An Emerging Testing Method for Metallics Based on NV Center in the Diamond

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Abstract: Metal substance detection plays an extremely important role in daily life, industrial manufacturing and even industrial security. The traditional methods include optical detection, X-ray detection, microwave detection and ultrasonic detection. These methods, playing a vital role in the field of non-destructive testing, can not only judge the presence or absence of metal, but also accurately detect the type and size of metal defects. For microwave detection, the detection efficiency of metal materials is limited by the response sensitivity of the detector to microwaves. In recent years, scientists have discovered a quantum sensing system based on the diamond nitrogen-vacancy (NV) color center. The system obtains optical detection magnetic resonance (ODMR) fluorescence spectra under the combined action of a 532nm laser and a certain frequency band of microwaves, and the signal contrast changes significantly with the microwave power. Based on the NV color center quantum sensing system, this paper studies its application in the field of metal detection, and takes steel detection as an example to detect the size of steel bars according to the changes in the spectral line, providing a new method for non-destructive testing such as metal substance detection.

Keywords: Diamond Nitrogen-vacancy Color Center, Rebar, Microwave Reflection, ODMR.
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1 Introduction

In the modern era of scientific and technological revolution, metal can be said to be an essential raw material in the industrial field, ranging from metal nanoparticles to naval vessels. In addition to being used as a conductive carrier in the field of electronics, metal is more used as a support carrier for equipment, construction, and large machinery. The quality of the metal directly affects the working performance and service life of these machinery. If there is a non-destructive testing method that can accurately and sensitively detect various defects of the metal, it can not only improve the detection efficiency of the equipment, but also timely detect the quality of the equipment and make early warning. Nowadays, there are many means of metal detection, the simplest such as visual detection, optical detection, more accurate such as ultrasonic, microwave and even X-ray detection methods. These methods have been widely used in our daily life, industrial manufacturing, life safety and even national defense. For example, the prosperity of the real estate economy has led to the rapid growth of China's GDP, and housing investment accounts for a large part of total GDP. But behind the boom, the quality of the construction has always affected the real estate industry. As the skeleton of the building, the steel bar determines the solidity of the building. Therefore, the quality of steel bars has become the primary problem in the process of building construction. Strictly controlling the quality of steel bars is of great significance to the quality of building construction.

The traditional technology can use the reflection effect of metal on microwave to measure the S11, S12 and other coefficients of microwave radiation antenna to determine whether there is metal in the surrounding environment. And the measurement tools are very mature, such as vector network analyzer, microwave power meter and so on.

This method can be well applied to steel detection[2-7]. With the progress of science and technology and the increasing demand for detection accuracy in real life, scientists seek new detection methods, that is, a detector can be used to measure the change of space microwave power very sensitively. In recent years, as a new type of quantum material, diamond nitrogen-vacancy color center (hereinafter referred to as NV color center) plays an important role in the field of quantum sensing[10-11]. The power change of external microwave is deduced by the interaction between the electron spin of NV color center and microwave[11-19]. Therefore, this paper draws on the above two measurement techniques, and realizes the steel bar detection in the traditional industry based on the quantum effect.

2 Principle of Measurement

2.1 NV Color Center Quantum Measurement System

2.1.1 Introduction and Basic Structure of NV Color Center

Diamond is composed of carbon, which is one of the allotropes of carbon. The diamond lattice exhibits a stable tetrahedral structure, so it has many excellent physical and chemical properties, such as acid and alkali resistance, high refractive index, etc. The diamond used in the laboratory is artificially synthesized. At present, there are two main synthetic methods: high temperature and high pressure method (HTHP) and electrochemical vapor deposition (CVD). In the process of diamond formation, other atoms are often doped, resulting in changes in its internal structure and physical properties. According to the different doping, diamond is divided into type I and type II. Type I diamond is mainly doped with nitrogen, and type II diamond is mainly doped with boron. Ib type diamond is mainly used in diamond NV center[10].

