Magnetic sensitivity technology based on microwave modulation of solid state spin system NV center

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Abstract: In view of the low resolution and accuracy of traditional magnetometer, a method of microwave frequency modulation technology based on nitrogen-vacancy(NV) center in diamond for magnetic detection was proposed. The magnetometer studied can reduce the frequency noise of system and improve the magnetic sensitivity by microwave frequency modulation. Firstly, ESR spectra by sweeping the microwave frequency was obtained. Further, the microwave frequency modulated was gained through the mixed high-frequency sinusoidal modulation signal generated by signal generator. In addition, the frequency through the lock-in amplifier was locked, and the signal which was proportional to the first derivative of the spectrum was obtained. The experimental results show that the sensitivity of magnetic field detection can reach 17.628 nT/$\sqrt{\text{Hz}}$ based on microwave frequency modulation technology. The method realizes high resolution and sensitivity for magnetic field detection.

Key words: solid state spin system; nitrogen vacancy (NV) center; microwave frequency modulation; magnetic sensitivity technology; lock-in amplifier

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0 Introduction

The nitrogen-vacancy (NV) in diamond holds the considerable advantage in the field of high-sensitivity physical detection, and it is commonly regarded as the important research area of manufacturing the magnetic field probe with high spatial resolution, precision, linearity and directional sensitivity[1,2] in the recent years. Its advantages such as special physical properties, high spatial resolution, favorable optical properties and ultra-long coherence time under the room temperature have enabled the spin sate of single electron to be obtained through optically detected magnetic resonance (ODMR). The diamond NV center theory can be adopted to open the huge development prospect of magnetic field imaging (MFI) at the same time of combining the advantages of operating diamond NV center under the room temperature and the SQUIDS method with the magnetic resonance force microscope (MRFM) as well as other function-related high-resolution methods. Compared with the current widely-applied magnetic force microscope (MFM), diamond NV center electron spin-based magnetometer can be used to determine the independent gradient magnetic field. Besides, the NV center is being widely applied in fields such as fluorescence imaging[3], quantum information processing[4], fluorescence biological tag[5] and quantum spin regulation and control[6].

The NV center is a stable defect of diamond's crystal structure; it consists of a substitutional nitrogen atom and a vacancy on adjacent lattice sites, such that the defect's symmetry axis may be oriented along one of four possible crystallographic directions[7-9]. Under the room temperature, the diamond NV center could realize the spin polarization and quantum regulation and control through the optical detection method or ODMR. What make NV center different from other centers are its specific spin energy level state and fluorescence characteristics, in addition to the characteristics such as stable spin quantum state of NV center in

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diamond[10], high magnetic-field sensitivity and controllability of quantum state. As a result, numerous researchers have made wide and in-depth researches on NV center in quantum information[12], magnetic-field measurement, angular surveying, fluorescence biological tag, etc. What shall be specially pointed out is that researchers have made considerable breakthroughs in the quantum information-related fields such as quantum state regulation and control, quantum entanglement and quantum register, as well as considerable progress in fields such as fluorescence detection and so on. What's more, research on diamond NV center is playing an important role in researching the solid quantum systems of other fields.

In the research on spin state regulation and control of diamond NV ensemble, it's very difficult to improve the magnetic-field sensitivity because of acquisition efficiency and system noise. According to the situations, the microwave modulation technique, IQ-mixer mixing modulation technique for sinusoidal reference signal and microwave source signal as well the lock-in amplifier have been adopted for the test, analysis and optimization of the magnetic-field sensitivity. Upon analyzing the experimental data at the current stage, at the modulation rate of $r_{mod}=$ 1 kHz and modulation amplitude of $v_{mod}=2.5$ MHz, the tested magnetic-field sensitivity has approached $\eta \approx 17.628\ \mathrm{nT}/\sqrt{\mathrm{Hz}}$.

1 Signal modulation of NV center spin and magnetic-field sensitivity test

The NV center's ground state is a spin tri-state, in which there is energy interval of 2.87 GHz between $m_s=\pm1$ and $m_s=0$. In the experiment of NV center spin control, the continuous modulation of optical excitation and microwave signal is adopted to realize the measurement of magnetic-field sensitivity at the same time of tracing and measuring the signals through the related pulse time-oriented sequential control and phase-locking amplifier.

