

Broadband microwave antenna for uniform manipulation of millimeter-scale volumes of diamond quantum sensors

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Y. Takemura,^{1,2} K. Hayashi,¹ Y. Yoshii,² M. Saito,² S. Onoda,³ H. Abe,³ T. Ohshima,³ T. Taniguchi,⁴ M. Fujiwara,¹ H. Morishita,^{1,5} I. Ohki,¹ and N. Mizuochi^{1,5,a)}

AFFILIATIONS

¹Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

²Sumida Corporation, KDX Ginza East Building 7F, 3-7-2, Irifune, Chuo-ku, Tokyo 104-0042, Japan

³National Institutes for Quantum Science and Technology (QST), Takasaki, Gunma 370-1292, Japan

⁴International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

⁵Center for Spintronics Research Network, Institute for Chemical Research, Kyoto University, Uji, Kyoto 611-0011, Japan

^{a)}Author to whom correspondence should be addressed: mizuochi@scl.kyoto-u.ac.jp

ABSTRACT

Quantum sensors based on nitrogen-vacancy (NV) centers in diamond are expected to demonstrate a wide variety of applications. For high-sensitivity quantum sensors with NV center ensembles, uniform manipulation of the electron spins of the NV centers in large volumes is required. In addition, a broad microwave frequency bandwidth for manipulating the NV centers' electron spin is necessary for vector magnetometry and measurement under a finite static magnetic field. Here, we demonstrate a broadband microwave antenna for uniform manipulation of millimeter-scale volumes of diamond quantum sensors. The simulation shows that the current is distributed at both edges of the loop coil of a single copper plate due to the skin effect. The loop coil acts like a Helmholtz coil, which realizes uniformity in the z-direction of the microwave magnetic field (B_1). The plate structure has a higher mechanical stability, durability, and a larger heat capacity than the Helmholtz coil, due to its large volume. The antenna achieves a higher performance than previously reported antennae, with a maximal B_1 of 4.5 G, a broad bandwidth of 287 ± 6 MHz, and a peak-to-peak variation of 9.2% over a 3.1 mm^3 cylinder volume. These performances show that the presented antenna is suitable for manipulating solid-state spin ensembles for high-sensitivity quantum sensors.

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I. INTRODUCTION

Nitrogen-vacancy (NV) centers in diamond have attracted considerable attention as solid-state spin qubits with long spin coherence times,^{1–3} which has led to fascinating research, including in the topics of quantum information processing⁴ and quantum sensors.^{1,5–7} In particular, the development of quantum sensors is remarkable due to their excellent characteristics with high sensitivity^{6–9} and a wide dynamic range.¹⁰ NV-based quantum sensors are expected to demonstrate a wide variety of applications in fields such as biology, medical science, and condensed matter physics. High-sensitivity sensing using NV ensembles distributed in the bulk diamond has attracted particular attention,^{6–8,11} where the

sensitivity is expected to be considerably enhanced by increasing the detection volume.

An NV center is a spin-1 system with a zero-field splitting (ZFS) of 2.87 GHz between $m_s = 0$ and $m_s = \pm 1$ in the ground state. Microwaves at a resonant frequency of around 2.87 GHz are used to manipulate the electron spin of NV centers. An intersystem crossing allows for optical initialization and readout via spin-dependent fluorescence or photocurrent.^{4,12} NV centers' spin levels are sensitive to external environmental changes, which makes it possible to measure a variety of physical quantities such as magnetic field,^{1,6–8,11} temperature,^{5,13} electric field,^{14–16} and pressure.¹⁷ The shot-noise-limited sensitivity of NV-based quantum sensors is

approximately given by¹⁸

$$\eta \approx \frac{1}{\gamma C \sqrt{\beta \tau}} \frac{1}{\sqrt{N}}, \quad (1)$$

where $\gamma = 2.8 \text{ MHz/G}$ is the electron magnetic moment, C is the measurement contrast, β is the fluorescence collection efficiency, τ is the duration of the measurement, and N is the number of NV sensors. The sensitivity can be improved by increasing N through a higher NV density or larger detection volume. Based on this, high-sensitivity sensing with NV ensembles has been developed.^{6–9,11} In 2015, Wolf *et al.* achieved a sensitivity of $0.9 \text{ pT}/\sqrt{\text{Hz}}$ (at 20 kHz) using an ensemble of $N \sim 10^{11}$ NV centers with a volume of $8.5 \times 10^{-4} \text{ mm}^3$.⁶ To achieve higher sensitivity, it is necessary to manipulate a larger number of NV center spins simultaneously, which requires the generation of strong and uniform microwaves, ideally over the entire diamond.