As shown in Fig.1(a), a carbon atom in the diamond lattice is missing to form a hole, resulting in a carbon atom around being replaced by a nitrogen atom, and the resulting N-V structure is called the NV color center. Because diamond has a symmetrical tetrahedral crystal structure, the NV center has symmetry of and four axes[14]. The NV color center can be divided into and according to the number of free electrons carried. Generally, the scientific research community chooses it as the research object. The whole is electronegative, and there are six electrons outside it (there are two electrons outside the N atom, three C atoms adjacent to the empty acupoint V each carry one electron, plus a free electron captured by the NV color center). Among the six electrons outside the NV center, two electrons are not paired, and the remaining four electrons are paired in pairs, so the electron spin number of the NV center is 1[15].

2.1.2 The Energy Level Structure and Transition Principle of NV Color Center

As shown in Fig.1(b), due to the number of external electron spins of the NV color center is 1, the ground state energy level will undergo zero-field splitting which is split into m_s=0 and m_s=±1 when the applied magnetic field is 0, and the zero-field splitting size is D=2.87 GHz at room temperature. When the NV color center is irradiated by a laser with a wavelength of 532 nm, if the NV color center is at m_s=0, it will be excited to the excited state m_s=0, and will return to the ground state m_s=0 after a period of time, and release a large number of red photons. If the NV color center is in the m_s=±1 state, it will be excited to the excited state m_s=±1 and some NV color centers will first return to the metastable state ^1A, and then transition back to the ground state m_s=0. This process will release a small amount of red photons. Therefore, when the NV color center is in different quantum states, the NV color center is irradiated with a 532 nm laser to collect red fluorescence with distinct intensity changes. When there is an external magnetic field, the ground state m_s=±1 of the NV center will undergo Zeeman

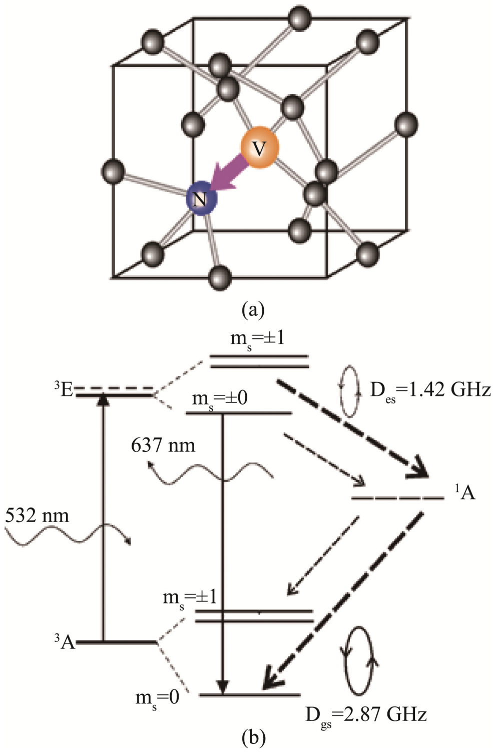


Fig.1 (a) Lattice Structure of Diamond NV Color Centers. (b) Energy Level Structure of Diamond NV.

splitting effect, splitting into the ground state m_s=+1and the ground state m_s=−1 and the size of the Zeeman splitting is proportional to the size of the external magnetic field[15-16].

2.1.3 Hamiltonian of NV Color Center and ODMR Fluorescence Spectrum

In general, there will be an environmental magnetic field $\vec{B}$ in space. At this time, the Hamiltonian of the electron spin of the NV color center can be expressed as:

$$H_s = DS^2 + G_s\mu_B\vec{B}\vec{S}$$

Among them, D=2.87GHz, G_s is the electron spin g factor, generally about 2.003, which is the Bohr magnetic moment. By solving the eigenvalues of the above equations, we can obtain:

$$E = \begin{bmatrix} G_e\mu_B B_Z + \dfrac{G_e\mu_B}{2}\dfrac{B_\perp^2}{D} \\ -G_e^2\mu_B^2\dfrac{B_\perp^2}{d} \\ -G_e\mu_B B_Z + \dfrac{G_e\mu_B}{2}\dfrac{B_\perp^2}{D} \end{bmatrix}$$

It can be seen from the above results that under the external 532 nm laser, two peaks about D symmetry can be obtained by sweeping the microwave pair with a bandwidth of 60 MHz and a center frequency of 2.87 GHz, which is the ODMR (optical detection magnetic resonance) fluorescence spectrum of NV color center. Fig.2(a) is the ODMR fluorescence spectrum of the NV color center in the case of zero magnetic field. Due to the stress distribution inside the diamond, two peaks appear.