The microwave or radio-frequency (RF) signals generated by the microwave signal generator (the one adopted in this experiment is MXG analog signal generator N5181B that could product the signal of 9 kHz—6 GHz microwave) shall be input into the RF switches and generate the TTL signals with the help of pulse-series generator, so as to realize the output and suspension of microwave signals. Signals from the on-off switches enter the microwave power amplifier to amplify the power through amplitude modulation. The amplified signals enter the lock-in amplifier (the one adopted in this experiment is the HF2LI Lock-in Amplifier) for phase locking to carry out the frequency stabilization and amplitude stabilization while obtaining the related waveform, frequency and amplitude information. Finally, the surrounding magnetic-field intensity can be calculated according to these information.

During the continuous wave measurement, the lasers and microwave with stable powers worked on the NV center. The fluorescence collection is carried out through photoelectric detection atom (PDA), so as to transform the fluorescence signals into the electrical signals and collect fluorescence at the sideband NV center. The laser power is 2.15 mV, and the microwave power is 19 dBm. The 532 nm continuous laser will firstly excite the spin state into the polarize state of ground state. When the microwave frequency reaches the energy level difference between $m_s=0$ and $m_s=\pm1$, the $m_s=0$ can be excited to $m_s=\pm1$. Consequently, when the microwave sweep frequency transmits the spin energy level from $m_s=0$ to $m_s=\pm1$, the particles are between the two energy levels, and they shall be re-populated. When the microwave frequency equals to the resonance frequency between $m_s=0$ and $m_s=\pm1$, particles of the $m_s=0$ state will be populated on the $m_s=\pm1$ state as the laser excitation. As it seldom releases photons back to the ground state after the transition of particles at $m_s=\pm1$ state, so the fluorescence of NV center will be significantly weakened during the resonant microwave frequency. Without the external magnetic field, and only considering influence of the terrestrial magnetism, the electron spin resonance will only be found near the 2.87 GHz. It can be known from the theoretical calculation that if the external magnetic field follows the [111] direction, ESR will have two valley bottoms at 2.87 GHz $\pm\ \Delta$, respectively, in which $\Delta=2.8$ MHz/Gauss.

During the specific experiment, we will add a modulation signal on the basis of the microwave source output. The phase locking can be realized through the modulation signals, and the magnetic-field sensitivity can be calculated according to the output parameters. Under the function of continuous microwave field, the laser power and microwave power can be fixed, in which the laser power is about 0.9 mV, while the microwave power is about

19 dBm, and the sweep frequency step length is 500 kHz. The single NV spin to microwave modulation is in proportion to the offset close to the modulation frequency of resonance luminescence. The ESR signals can be recorded by the lock-in amplifier and used to calculate the magnetic-field intensity and sensitivity. While adding the sinusoidal signal at modulation rate of $r_{mod}=7$ kHz and modulation amplitude of $v_{mod}=3$ MHz, the signals will be obtained as shown in Figs. 1—3.

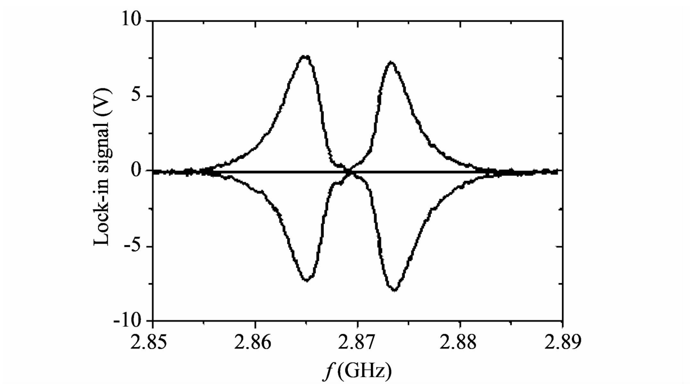

Fig. 1 Modulation signal of lock in amplifier at $r_{mod}=7$ kHz

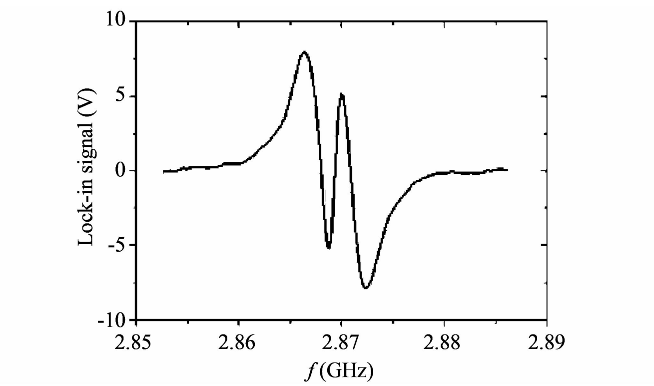

Fig. 2 Modulation signal amplitude of lock in amplifier signal at $r_{mod}=7$ kHz