For microwave irradiation of NV centers, thin copper wires³ or millimeter-scale coaxial loop coils^{19,20} are commonly used. Alternatively, lithographically fabricated microstrip waveguides^{21–24} or coplanar waveguides^{25–27} on the diamond surface can be used. While such waveguides have a broad bandwidth and allow the manipulation of the NV center at an arbitrary frequency, they are not suitable for generating uniform microwaves over a large area due to the lack of a loop structure. 2D resonators such as the split ring,^{28,29} Ω loop,^{30–33} and planar ring^{34,35} have been implemented. While these resonators have a narrow bandwidth of less than a few hundred MHz, they achieve high spatial uniformity over an $\sim \text{mm}^2$ area (Table I). However, these resonators can only generate uniform microwaves in the two-dimensional plane. For example, as shown in Wolf *et al.*,⁶ NV centers are distributed throughout a diamond sample, so three-dimensional uniformity, including the vertical direction, is essential. In this context, metal cavity resonators,^{36,37} loop gap resonators,³⁸ dielectric resonators,^{8,39–42} three-dimensional lumped element resonators,⁴³ and Helmholtz coils⁴⁴ have been demonstrated. Such three-dimensional resonators can irradiate microwaves uniformly not only in a plane but also in the vertical direction over an $\sim \text{mm}^3$ volume. Zhang *et al.* simultaneously manipulated NV ensembles distributed in a volume of 0.5 mm^3 using dielectric resonators and achieved a sensitivity of $2.6 - 6 \text{ pT}/\sqrt{\text{Hz}}$ (at $0 - 200 \text{ Hz}$).⁸ However, these three-dimensional resonators provide a narrow bandwidth of $\lesssim 100 \text{ MHz}$, and it is very difficult to drive NV centers simultaneously at multiple resonances, for example, vector magnetic field measurements and double quantum sequences under a finite static magnetic field.^{20,45–48} To overcome such issues, microwaves that are both uniform and intense over a large area and a broad bandwidth are crucial for the antenna design.

Here, we present an antenna with three-dimensional microwave uniformity, high field strength, and broad bandwidth, which would be versatile in the application of spins of NV centers. Our microwave antenna is based on a Helmholtz coil in principle, although our loop coil consists of a single copper plate. It is evaluated by a simulation and an experiment and achieves high performance as a broadband microwave antenna for uniform manipulation on millimeter scale volumes.

TABLE I. Comparison of microwave antennas' performances.

Reference	41	38	28	34	44	This result
Design	Dielectric resonator antenna	Loop gap resonator	Double split-ring resonators	Planar ring antenna	Helmholtz coil	Helmholtz coil
Area (mm^2)	4.1	~ 50	1.1	~ 1	12.6	8.04
P_{in} (W)	5.2	16	0.5	1	0.5	16
B_{imax} ($\text{G}/\sqrt{\text{W}}$)	2.2	1.2	8.4	2.7	1.2–1.8 (simulation)	1.1
B_1 uniformity (%)	< 1 (rms) at 7 mm^3	3 (pp) at 11 mm^2	4.4 (rms) at 1.1 mm^2	18 (pp) at 0.6 mm^2	< 6 (pp) at 25.2 mm^2	9.2 (pp) at 3.1 mm^3
Bandwidth (MHz)	30	80	40	400	110	287

This article is structured as follows. Section II describes the simulation method, the detailed design of the microwave antenna, and the measurement setup. Section III details the evaluation results for the microwave antenna. Section IV compares our microwave antenna with other antennae and discusses the advantages of our antenna. Section V summarizes the results.

II. EXPERIMENTAL DETAILS

A. Simulations

The performance of the antenna is simulated using three-dimensional (3D) electromagnetic field analysis software (Femtet, Murata Software Co., Ltd.). In the simulations, a 3D model of the antenna is calculated and appropriate boundary conditions are used. The stray capacitance that occurs in the actual design is neglected.