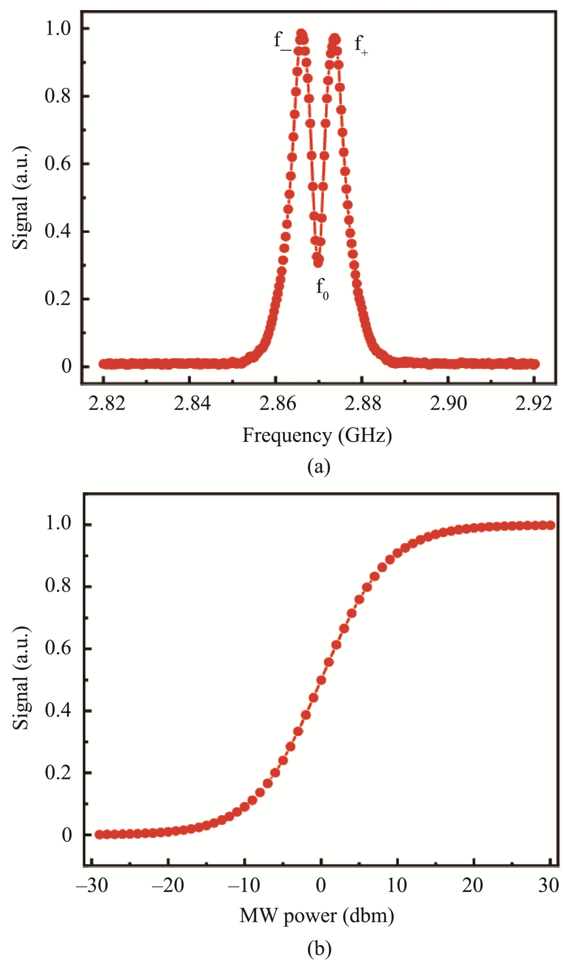


Fig.2 (a) ODMR Fluorescence Spectrum Detected without Applied Magnetic Field. (b) the Relationship between the Signal Intensity of the ODMR Spectral Line and the Microwave Power, Where the Unit of the Microwave Power Is: dbm

2.1.4 Hamiltonian of NV Color Center and ODMR Fluorescence Spectrum

The ODMR introduced above is detected under the simultaneous action of 532 nm laser and microwave, and the line shape of ODMR is not only related to the nature of the electron spin inside the diamond, but also related to the applied laser power and microwave power. Considering the excited state and metastable state of the NV color center, by solving the steady-state solution of the five-level (plus the three-level state of the ground state) state equation[12-13], the contrast (or signal intensity) C of the spectral line of ODMR can be quantitatively calculated with the same laser power. The change of microwave power P_{MW} satisfies the following relationship:

$$C \propto \frac{P_{MW}}{P_{MW} + k_1}$$

Where k_1 is a constant, and the unit of P_{MW} is mW. In the actual experiment, the unit of P_{MW} is converted to dBm, that is, $f(dbm)=10\lg(\frac{P_{MW}}{1mw})$. Then the function image of ODMR contrast and microwave power is shown in Fig.2(b). Therefore, the change of microwave power can be directly reflected in the signal intensity of the ODMR spectral line. The signal intensity is not only related to the excitation intensity, but also related to the collection efficiency of the system for fluorescence. In order to improve the sensitivity of the system to microwave power detection, diamond samples grown at high temperature and pressure and containing high concentration NV color centers were used in the experiment. The excitation intensity of 532 nm up to 100 mW was used.

