Antenna for microwave manipulation of NV colour centres

Man Zhao[1], Qijing Lin[2] ✉, Liangquan Zhu[1], Libo Zhao[1], Zhuangde Jiang[1]

[1]*State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, People's Republic of China*
[2]*Collaborative Innovation Center of High-End Manufacturing Equipment, Xi'an Jiaotong University, Xi'an, People's Republic of China*
✉ *E-mail: qjlin2015@xjtu.edu.cn*

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Nitrogen-vacancy (NV) colour centres in diamond have attracted extensive attention in quantum precision measurement, computation and communication. In these fields, microwave manipulation is a technology in which antenna is used to radiate special microwave to manipulate the quantum spin state of NV colour centres. In this work, high frequency structure simulator software is used to design a microstrip antenna with a resonance frequency of 2.8756 GHz. Based on simulation and experiments, near field radiation of antenna is optimised to improve its microwave manipulation quality. This antenna will be helpful in the development of hybrid quantum devices of NV centres.

1. Introduction: For excellent spin and coherence properties of nitrogen-vacancy (NV) colour centre in diamond, it has attracted extensive attention in the field of quantum precision sensing, computing and communication. As a point defect in solid-state system, NV colour centres have been considered as one of the most promised candidates of the spin carrier, and the quantum nature of spin was shown through quantum superposition and entanglement [1, 2]. The electronic spin state of NV centres could be initialised by laser pump, manipulated by microwave and read out through fluorescence intensity at room temperature [3]. In these fields, the antenna was used to radiate special microwave to manipulate the quantum spin state of NV colour centres in microwave manipulation. We discuss and present the design and numerical simulation results of the antenna. And the microstrip antenna was fabricated and measured. These results will be helpful in the development of hybrid quantum devices for applications in microwave manipulation and quantum technology.

2. Methods: The mainstream technologies about NV centres are laser pump, microwave manipulation and fluorescence reading out. Also microwave manipulation involves different microwave pulse sequences such as optically detected magnetic resonance (ODMR), electronic spin resonance, Rabi oscillation and spin-echo technologies [4–8]. For instance, ODMR signal is read out by the fluorescence intensity when microwave frequency sweeping applied under stable microwave and laser conditions. When the frequency of the microwave is NV centre's Zero field splitting point 2.87 GHz, NV centres would be on a resonance state between two electronic energy levels leading to fluorescence intensity decrease [9]. Thus, microwave manipulation was achieved. In general, the resonance frequency of the antenna should be adjusted to the Zero field splitting point of NV centres 2.87 GHz, and there should be a working bandwidth to meet the sweep function. And the strength of microwave should be strong enough to minimise full width at half maximum of resonance signal in ODMR which means a better manipulation quality.

The studies based on properties of NV colour centres and the effect of microwave on the spin have shown that better microwave radiation performance is needed because the surrounding environment would influence coherence and spin properties of NV centre rapidly [10]. In addition to this, spatial uniformity of the magnetic field is required to guarantee the spatial coherence and extending ensemble spin coherence time, especially for bulk diamond [11, 12]. Besides, a wide bandwidth of the antenna is also required. By developing a microwave radiation structure with good spatial uniformity, the noise caused by the spatial heterogeneity of the microwave field is reduced, and the manipulating precision is improved. The spatial heterogeneity of the microwave field would lead to the broadening of the NV-colour centre resonance line width, thus reducing the quality of coherent spin.

Therefore, it is necessary to design a highly uniform and efficient microwave feeding device. First, we model the antenna through simulation software, design different types of feeding antennas, then use the micro-machining process to fabricate the feeding device and verify the performance of the device by experimental result. In summary, we intend to achieve a high uniformity microwave field in a certain region with strong strength and wide working bandwidth to ensure the spatial coherence of the colour system and the ensemble spin coherence time.

Traditional methods normally use Helmholtz coil and copper wires as antenna to realise microwave radiation, however, there are some disadvantages that microwave field is inhomogeneous, and the antenna is easy to damage, not conducive to integration [13]. The microstrip antenna is a new type of antenna that has been developed for 30 years. In practical applications, the microstrip antenna is small in size, light in weight and especially easy to integrate, compared with the traditional copper wire antenna. Recently, Harvard University has studied a planar open-loop resonator with good spatial uniformity and efficient microwave magnetic field coupling [14]. In another research, dielectric resonator antenna (DRA) was proposed to provide three-dimensional (3D) uniform microwave field with hollow cylinder dielectric resonator [15]. A planar split-ring resonator for uniform and efficient coupling has also been studied by Bayat *et al*. [14].