B. Design of the microwave antenna

The antenna consists of an input port, a matching circuit built into a polytetrafluoroethylene (PTFE) circuit board for impedance matching throughout the antenna, and a single loop coil for generating and applying microwaves to the diamond sample, as shown

in Fig. 1(a). The loop coil consists of a copper plate and has a diameter of 3.2 mm and a height of 1.0 mm. To suppress the heating effect, we did not insert the intentional resistance for impedance matching and used a circuit board of low dissipation factor material (PTFE). We confirmed that the temperature of the antenna and the circuit board was less than 30 °C at the input microwave power of 16 W.

The loop coil is equivalent to a parallel RLC circuit, in which the capacitance C_0 arises from the loop coil gap. The circuit board has inductance L_1 and conductance C_1 and is connected to the loop coil in series. The total impedance Z_T is expressed as

$$Z_T = R_T + j \left(\frac{\omega L_0}{1 - \omega^2 L_0 C_0} + \omega L_1 - \frac{1}{\omega C_1} \right), \quad (2)$$

where R_T is the total resistance of the antenna, L_0 is the inductance of the loop coil, and ω is the angular frequency of the microwave. The imaginary part of Eq. (2) is zero at the resonant frequency. The peak of the standing wave is located in the loop coil by optimizing the feedline length and shape, circuit type, and impedance. Optimal values for all parameters are derived from the simulation. Figure 1(b) shows the simulated result of the current distribution for a 2.93 GHz microwave applied to the antenna. The red dotted lines indicate the

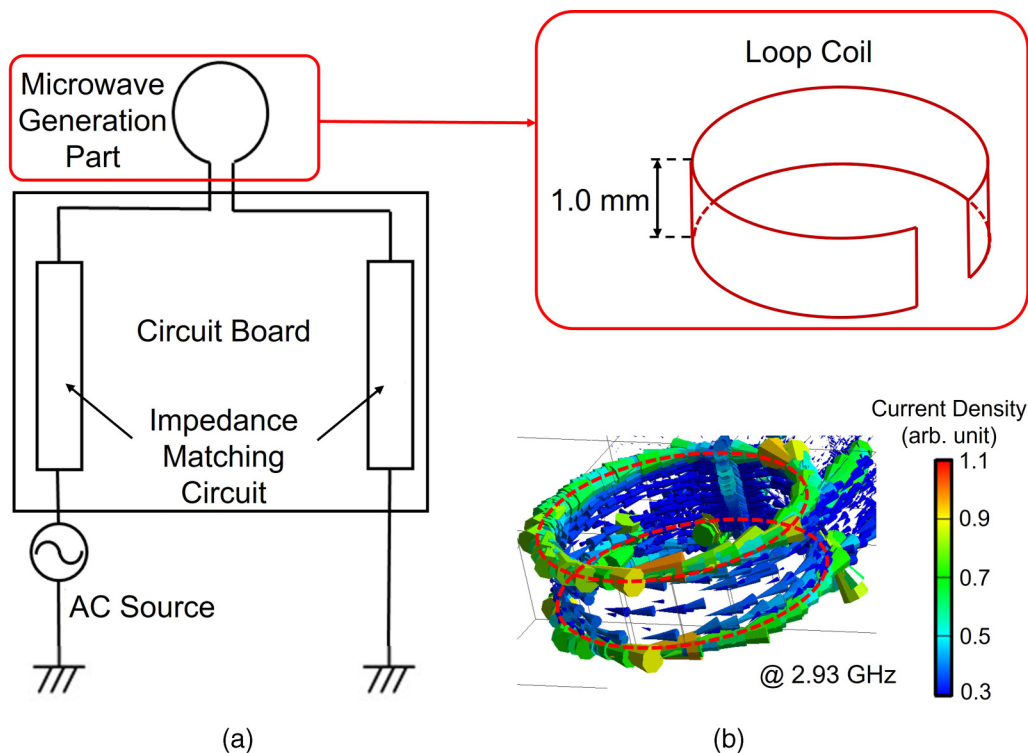


FIG. 1. (a) Schematic of the microwave antenna configuration. The antenna is chiefly composed of an input port, a matching circuit for impedance matching throughout the antenna, and a microwave generation part for applying microwaves to the diamond sample. The microwave generation part is a loop coil consisting of a copper plate with a diameter of 3.2 mm and a height of 1.0 mm. (b) Simulated result of the current distribution for an applied microwave of 2.93 GHz. The loop coil performs as a double coil, generating highly uniform microwaves in three dimensions.

long sides of the copper plate that makeup the loop coil. From the simulation, the current is distributed at both edges of the loop coil due to the skin effect,⁴⁹ acting as a double coil.