2.2 Effect of Metal Substance on Microwave

Microwave refers to the electromagnetic wave of a certain frequency band, and its wavelength range is 1mm-1m. The traditional metal detection principle is based on the following facts:

1. Microwave has reflection characteristics for metal materials, and the reflectivity is close to 100 %; microwave has transmission characteristics for non-metallic materials.

2. When the microwave propagates from the air to the metal surface (from the wave-thin medium to the wave-dense medium), the reflected microwave undergoes a π-phase mutation for the incident microwave, which is called half-wave loss. The microwave finally acting on the NV color center probe is the superposition of incident microwave and reflected microwave. Fig.3 is the half-wave loss effect schematic diagram.

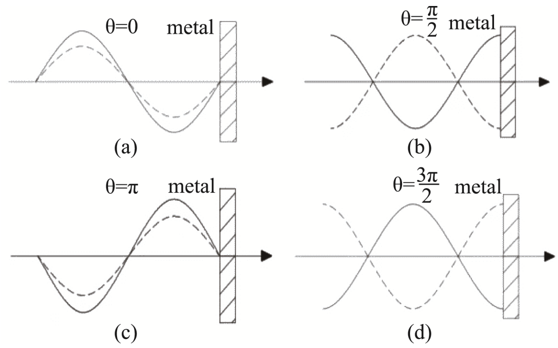


Fig.3 Half-wave Loss Effect of Microwave Irradiation on Metal Surface

3 Instrument and Method

The above is the basic structure of the diamond NV color center and its microwave detection principle. Next, the components of the detection system are introduced in detail.

3.1 Construction of NV Color Center Quantum Measurement System

Firstly, we need to build a quantum measurement system based on NV color center. The working principle of the system is shown in Fig.4. It includes optical system, microwave system and control system.

The optical system consists of 532 nm laser, fiber coupler, dichroic plate, filter and photodetector. A 532 nm green laser is generated by the laser and transmitted to the NV color center probe through a two-color plate. The NV color center produces red fluorescence under the action of green laser, and the stray light is filtered out by the filter and collected by the photodetector.

The microwave system consists of microwave source, microwave switch, microwave amplifier and microwave circulator. The RF signal emitted by the microwave source is modulated by the phase-locked modulation, the microwave amplifier is amplified, and the microwave circulator acts on the diamond NV color center probe by the microwave antenna.

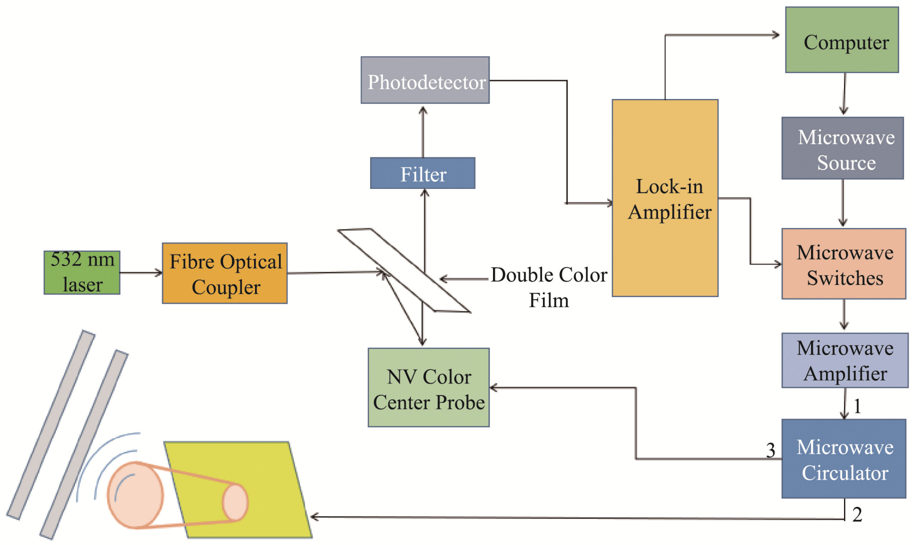


Fig.4 Schematic Diagram of Quantum Measurement System Based on NV Color Center

The microwave source and lock-in amplifier are controlled by computer. Among them, the microwave source needs to set the microwave power, frequency sweep range and scanning step; the lock-in amplifier needs to set the reference mode, modulation frequency, modulation depth, etc. Finally, the microwave frequency-phase-locked output voltage value is collected, and the function curve is drawn to obtain the final ODMR fluorescence spectrum.