In our approach, one kind of annular slot microstrip antenna is designed as shown in Fig. 1. There is a simulation model of the antenna shown in Fig. 2. The antenna is composed of the radiating patch, dielectric substrate and grounding plate. The material of the substrate is epoxy fibreglass (FR4) whose relative permittivity is 4.4, and copper is used to make the radiating structure and grounding plate. The thickness of the substrate is 1.6 mm. Parameters a and b are length and width of the substrate designed as 14.2×33 mm^2, respectively. And the copper film on the lower layer of the dielectric substrate is the reference ground of the microstrip antenna, the size of which is 14.2×0.5 mm^2. The geometric dimensions of the microstrip antenna are listed at Table 1, and what these parameters represent are shown in Fig. 2. In the high frequency structure simulator (HFSS) simulation model, the driven model is used, the radiating patch and

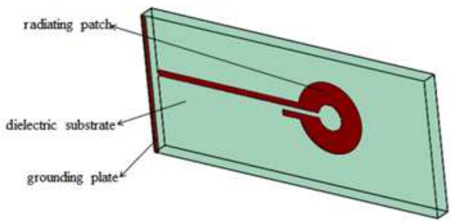

Fig. 1 *Schematic diagram of the microstrip antenna*

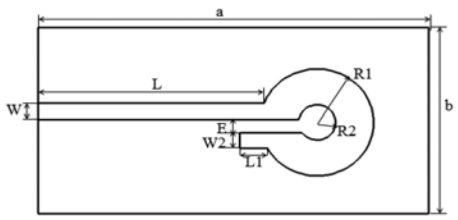

Fig. 2 *Simulation model of microstrip antenna*

Table 1 Main parameters of the microstrip antenna

Parameter	Value, mm
a	33
b	14.2
L	19.2689
*L*1	2.1
W	0.5836
E	0.5083
*R*1	3.6599
*R*2	1.3179
*W*2	0.5

grounding plate is set as Perfect E and excitation is designed as Wave Port. We use parameter sweep function in HFSS software to study the relationship between resonance frequency and parameters of the radiating structure. The optimisation analysis function was used to achieve an optimal parameter solution of the radiating structure in good impedance match.

The radiation patch of the antenna is composed of feeding strip line, unsymmetrical microstrip radiative loop and tape. Parameters *L* and *W* are the length and width of the feeding strip line designed as $19.2689 \times 0.5836\ \text{mm}^2$. The radiative part is generally connected to the signal source through feeding strip line, joint of radiative part and feeding strip line is called the input end of the antenna, the impedance value of which is defined as the input impedance. It is necessary to design the input impedance of antenna the same as feeding strip line's as much as possible, which makes the return loss of resonator as small as possible in working bandwidth to ensure strong enough microwave strength. Usually, we use S_{11} to represent return loss of resonator which indicates the performance of impedance matching and radiation efficiency. And the value of S_{11} should be as small as possible, working bandwidth is usually considered as the frequency range when $S_{11} \leq -10$ dB. The input impedance of the antenna depends on structure, operating frequency and the surrounding environment. In a few cases, it can be strictly calculated by theory. Therefore, in this experiment, we use simulation and experimental methods to reach well impedance matching. The gap width *E* of the microstrip loop could be modulated to change the input impedance. A plot of S_{11} of the antenna as a function of the gap width *E* is shown in Fig. 3. The gap width of the microstrip loop has a high influence on return loss of the antenna S_{11}, but only has a modest effect on the resonant frequency. Then through optimisation of the antenna's geometric dimensions, S_{11} was reduced to approximately −26.76 dB.

A strip of copper tape is designed at another end of the unsymmetric microstrip loop to adjust the resonance frequency. It is a common practice to use stubs or strips for frequency adjusting in microwave antenna designing [16]. Fig. 4 shows the relationship between length of this strip *L*1 and resonance frequency of the antenna, from which we can see that the length should be designed around 2 mm to adjust resonance frequency to 2.87 GHz, In addition, the resonance frequency of the antenna can also be modulated by adjusting the outer radius of the microstrip loop *R*1. Fig. 5 is a graph of the antenna's resonant frequency function with *R*1 as abscissa. The numerical simulation result shows that when

