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RESEARCH ARTICLE

Integrated coplanar waveguide coil on diamond for enhanced homogeneous broadband NV magnetometry

[version 1; peer review: 2 approved, 2 approved with reservations]

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v1 **First published:** 01 Mar 2024, **4**:44
https://doi.org/10.12688/openreseurope.16875.1
Latest published: 01 Mar 2024, **4**:44
https://doi.org/10.12688/openreseurope.16875.1

Abstract

Nitrogen-vacancy (NV) centers in diamond have emerged as promising quantum sensors due to their highly coherent and optically addressable spin states with potential applications in high-sensitivity magnetometry. Homogeneously addressing large ensembles of NV centers offers clear benefit in terms of sensing precision as well as in fundamental studies of collective effects. Such experiments require a spatially uniform, intense, and broadband microwave field that can be difficult to generate. Previous approaches, such as copper wires, loop coils, and planar structures, have shown limitations in field homogeneity, bandwidth, and integration in compact devices. In this paper, we present a coplanar waveguide (CPW) gold coil patterned on a 3 × 3 mm2 diamond substrate, offering full integration, enhanced stability, and broad bandwidth suitable for various NV sensing applications. Coil fabricated on diamond offers several advantages for magnetometry with NV centers ensemble, including enhanced heat dissipation, seamless integration, scalability, and miniaturization potential. We optimize critical geometrical parameters to achieve a homogeneous magnetic field with a coefficient of variation of less than 6% over an area of 0.5 mm2 and present experimental results confirming the performance of the proposed CPW coil.

Plain language summary

In recent years, there has been significant interest in using nitrogen-vacancy (NV) centers in diamond as quantum sensors for high-sensitivity magnetometry. These NV centers, particularly the negatively charged ones, offer promising applications due to their coherent spin states that can be manipulated using microwave fields and optically detected magnetic resonance techniques. However, to improve measurement precision and signal-to-noise ratio, it's

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advantageous to address large ensembles of NV centers, which requires a spatially uniform, intense, and broadband microwave field. Various methods, such as copper wires, loop coils, and planar structures, have been explored to achieve this, but with limited capability. To address their limitations, a coplanar waveguide (CPW) gold coil patterned on a CVD diamond substrate is proposed. This design offers a highly homogeneous magnetic field, full integration with the diamond substrate, scalability, miniaturization, and efficient heat dissipation, making it a promising solution for NV magnetometry applications. Experimental results confirm its performance, making it a remarkable advancement in this area.

Keywords
Nitrogen-vacancy centers, Diamond quantum sensors, Magnetometry, Coplanar planar waveguide coil, Microwave field homogeneity, Broadband antenna design, Diamond substrate integration.



This article is included in the Horizon 2020 gateway.



This article is included in the Wireless Communications collection.

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Author roles: Babashah H: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Losero E**: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Resources, Supervision, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Galland C**: Conceptualization, Funding Acquisition, Project Administration, Supervision, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No [754354].

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How to cite this article: Babashah H, Losero E and Galland C. **Integrated coplanar waveguide coil on diamond for enhanced homogeneous broadband NV magnetometry [version 1; peer review: 2 approved, 2 approved with reservations]** Open Research Europe 2024, **4**:44 https://doi.org/10.12688/openreseurope.16875.1

First published: 01 Mar 2024, **4**:44 https://doi.org/10.12688/openreseurope.16875.1

1 Introduction

The investigation of nitrogen-vacancy (NV) centers in diamond as quantum sensors has attracted considerable interest in recent years, driven by their promising applications in high-sensitivity magnetometry[1–3]. Specifically, the negatively charged NV center has been the subject of extensive research due to its highly coherent spin states, which can be controlled through microwave fields and polarised and probed using continuous wave optically detected magnetic resonance (CW-ODMR) techniques[4].