C. Experimental setup

The reflection coefficient S_{11} is measured using a network analyzer (E5063A, Keysight Technologies Co., Ltd.). Continuous-wave optically detected magnetic resonance (CW-ODMR) and Rabi measurements by pulsed-ODMR are performed with a home-built confocal microscope with a magnetic resonance system. The NV center is excited by a 532 nm laser (Juno 532 nm, Showa Optronics Co., Ltd.). An acousto-optic modulator controls the duration and interval of laser illumination. The fluorescence is detected by an avalanche photodiode (SPCM-AQRH, Excelitas Technologies Co., Ltd.) through an objective lens (M Plan Apo HR 100, Mitutoyo Co., Ltd.). The position of the objective lens is fixed, and the diamond sample and the antenna are moved in the XYZ directions with three-axis translation stages. A microwave with a power of 16 W is generated by a signal generator (SMIQ03, Rohde&Schwarz) with an amplifier (ZHL-16W-43-S+, Mini-Circuits Co., Ltd.). A solid-state switch (ZASWA-2-50DR+, Mini-Circuits Co., Ltd.) is employed to generate microwave pulses. A circulator is connected to the antenna to protect RF components from signal reflection.

A diamond sample of 1.8×10^{18} NV/cm³ is mounted at the center of the loop coil with the [111] axis parallel to the loop coil axis. The diamond was synthesized by high-pressure high-temperature (HPHT) processes. The NV centers were created through 2 MeV electron irradiation with a fluence of 1.0×10^{18} /cm²

at 745 ± 10 °C and subsequent annealing at 1000 °C for 1 h in Ar gas. After annealing, the diamonds were cleaned in a boiling mixture of acids (1:1 sulfuric, nitric) to remove graphitic carbon and oxygen termination at the surface. The NV center concentrations were investigated by comparing the fluorescent intensity between a single NV center and our sample.

III. RESULTS

To confirm the performance of the designed antenna, S_{11} is simulated, where S_{11} is the return loss of the antenna and is expressed as

$$S_{11} = -10 \log_{10} \frac{P_R}{P_T} \text{ (dB)}, \quad (3)$$

where P_T is the input power to the antenna and P_R is the reflected power from the antenna. Figure 2(a) shows the simulated result of S_{11} . The simulation indicates a resonant frequency of 2.93 GHz and S_{11} of -9.7 dB. In addition, a return loss is -6 dB (transmittance over 75%) in the range of 2.89–2.97 GHz. Figure 2(b) shows the measurement result of S_{11} . The measured resonant frequency is 2.92 GHz, and S_{11} is -9.9 dB. These values are almost consistent with the simulated results. On the other hand, the simulated bandwidth is 75 MHz (at -6 dB) while the experimental bandwidth is 181 MHz (at -6 dB), which is a difference of more than a factor or two. This difference is considered to be due to stray capacitance between the antenna and other systems, such as jigs to fix the antenna, and shape errors of the actual antenna, such as feedlines.