3.2 Microwave Measurement Method of NV Color Center Quantum Measurement System

3.2.1 The Relationship between ODMR Peak and Microwave Power Was Measured

Because the experimental principle is based on the reflection effect of the metal on the microwave, the microwave power felt by the NV color center changes, so it is necessary to first measure the response curve of the NV color center ODMR fluorescence spectrum to the microwave change. During the experiment, the peak value of ODMR fluorescence spectrum is recorded and plotted as a function curve for each set of microwave power. In the actual test, the frequency of the microwave is locked at the f_{-}, f_0, f_{+} positions of the zero-field ODMR in Fig.2(a). The final result is shown in Fig.5.

When the slope of the above function curve is the largest, the sensitivity of ODMR to microwave changes is the largest, and the measurement results are the most accurate. According to the test results, for the three set frequencies, when the microwave power is -15 dBm, the slope of the curve is the largest, and the sensitivity of ODMR to microwave power changes is the largest. However, due to the change of the external magnetic field, the NV color center m_s=±1 Zeeman splitting amount will change, which is manifested in the change of the microwave frequency (f_{-}, f_{+}) corresponding to the peaks on the left and right sides of the ODMR pattern, which will also lead to the change of the signal intensity. In order to eliminate the influence of external weak magnetic field changes on the experimental results, the valley value in the middle of ODMR is usually selected for measurement.

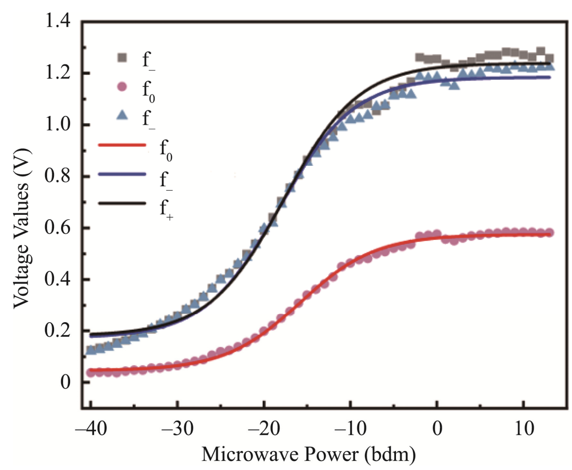
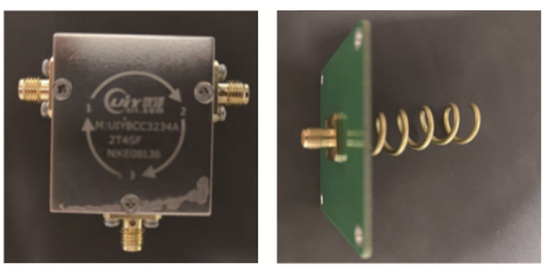


Fig.5 The Peak (Corresponding to and in the Graph, Respectively) Voltage and Valley (Corresponding to the Graph) Voltage of the ODMR as a Function of Microwave Power

3.2.2 Microwave Reflection Effect

When measuring the reflection effect of metal on microwave, the system is modified by using the characteristics of microwave circulator. The schematic diagram of microwave circulator is shown in Fig.6(a). The microwave circulator includes three interfaces 1, 2 and 3. In practice, the transmission of microwave conforms to the 1-2-3 clockwise direction in the figure. When 1 receives the input signal of the microwave, 2 is the output signal of the microwave, and 3 can collect the reflected signal of the microwave. After the microwave signal modulated by the microwave switch passes through the circulator, the microwave is radiated outward through the peripheral antenna. In order to detect the position of the metal more effectively, a directional high-gain circularly polarized antenna is used in the experiment, as shown in Fig.6(b). When there is metal in the radiation space area of the antenna, the microwave will be reflected, and part of the reflected microwave will be collected by the antenna and finally detected by the three interface through the circulator. In practice, affected by the matching impedance of the microwave antenna, even if there is no metal, a part of the microwave will be reflected back. The presence of metal will affect the overall strength of the reflected microwave, and the reflected microwave power will be detected by the NV color center quantum sensor in Fig.5.