Whenever nanoscale spatial resolution is not targeted, it is advantageous to address large ensembles of NV centers in order to improve the signal-to-noise ratio and enhance the measurement precision, theoretically scaling as $1/\sqrt{N}$ for N identical color centers contributing to the signal. This advantage is only fully leveraged under a spatially uniform, intense, and broadband microwave field, which should ideally be generated within a compact and integrated design[5]. Achieving these conditions ensures optimal performance and compatibility across various applications, spanning the fields of medical imaging, nanoscale nuclear magnetic resonance (NMR) spectroscopy[6], quantum information processing[7], geophysical exploration[8], navigation and positioning[9], magnetic microscopy[10], and high dynamic range magnetic field sensing[11,12].

The primary challenge lies in generating highly homogeneous broadband microwave fields over a large area at the center frequency of 2.87 GHz. Various methods have been explored to overcome this challenge, with mixed results. Copper wires, for instance, are capable of generating intense magnetic fields, which are useful for single NV centers[13]. However, they exhibit poor magnetic field homogeneity. Furthermore, the alignment of the copper wires with the NV centers can lead to substantial variations in microwave magnetic field strengths (B_1), affecting the performance of the magnetometer. Loop coils offer an alternative approach and produce a B_1 field with superior homogeneity[14]. However, this field is relatively low, limiting their effectiveness. Researchers have turned to planar structures on different dielectric substrates in an attempt to address these issues.

Bayat *et al.*[15] developed a double split ring resonator, which generates spatially uniform magnetic fields and efficiently couples to NV centers. While the resonator does produce a B_1 of around 0.78 Gauss, it suffers from a low bandwidth of 40MHz. Sasaki[16] introduced a planar ring antenna that generates a higher B_1 of 3.2 Gauss and has a larger bandwidth of 400 MHz. Despite these improvements, the design is not compact and it suffers from a poor reflection coefficient, which reduces the microwave excitation efficiency and requires the use of a microwave isolator to prevent potential damage to the driving circuit. Opaluch[17] proposed a planar antenna fabricated on a glass substrate, which presents a large bandwidth and a relatively high B_1 of 2 Gauss. However, the homogeneous field area is limited to a maximum of 0.28 mm^2. Additionally, the design is not fully integrated on a typical diamond-sized substrate (3mm × 3mm) due to its large size, hampering the development of a fully integrated sensor. In summary, while each of these approaches offers certain advantages for NV- ensemble-based magnetometry, none provides an ideal solution. Further research and development are needed to create a planar antenna design that generates a spatially homogeneous, intense, and broadband microwave field while maintaining a compact, integrated form factor making it a good candidate for real applications.

To address these limitations, we propose a coplanar waveguide (CPW) gold coil patterned directly on the 3 × 3 mm^2 surface of a CVD diamond substrate, designed to achieve a highly homogeneous magnetic field over a large area of 0.5 mm^2. The proposed CPW coil offers the advantage of full integration with a diamond substrate hosting NV centers, which can significantly enhance the sensor's stability and robustness. This design has the advantage of being both scalable and miniaturized, as well as providing efficient heat dissipation during the operation of the coil thanks to the diamond high thermal conductivity. Additionally, the CPW coil features a broad bandwidth suitable for sweeping microwave fields from 1.5 to 4 GHz, a requirement for certain NV applications[16]. To facilitate ease of testing and operation, we also propose simple printed circuit board (PCB) and holder designs that eliminate the need for RF probe needles. Importantly, the magnetic field generated by the CPW is entirely perpendicular to the diamond plane. We have optimized critical geometrical parameters, such as the diameter of the omega-shaped resonator, the width of the waveguide, and the gap size, to achieve the desired magnetic field homogeneity. S-Parameter analysis and experimental results from Rabi measurements demonstrate good agreement with simulation results, confirming the performance of the proposed CPW coil. By addressing the challenges associated with earlier antenna designs, our CPW coil provides a more effective solution for NV magnetometry applications, combining homogeneity, broad bandwidth, and ease of use with the potential for full integration on a diamond substrate. The performance of the proposed antenna compared with the other options present in the literature is summarized in Table 1.