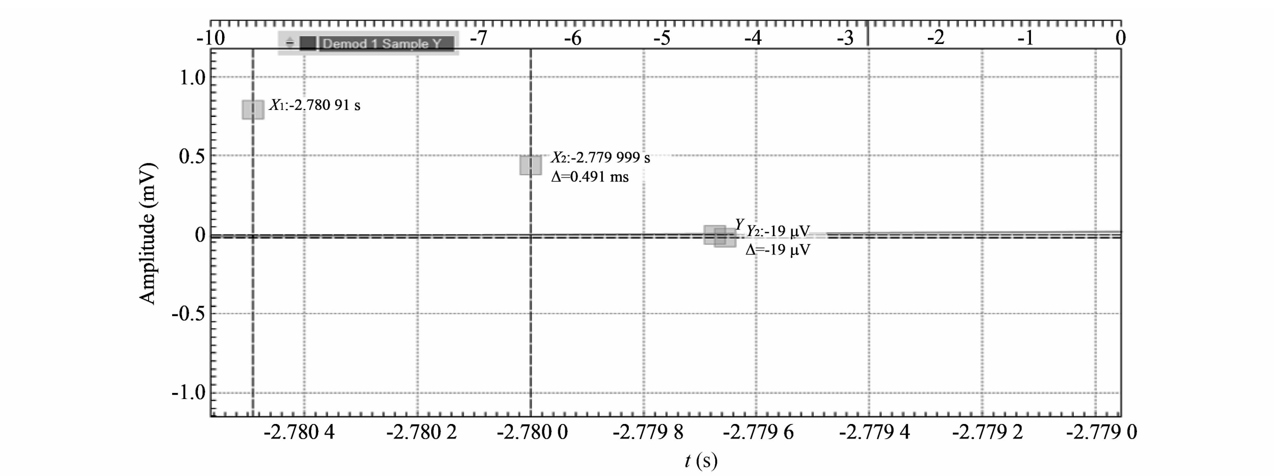

Fig. 3 The minimum resolution time of modulation signal at $r_{mod}=7$ kHz

In Fig. 3, the minimum resolvable time δt of the signal can be tested by the lock-in amplifier. During adding the sinusoidal signal at modulation rate of $r_{mod}=1$ kHz and modulation amplitude of $v_{mod}=2.5$ MHz, the signals can be obtained as shown in Figs. 4—5.

The minimum time resolution rates will be different when the modulation rates of modulation signals are different. According to existing experimental conditions, the optimal parameters can be determined to realize the maximum magnetic-field sensitivity. After obtaining these parameters, we can calculate the magnetic-field sensitivity.

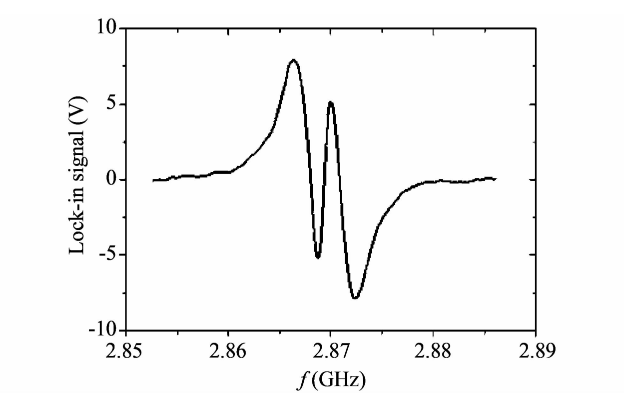

Fig. 4 Modulation signal amplitude of lock in amplifier signal at $r_{mod}=1$ kHz