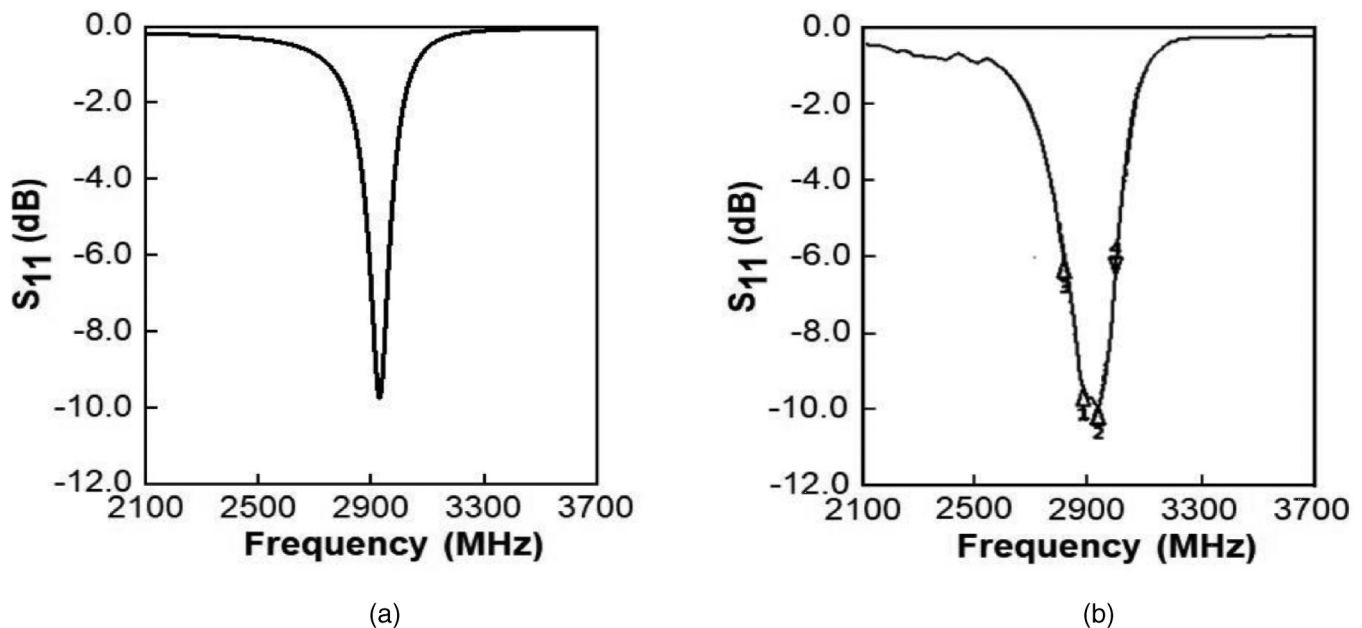


FIG. 2. (a) Simulated result of S_{11} showing the resonant frequency of 2.93 GHz, the minimum S_{11} of -9.7 dB, and the bandwidth of 75 MHz (at -6 dB). (b) Experimental result using a network analyzer. The resonant frequency is 2.92 GHz, the minimum S_{11} is -9.9 dB, and the bandwidth is 181 MHz (at -6 dB).

The above results show experimentally that the designed antenna could operate in the resonance frequency region of the NV centers.

The strength of the microwave magnetic field B_1 within the loop coil is evaluated by the Rabi measurement. For quantum sensors, it is necessary to realize Rabi oscillation to manipulate spins coherently and to have a sufficiently large B_1 for fast manipulation. We carry out CW-ODMR to identify the resonance frequency of NV electron spins. The static magnetic field B_0 shifts the energies of the $m_s = \pm 1$ ground state due to the Zeeman effect. The Zeeman shifts are expressed as

$$\Delta E_{\text{Zeeman}} = \gamma B_0 \cdot S_i, \quad (4)$$

where S_i is the $S = 1$ spin operator oriented along one of the four diamond crystallographic axes. The CW-ODMR spectrum is shown in Fig. 3(a). A static magnetic field is applied along one of the three NV axes except [111] using a permanent magnet. The lowest and highest frequencies are the peaks of the NV axis parallel to the static magnetic field.

A typical Rabi oscillation is measured at the highest resonant frequency (2909 MHz), as shown in Fig. 3(b). The data are fitted with an exponentially decaying sinusoid to extract the Rabi frequency f_R . The relation between f_R and B_1 is expressed as³⁴

$$B_1 = \frac{\sqrt{2}f_R}{\gamma \sin \beta}, \quad (5)$$

where β is the angle between the NV axis and B_1 . The fitting result gives $f_R = 8.1$ MHz at the center of the loop coil, and $B_1 = 4.5$ G is calculated. This is the maximal value in our measurements.