(a) (b)

Fig.6 (a) Photo of Microwave Circulator (b) High-gain Circularly Polarized Antenna.

During the experiment, the microwave frequency is set at the position, and the input microwave power is set at the position with the largest slope in Fig.5. Finally, the circularly polarized antenna is fixed above the metal to be tested, and the operation of the guide rail is controlled to control the position of the metal to be tested. When the metal passes directly below the circularly polarized antenna, the change of the output voltage of the lock-in amplifier is observed and recorded.

4 Results and Discussion

In the experiment, the steel bar is selected as the metal to be tested. For the detection of the steel bar, in addition to judging the presence or absence of the steel bar, it is also necessary to identify the size and morphology of different steel bars. Therefore, two sets of experiments were carried out respectively: detecting four steel bars of the same diameter; four steel bars with different diameters were detected.

4.1 Test of Four Identical Steel Bars

In order to determine the relationship between the peak value of the response and the diameter of the steel bar, four steel bars with a diameter of 11.5 mm were selected for testing. The steel bar is placed flat on the translation platform, and the vertical distance between the polarization antenna and the steel bar placement plane is adjusted to 10 cm. Then the polarization antenna is fixed, the sample steel bar is moved back and forth at a constant speed, and the microwave frequency is set at the valley value of ODMR. Then the NV color center sensor is used to measure the microwave change of the 3 port of the circulator. Finally, the experimental data is shown in Fig.7.

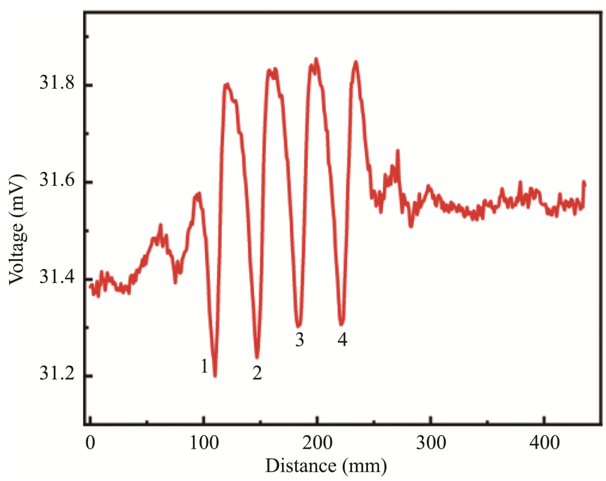


Fig.7 The Response of Microwave to Steel Bars of the Same Diameter, the Abscissa Is the Distance of the Steel Bar Moving, and the Ordinate Is the Voltage Signal Output by the NV Color Center Sensor

The existence of four peaks can be clearly and directly seen from the test results. Firstly, the effectiveness of the detector for metal detection is directly proved. Then it is judged that the output signal has a certain periodicity, and its four peaks (1-4) correspond to the position of each steel bar just below the polarization antenna. At this time, the microwave power changes the most, so the position of the steel bar can be judged according to the position of the peak. On the other hand, it can also be seen that the line shape and full width at half maximum of each peak remain almost unchanged, indicating that the measurement results of the same steel bar are consistent, and then the overall change of the signal is mainly caused by the overall layout of the steel bar and the change of microwave power caused by the operation of the electric translation device.