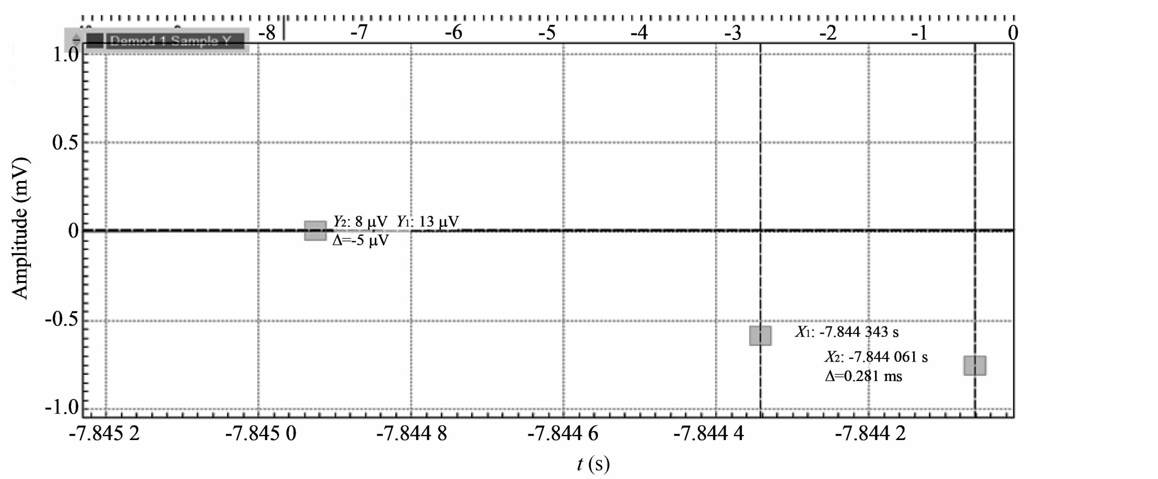

Fig. 5 The minimum resolution time of modulation signal at $r_{\mathrm{mod}}=7$ kHz

2 Calculation of magnetic-field sensitivity

The magnetic-field intensity and sensitivity can be calculated according to the Hamiltonian. The formulas are

$$H_{\mathrm{tot}} = H_{\mathrm{S}} + H_{\mathrm{SZ}} + H_{Z}, \quad (1)$$

$$\begin{cases} H_{\mathrm{S}} = D\boldsymbol{S}_Z^2 + E(\boldsymbol{S}_X^2 - \boldsymbol{S}_Y^2) + g\mu_{\mathrm{B}}\boldsymbol{B}\cdot\boldsymbol{S}, \\ H_{\mathrm{SI}} = A_{/\!/}\,\boldsymbol{S}_Z I_Z + A_{\perp}\,(\boldsymbol{S}_X I_X + \boldsymbol{S}_Y I_Y), \\ H_{\mathrm{I}} = PI_Z^2 - g_{\mathrm{I}}\mu_{\mathrm{N}}\boldsymbol{B}\cdot\boldsymbol{I}, \end{cases} \quad (2)$$

where H_{S} is the part influenced by the electron spin; H_{SZ} is the coupling unit of refine structure; H_Z is the core spin part; g is Landes constant; μ_{B} is Bohr magneton; $\boldsymbol{S}_X$, $\boldsymbol{S}_Y$, $\boldsymbol{S}_Z$ are Pouli matrices; D is zero-field splitting; I is spin coefficient. In the spin control experiment of NV center, the latter two functions can be ignored. According to H_{S}, D and E are the splitting parameters under the zero magnetic-field conditions, in which D is 2.87 GHz. $g\mu_{\mathrm{B}}\boldsymbol{B}\cdot\boldsymbol{S}$ is the Zeeman splitting item under the existence of magnetic-field axis which will result in $m_s = \pm 1$ energy level splitting. Continuing being dissolved, the computational formula of the sensitivity in this experiment can be obtained as

$$\eta = \delta B\sqrt{t}, \quad (3)$$

where δB is the mininum value of magnetic field-intensity, and t is the measurement time interval of the valid data in this experiment. There is another method to test the sensitivity, that is

$$\eta = \frac{\sigma}{\sqrt{r}\,\dfrac{\mathrm{d}S}{\mathrm{d}B}}, \quad (4)$$

where σ is the standard deviation of the measurement; r is the recurrence rate, generally, $r=2r_{\mathrm{mod}}$, and r_{mod} is the modulation rate; $\mathrm{d}S/\mathrm{d}B$ is the variance rate of response signal to the magnetic-field intensity, which can be calculated by de-coherence time t_2. Influence of different parameters on the ESR signals can be obtained by changing the modulation rate or modulation amplitude at the time of measurement, making sure that the modulation depth should not be greater than the full width at the half maximum of ESR signals.