The distributions of B_1 in the xz and yz planes of the loop coil are simulated, as shown in Fig. 4(a). For application to high-sensitivity quantum sensors, we designed and evaluated for uniformity within a radius of 1 mm from the center of the coil, which is a 3.1 mm^2 circular area. Focusing on the z -direction in the loop coil, the microwaves are nearly uniform over 1 mm along the z -direction, as expected from the principle and shown in the lower xz plane figure in Fig. 4(a). B_1 is measured at three points, the center point of the loop coil and points ± 1 mm away from it in the x -direction, where the simulation suggests the lowest uniformity, indicated by the red dots in Figs. 4(a) and 4(b). The B_1 uniformity is quantitatively evaluated using the peak-to-peak variation σ_{pp} defined as

$$\sigma_{pp} = \frac{B_{1\text{max}} - B_{1\text{min}}}{B_1} \times 100. \quad (6)$$

The values of B_1 at each measurement position are shown in Table II, and $\sigma_{pp} \approx 9.2\%$ is estimated for the three points, implying B_1 uniformity over a 3.1 mm^2 circular area. Including the uniformity over 1 mm along the z -direction in Fig. 4(a), the estimated region of the peak-to-peak variation can be extended to the volume of a 3.1 mm^3 cylinder. This is a comparable high level of performance in terms of uniformity as a relatively narrow band antenna for an NV center.^{28,38,42,44}

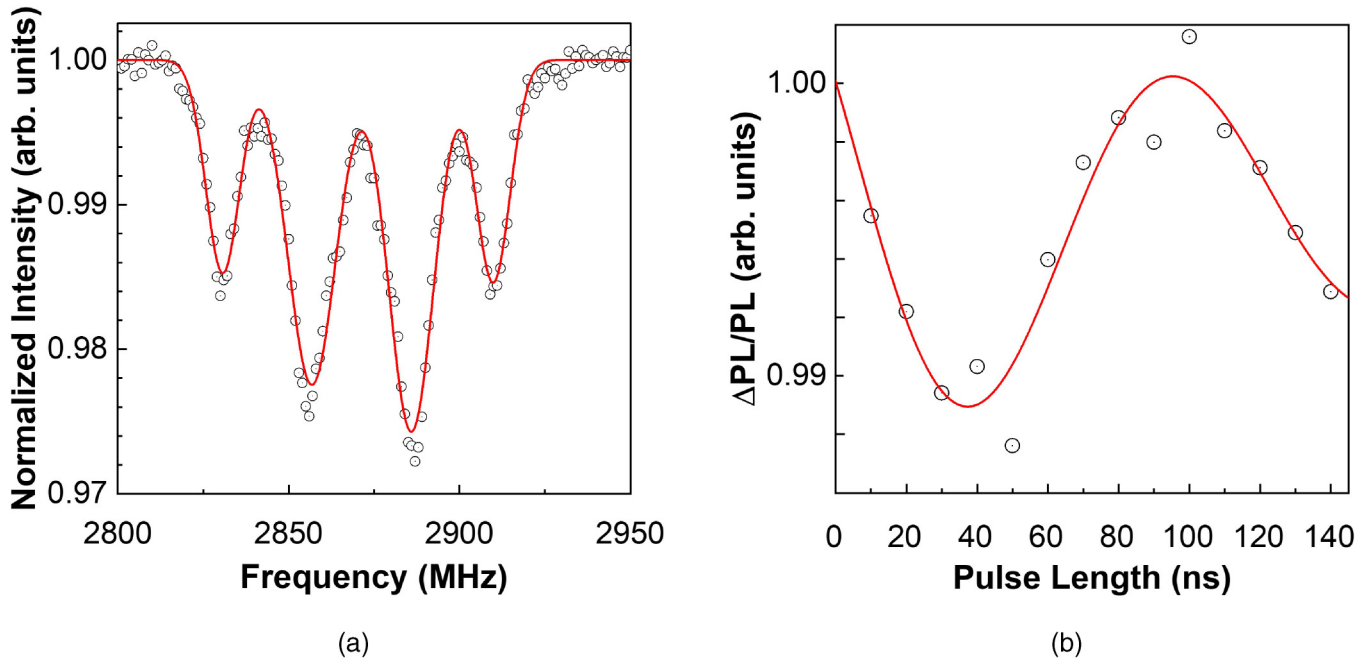


FIG. 3. (a) Experimental result of CW-ODMR. The experimental data (white circle) are fitted (red line) to four Gaussians. A resonance frequency of 2909 MHz (red arrow) is used in the Rabi measurement. (b) Experimental result of Rabi measurement. The experimental data (white circle) are fitted (red line) to an exponentially decaying sinusoid. A Rabi frequency of 8.1 MHz is estimated.

