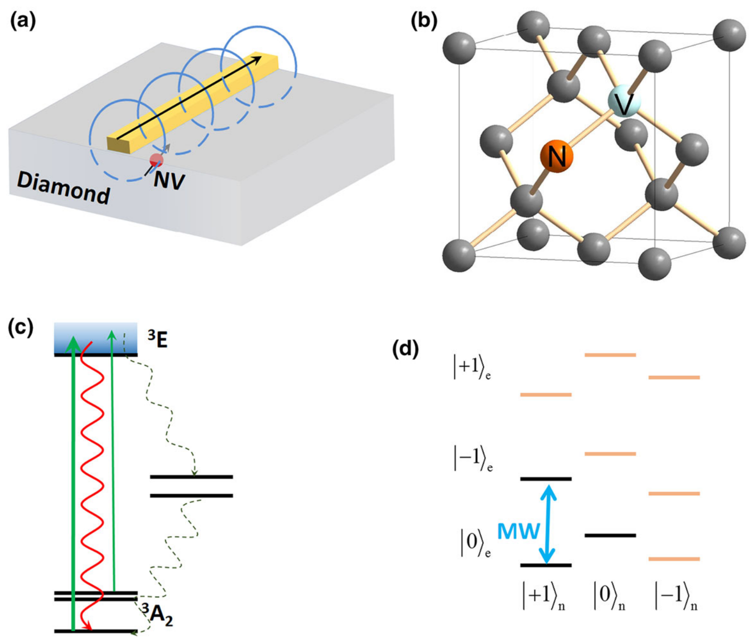

Fig. 1 (Color online) Experimental system and method. **a** Schematic diagram of the setup for the magnetometer. The waveguide is used for applying alternating magnetic fields and the NV sensor nears this copper wire. **b** Atomic structure of an NV center in diamond. **c** The electronic energy level structure of a negatively charged NV center. **d** Energy level structure of the ground state $^3A_2$. The hyperfine structure is induced by the host ^{14}N nuclear spin

of the RF field can be routinely derived from Rabi frequency of the nuclear spin [26]. However, this method can not be always practicable because the energy levels of the nuclear spin can not be arbitrarily adjusted. But we find that the transverse RF field induces a shift of electronic energy levels and this shift can be used for measuring the transverse amplitude of RF field. Besides, we find that the transitions between the electronic energy levels are also affected by the phase and longitudinal amplitude of RF field. They can also be utilized to detect the phase and longitudinal amplitude of RF field which are difficult to be detected. Based on those effects on NV electronic energy levels induced by RF field, we propose a new method to detect the phase and the amplitude of the RF field.

The implementation of our method can be roughly divided into two steps. Firstly, we obtain the transverse amplitude and eliminate the effect caused by the transverse component since it would also affect transitions between NV electronic energy levels and then disturb our detection of the phase and longitudinal amplitude. Secondly, we detect the phase and longitudinal amplitude by eliminating their effects on NV electron spin transition with a compensating MW field. When their effects are eliminated completely, the oscillating frequency of electron spin would reach the maximum value. Because the optimal compensating MW field corresponds to the phase and longitudinal amplitude of the RF field, we can realize the detection by searching this optimal compensating MW field.

The magnetometer system is composed of three parts: the NV center, the applied RF field and the applied MW field. So the Hamiltonian of our system is

$$H = H_{\mathrm{NV}} + H_{\mathrm{RF}} + H_{\mathrm{MW}}. \quad (1)$$

Applying an external static magnetic field along the NV axis, the Hamiltonian of NV center ($\hbar = 1$) [31] is

$$H_{\mathrm{NV}} = DS_z^2 + \gamma_e B_0 S_z - \gamma_n B_0 I_z + QI_z^2 + \boldsymbol{S} \cdot \mathbb{A} \cdot \boldsymbol{I}, \quad (2)$$

where the z direction is along the NV symmetry axis. Here, $\gamma_e = 2.8025$ MHz/G is the gyromagnetic ratio of the NV electron spin, $\gamma_n = 0.3077$ kHz/G is the gyromagnetic ratio of the nuclear spin, $D = 2870$ MHz is the zero-field splitting of the NV electron spin, $Q = -4.945$ MHz is the quadrupole splitting of the nuclear spin, B_0 is the magnitude of the magnetic field along the NV symmetry axis, $\mathbb{A}$ is the hyperfine coupling tensor for nuclear spin, and $\boldsymbol{S}$, S_z, $\boldsymbol{I}$, I_z are the spin operators of the electron and nuclear spins for this $S = 1$ system respectively.

In static magnetic field of 500 G, the nuclear spin is polarized and we just concern about the transition between electron spins. The Hamiltonian relating to the NV electron spin can be simplified as

$$H_{\mathrm{NV_e}} = DS_z^2 + \gamma_e B_0 S_z = \omega_+ |+1\rangle_{e\,e}\langle +1| + \omega_- |-1\rangle_{e\,e}\langle -1|, \quad (3)$$

with $\omega_\pm$ representing the energy of $|\pm 1\rangle$.