The modulation rate $r_{\mathrm{mod}}=7$ kHz of the sinusoidal signal shall be calculated first before modulating the magnetic field-intensity at the modulation amplitude of $v_{\mathrm{mod}} = 3$ MHz. The modulated signals obtained according to the experiment test are shown in Figs. 1—4. It can be known through the analysis that the microwave frequency corresponding to a period of the test signal at $t = 5.12$ s is 50 MHz (2.85 GHz—2.90 GHz), while the minimum resolution corresponding time of the tested signal is $\delta t=0.491$ ms. It can be calculated as

$$5.12\times 10^3/50\times 10^6 = 0.491/v. \quad (5)$$

It can be calculated that $v\approx 4.795$ kHz.

The magnetic field intensity and sensitivity can be calculated according to the Hamiltonian, where the simplified formula can be directly used for calculation. It can be pointed out that the magnetic field axis in the experiment is along the [111] direction. The Zeeman splitting and Bohr magneton can be represented as

$$\begin{cases} hv = 2g\mu_{\mathrm{B}}B, \\ \mu_{\mathrm{B}} = \dfrac{he}{2m_{\mathrm{e}}}, \end{cases} \quad (6)$$

$$B = \frac{m_e v}{g e}. \tag{7}$$

Therefore, according to Eq. (7), the magnetic field intensity can be calculated as

$$B = \frac{9.109 \times 10^{-31} \times 2.74 \times 10^{3}}{2.0023 \times 1.602 \times 10^{-19}}.$$

Namely $\delta B \approx 13.617$ nT, and according to Eq. (3), sensitivity can be obtained as follow

$$\eta = \delta B \sqrt{t} = 13.617 \text{ nT} \times \sqrt{5.12 \text{ s}} \approx 30.811 \text{ nT}/\sqrt{\text{Hz}}.$$

Therefore, the magnetic-field sensitivity when the modulation signal is the sinusoidal signal with the modulation rate of $r_{mod} = 1$ kHz and modulation amplitude of $v_{mod} = 2.5$ MHz can be calculated.

Modulated ESR signals obtained according to the experiment test are as shown in Figs. 4 and 5. It can be known that the corresponding microwave frequency is 50 MHz (2.85 − 2.90 GHz) while a period of the tested signal is $t = 5.125$ s and the minimum resolution corresponding time is $\delta t = 0.281$ ms. It can be obtained that $v \approx 2.742$ kHz and $\delta B \approx 7.787$ nT according to the Eq. (3), and the magnetic field sensitivity can be obtained as $17.628 \text{ nT}/\sqrt{\text{Hz}}$.

3 Conclusion

On the principle of NV ensemble-based electron spin resonance, methods of continuous 532 nm laser excitation, microwave signal modulation and IQ-mixer nixing sinusoidal reference signal are adopted to modulate the ESR with the lock-in amplifier and measure the magnetic-field sensitivity. Upon the microwave modulation and demodulation calculation, it can be obtained that the magnetic-field sensitivity has reached $\eta \approx 17.628 \text{ nT}/\sqrt{\text{Hz}}$. This method is of important reference meaning for the improvement of magnetic-field sensitivity on the basis of NV center magnetic measurement field.

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基于固态自旋系综 NV 色心微波调制的磁传感技术研究

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摘　要： 针对传统磁场检测设备分辨率低、测量精度低的现状，提出了一种基于金刚石 NV 色心微波频率调制进行磁检测的方法。通过频率调制方法，可以降低测量系统中低频噪音干扰，提高测量灵敏度。首先通过扫描微波频率得到 ESR 谱线，然后利用混合高频正弦调制信号进行频率调制，并使用锁相放大器对频率进行锁定，得到频率与光谱一阶导数成比例的信号。实验结果表明，磁场检测灵敏度可达 17.628 nT/$\sqrt{\mathrm{Hz}}$。该方法实现了高分辨率、高灵敏度的磁场检测。

关键词： 固态自旋系综；NV 色心；微波频率调制；磁传感技术；锁相放大器

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