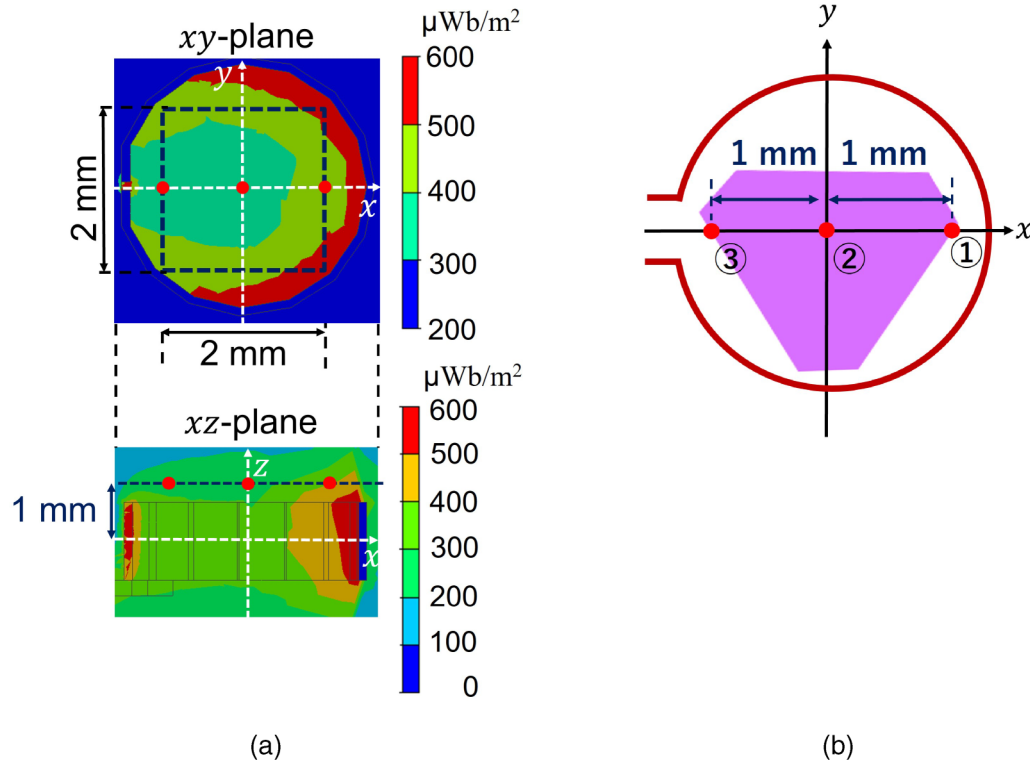


FIG. 4. (a) Simulated result of the B_1 distribution in the loop coil. The upper figure is the result of the cross section of the loop coil in the xy plane. The lower figure is the result of the cross section in the xz plane. (b) Schematic of the diamond sample and the loop coil when the B_1 distribution is measured. The three red dots show the measured positions.

The frequency dependence of B_1 is measured at the center of the loop coil, as shown in Fig. 5. The NV resonance frequency is varied by changing the static magnetic field strength applied to the sample. Here, the data are fitted to estimate the bandwidth, assuming a Gaussian fitting function. The estimated bandwidth is 287 ± 6 MHz. This indicates that our antenna can be used for various frequency measurements within a range of approximately ± 144 MHz from the resonant frequency. This is greater than that achieved for broadband microwave antennas by other research groups.^{34,42,44}

IV. DISCUSSION

The antenna presented here achieves a maximal B_1 of 4.5 G, a bandwidth of 287 ± 6 MHz, and $\sigma_{pp} \approx 9.2\%$ over a 3.1 mm^3

cylinder volume. Each of these performance parameters is high compared to microwave antennas with high B_1 uniformity developed by other groups, as shown in Table I. Furthermore, a nearly uniform B_1 is generated in the z -direction of our loop coil, which enables NV centers to be manipulated uniformly in three dimensions. The bandwidth estimated from Rabi measurements is about 1.5 times broader than the S_{11} result measured with a network analyzer. This difference is due to differences in the measurement position, since the characteristics at the input port of the coil are measured for S_{11} , whereas the Rabi measurement is performed at the center of the coil. Another possible contributor to the difference is the stray capacitance between the coil and other systems, such as objective lenses and jigs. Although our loop coil consists of a single copper plate, its operation is equivalent to that of a double coil. Therefore, a stronger magnetic field can be expected using a thinner loop coil. However, in such a case, it should be noted that the volume of the magnetic field uniformity in the z -direction is smaller, so the design must be appropriate for the thickness of the diamond sample. Compared to a Helmholtz coil, our loop coil has a higher mechanical stability and durability and a larger heat capacity due to its large volume, which is expected to suppress heating of the system. Optimizing the resonance frequency by employing trimmer capacitors may also be possible.