This paper is organized as follows: Section 2 discusses the antenna design and geometry, detailing the specific features that contribute to its performance. Section 3 delves into the fabrication process of the CPW on the diamond substrate, as well as the construction of the PCB stack. In Section 4, we analyze the antenna's performance, comparing simulation and experimental results, and present the characterization of the NV ensemble using the proposed antenna. This assessment will demonstrate the effectiveness of the CPW coil in achieving the desired magnetic field and homogeneity. Finally, Section 5 provides a conclusion, summarizing the key advantages of the proposed CPW coil and its potential impact on the field of NV magnetometry.

2 CPW Design and Geometry

The design of the CPW coil has been performed through numerical simulations utilizing finite element method (FEM) techniques in ANSYS HFSS software. We began by parametrically defining a gold pattern, with all the parameters illustrated in Figure 1a. The gold pattern is simulated with a bulk

Table 1. Comparison of different antennas parameters.

Design	B_1 (Gauss)	Field Area (mm^2)	Bandwidth (MHz)	Dimension (cm^2)
Bayat[15]	0.78	4.5	40	2 × 2
Sasaki[16]	3.2	3.1	400 (S_{11} < −2dB)	5 × 3
Oplauch[17]	1.1	0.2	0-6200	1.6 × 1.1
This work	1.6	0.5	2000-2900	0.3 × 0.3

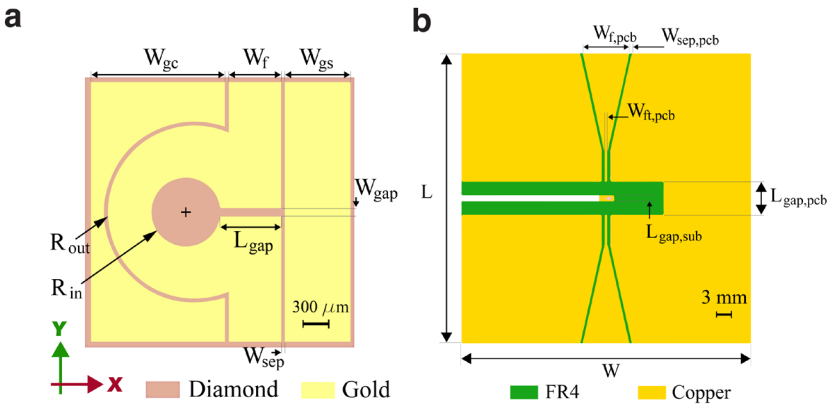


Figure 1. (**a**) Schematic diagram of the proposed antenna, patterned on a (3 × 3)mm² diamond chip and designed for efficient coupling of the microwave field to NV centers. (**b**) Schematic diagram of the PCB holder for ease of excitation and characterization of the CPW antenna. The PCB design comprises two layers. On the top layer, a 50Ω coplanar waveguide with SMA connectors is patterned and truncated. The top layer is then connected to a transmission line in the bottom through three vias for the ground and excitation ports.

conductivity of $\sigma = 4.5 \times 10^7$ S/m, the diamond substrates with dimensions 3.1 mm ×3.1 mm ×0.5 mm diamond substrate, featuring a thickness of 500 μm and a relative permittivity of $\epsilon_r = 5.7$. The structure is excited through a 50Ω wave port. To avoid higher-order modes and ensure the correct fundamental mode is excited, we select a wave port size smaller than the lowest wavelength employed in the simulation. Additionally, we set the height of the wave port to be at least five times the thickness of the diamond substrate, and the width to be at least three times the width of the feed line denoted as W_f. For the boundary conditions, we utilize a radiation box with dimensions ten times larger than the structure, which provides sufficient numerical stability throughout the simulation run time. Furthermore, a genetic algorithm optimization approach is employed to optimize the antenna parameters, including W_f, W_{sep}, W_{gap}, and L_{gap}. The optimization aims to maximize the B_1 field generated at the coil's center while minimizing the coefficient of variation (CV) for its magnitude at the green circles given in Figure 6a. Simultaneously, it enforces an acceptable reflection coefficient (S_{11}) of less than −10 dB. We set the convergence criterion, the maximum magnitude difference between successively calculated S-parameters, to be lower than 1×10^{-5} for each simulation.