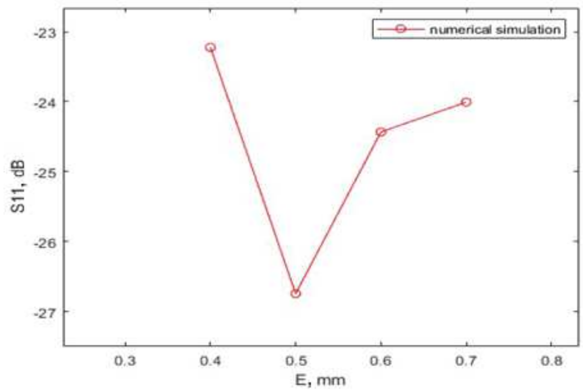

Fig. 3 *S_{11} of resonator as a function of E*

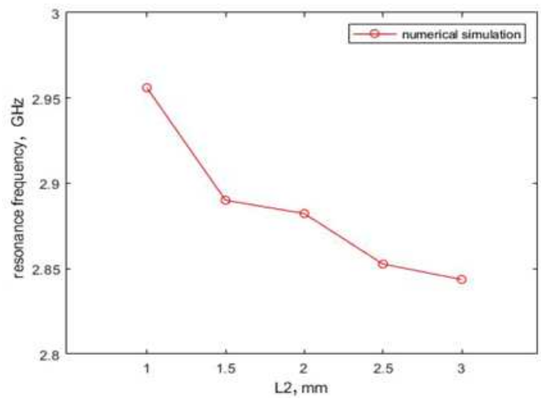

Fig. 4 *Resonance frequency of resonator as a function of L1*

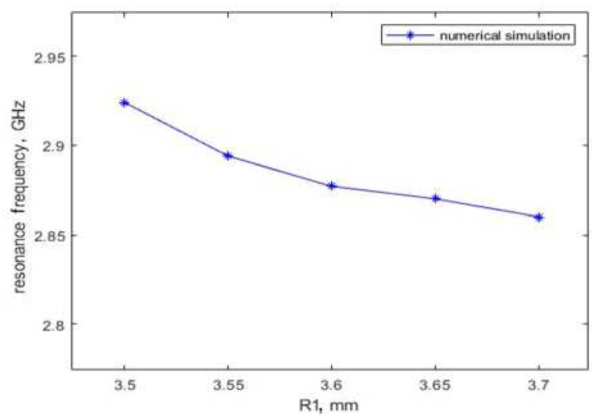

Fig. 5 *Resonance frequency of resonator as a function of R1*

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changing $R1$ from 3.5 to 3.7 mm, the resonant frequency can be adjusted from 2.860 to 2.924 GHz. Finally, optimisation function is used to calculate the accurate numerical value of strip length $L1$ and outer radius of the microstrip loop $R1$ which are designed as 2.1 and 3.6599 mm ensuring the resonance frequency 2.87 GHz and low return loss.

3. Result and discussion: The antenna's picture of real product is shown in Fig. 6, the radiation patch was fabricated on a printed circuit board by using traditional etching technique. The material of the patch is copper with a thickness of 21 µm. The inner pin of SubMiniature version A (SMA) connector is soldered to the microstrip antenna feed port, and the connector housing of the SMA connector is connected to the microstrip antenna reference ground. Furthermore, network analyser was used to measure S_{11} of the antenna. As Fig. 7 shows, the test result of working bandwidth (2.79–2.97 GHz) is just a little smaller than the simulation result (2.78–2.98 GHz). At the same time, the minimum value of S_{11} is −25.76 dB in simulation result at resonance frequency 2.8750 GHz, which has good consistency with the measurement result in the minimum value of S_{11} is −23.45 dB at resonance frequency 2.8756 GHz. And the small return loss indicates the antenna's well impedance matching and few return loss to get stronger microwave with lower energy input. As there is a good consistency between the experimental result and simulation result, we can conclude that the model built using HFSS software would be helpful in guiding the further designing of the antenna.

Homemade magnetic near field scanning probe was used to measure magnetic field strength at the 2 mm upper surface of the substrate. The probe is made of copper coil whose diameter is 4 mm. Besides, the probe could make 2D scanning of the *xy* axis to get the distribution of magnetic field strength. Fig. 8 shows the measuring process of the antenna we design and Fig. 9 shows the measurement result, in which *X* label is parallel to the long side of the antenna. Measurement data is a dimensionless value which can only make a qualitative representation of the magnetic field strength. High magnetic field strength is achieved near the gap and loop, and there is a relatively homogeneous magnetic field distribution.

The near-field high-frequency magnetic probe and frequency analyser were used to measure magnetic field strength of the microwave quantitatively but not accurately. As Fig. 10 shows, the probe produced by Shenzhen Zhiyong Electronics Company was used to measure the magnetic strength, with 30 MHz–3 GHz frequency range and 2 mm resolution. The field intensity distribution in the probe coil was assumed uniform. The probe was put 0.8 mm from the substrate to sweep the magnetic field and the probe should be vertical to the antenna. At 2.87 GHz, the measurement result shows that the maximum value is −20.86 dBm, when the power of Pin = 10 mW inputted to the antenna. −20.86 dBm could be converted to 88.14 dBuA/m, equal to 0.02818 A/m. Besides, the magnetic strength is 0.01862 A/m at 2.77 GHz and 0.01622 A/m at 2.97 GHz. The microwave strength achieved is strong enough to make microwave manipulation.