TABLE II The distribution of B_1 at the positions shown in Fig. 4(b).

Position	B_1 (G)
①	4.25
②	4.00
③	3.88

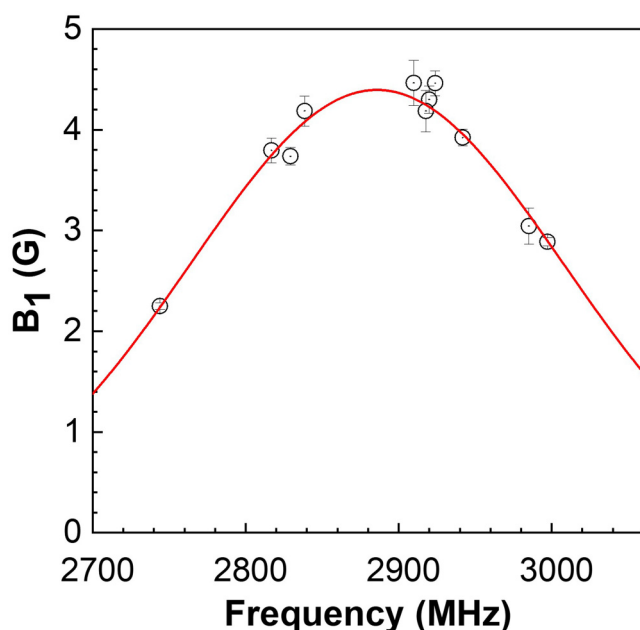


FIG. 5. Frequency dependence of B_1 at the center of the loop coil. The data (white circle) are fitted (red line) assuming a Gaussian as the fitting function. A bandwidth of 287 ± 6 MHz is estimated.

V. SUMMARY

A broadband microwave antenna is demonstrated for uniform manipulation of millimeter-scale volumes of diamond quantum sensors in diamond. Our antenna generates a microwave with a maximal B_1 of 4.5 G, a bandwidth of 287 ± 6 MHz, and a peak-to-peak variation of 9.2% over a 3.1 mm^3 cylinder volume. The simulation confirms that the current is distributed at both edges of the loop coil due to the skin effect, which indicates that our antenna acts as a Helmholtz coil, contributing to the uniformity of B_1 in the z -direction. Our antenna achieves both millimeter-scale high B_1 uniformity in three dimensions and a broad bandwidth compared to other previously reported antennas, resonators, and coils. We expect combining our antenna with NV ensemble-based sensors will contribute to improving quantum sensors and vector imaging applications. Furthermore, changing the center frequency can also be useful for the performance of other solid-state centers.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Y. Takemura: Formal analysis (equal); Investigation (equal); Writing – original draft (equal). **K. Hayashi:** Data curation (equal); Formal analysis (equal); Investigation (equal); Writing – original draft (equal). **Y. Yoshii:** Conceptualization (equal); Data curation (equal); Funding acquisition (equal); Supervision (equal). **M. Saito:** Data curation (equal); Investigation (equal). **S. Onoda:** Investigation (equal); Methodology (equal); Resources (equal). **H. Abe:** Methodology (equal); Resources (equal). **T. Ohshima:** Investigation (equal); Methodology (equal); Resources (equal). **T. Taniguchi:** Methodology (equal); Resources (equal). **M. Fujiwara:** Investigation (equal); Methodology (equal); Resources (equal). **H. Morishita:** Investigation (equal); Methodology (equal); Software (equal). **I. Ohki:** Investigation (equal); Methodology (equal); Resources (equal). **N. Mizuochi:** Conceptualization (equal); Funding acquisition (equal); Supervision (equal); Validation (equal); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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