4.2 Response of Microwave to Steel Bars with Different Diameters

In order to verify the feasibility of the sensor in the measurement of steel bar size, four steel bars with different diameters are used for testing. Similarly, the four steel bars are arranged horizontally. Their diameters are 18mm, 15.5mm, 11.5mm and 8mm respectively. The distance between adjacent steel bars is 10cm. The fixed polarization antenna is unchanged, and the sample steel bars are moved back and forth at a constant speed. The same detection method is used. The measured experimental data are shown in Fig.8.

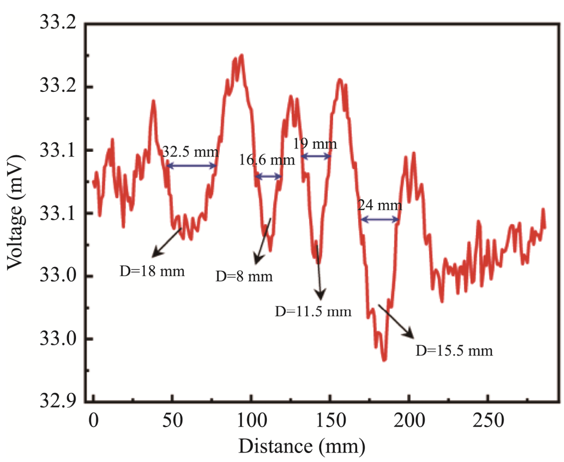


Fig.8 Response of Microwave to Steel Bars with Different Diameters

From the test results, it can be seen that the diameter of the steel bar is different, and the measured peak shape is also different, which is embodied in the half-width of the peak. The line widths of the four steel bars in the graph are 32.5mm, 16.6mm, 19mm and 24mm, respectively. The ratio of half-width to half-width is 1.96: 1: 1.14: 1.45 and the corresponding steel bar size ratio is 2.25: 1: 1.43: 1.9. There is a big difference between the two. The main reason is that the half-width of the peak is not only related to the size of the steel bar, but also to the distance between the quantum sensor and the steel bar. It is difficult to ensure that the vertical distance between the sensor and each steel bar is consistent in the experimental measurement, which makes it necessary to further determine the distance between the steel bar and the probe[3,4,7] in the actual measurement of the size of the steel bar.

5 Conclusion and Future

Based on the above test results, we can get the following conclusions:

The NV color center quantum measurement system is extremely sensitive to the change of microwave power at a suitable microwave frequency. When the microwave is emitted from the air to the metal surface, it will attenuate based on various effects. Therefore, the NV color center system can be used to realize the detection of industrial steel bars.

The advantages of NV color center quantum magnetic system:

(1) The NV color center ODMR fluorescence spectrum is sensitive to microwave power. The steel bar detection based on this principle has many advantages such as high sensitivity and easy experimental manipulation.

(2) Based on the NV color center quantum detection system, the principle of steel bar detection is similar to that of traditional detection technology. Both of them detect steel bars through the attenuation effect of microwave, but the system shows the detection results in a new way - and by changing the spin state of the NV color center to detect the change of the voltage indication of the lock-in amplifier to reflect the presence or absence of steel bars. Verify the old technology

through emerging theories.

(3) The quantum detection system based on NV color center can not only detect the presence or absence of steel bars, but also detect the thickness of steel bars, which cannot be solved by traditional detection methods. During the experiment, when other variables remain unchanged, the diameter of the steel bar is proportional to the full width at half maximum of the curve. It is believed that under the premise of future algorithm optimization, the NV color center quantum measurement system can achieve accurate measurement of the thickness of steel bars.

The disadvantages of NV color center quantum magnetic system:

At present, the quantum sensing system based on NV color center has higher requirements on whether the steel bar is rusty. When the surface of the steel bar is highly oxidized and rusty, it will be found that the voltage value of the lock-in amplifier does not change significantly, so the measurement results are not accurate. In the future, on the one hand, with the improvement of industrial technology, the probability of steel corrosion will decrease; on the other hand, the existing microwave antenna can be replaced by a microwave circuit board with higher radiation efficiency, which improves the sensitivity of ODMR fluorescence spectrum to microwave.

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