With a bulk of diamond, there would be a red shift of the resonant frequency approximately of 100 MHz because of the changes in the effective dielectric constant of the resonator, but it does not affect other performance indicators [14]. And the red shift of the

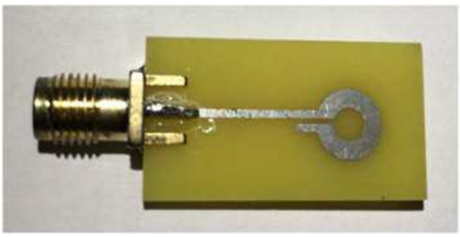

Fig. 6 *Real product of the microstrip antenna*

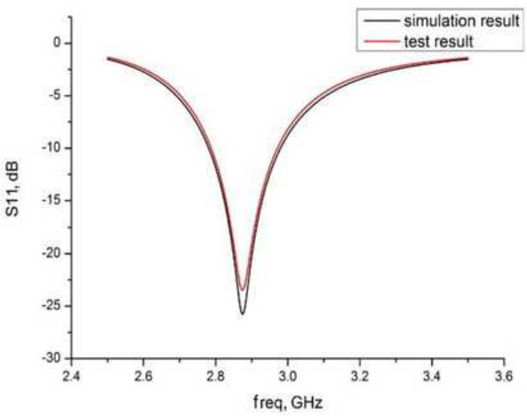

Fig. 7 *S_{11} parameters of the microstrip antenna*

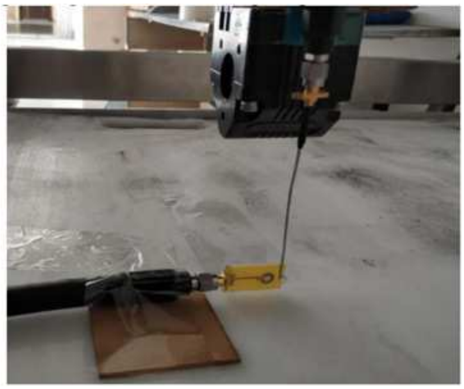

Fig. 8 *Homemade magnetic near field probe*

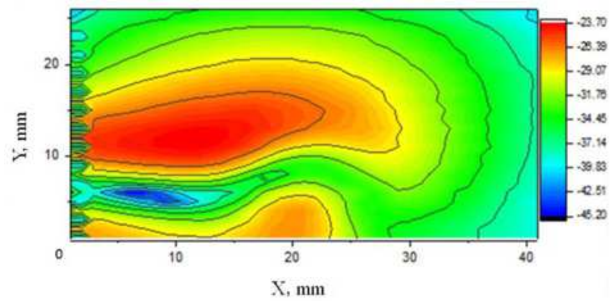

Fig. 9 *Distribution of magnetic field strength*

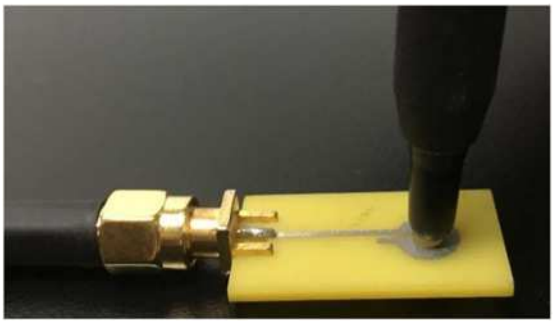

Fig. 10 *Near-field magnetic probe measurement*

resonance frequency would be neglected in the case of nano-diamond. The magnetic field is sharply attenuated from the antenna in the vertical direction, which only provides a 2D uniform field near the substrate. So the antenna is not suitable for a large bulk of diamond. For ensemble diamond application, 3D uniform microwave magnetic field is needed in a relatively large space. A DRA could be applied to meet this application.

The microstrip antenna for microwave manipulation of NV colour centres has been simulated, designed, fabricated and measured. This work is still in process. It will be helpful in the development of hybrid quantum devices for applications in quantum technology based on NV centres.

4. Conclusions: Concerning the results of numerical simulations by using HFSS software, we study and design the antenna. The prototype of the antenna was fabricated and measured in the microwave frequency range. The resonant frequency is achieved at 2.8756 GHz of which S_{11} is -23.45 dB. The bandwidth of the microstrip antenna is 0.20 GHz. It is enough to meet large scale measurement. At feeding power of 10 mW, the max of magnetic field intensity reached 0.02818A/m. Experiments of the microstrip antenna and diamond with NV centres are in process.

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