In addition to the CPW design, a two-layer printed circuit board (PCB) and a 3D-printed holder has been designed to facilitate easy excitation and characterization of the antenna without necessitating an RF probe station setup. This configuration is achieved by placing the antenna between the PCB and the holder, which establishes the connection. We selected a PCB with a thickness of 800 μm, composed of FR4 substrate with a relative permittivity of 4.4. Figure 1b depicts the schematic of the designed PCB, which employs a CPW design. The feed line width and separation are chosen to attain a 50 Ω impedance at the input and then truncated to gradually reach the CPW dimension limits. The CPW diamond coil is connected to the PCB inputs through three vias at each port. The optimized dimensions for both the diamond CPW coil and the PCB are provided in Table 2. Alternatively, the antenna can be excited without the need for a PCB by directly soldering micro-miniature RF connectors to the CPW on the diamond chip.

3 Fabrication Process

We fabricate our antenna on a commercially available ⟨100⟩ polished CVD-grown single crystal diamond substrate, presenting a uniform native NV concentration of ∼ 1.5 ppb (3.1 mm×3.1 mm×0.25 mm, optical grade, Element6). The fabrication process flow is depicted schematically in Figure 2. First, the sample is mounted using an adhesive (QuickStick mounting wax) on a standard Si wafer to facilitate handling and processing. To eliminate potential contamination, the sample is cleaned in acetone and then subjected to a piranha solution (3:1, H_2SO_4 : H_2O_2, 3 min) treatment.

Table 2. Dimensions of the proposed CPW coil and printed circuit board (PCB), in μm.

W_{gc}	W_f	W_{gs}	W_{sep}	W_{gap}
1550	600	75	50	100
L_{gap}	R_{in}	R_{out}	$W_{f,pcb}$	$W_{ft,pcb}$
700	400	950	8500	500
$W_{sep,pcb}$	$L_{gap,pcb}$	$L_{gap,sub}$	W	L
500	6000	1000	53000	53000

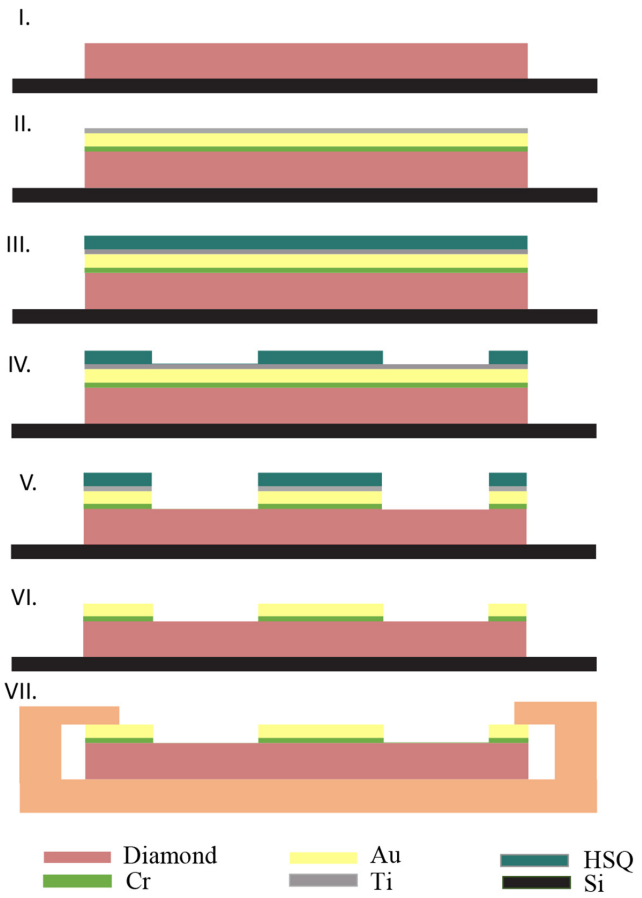


Figure 2. Fabrication process for our gold CPW antenna on diamond. I. Diamond substrate cleaning, non-contact fine polishing (see main text) and mounting on a Si carrier wafer. **II**. Evaporation of Cr (10nm) - Au (200nm) - Ti (10nm). **III**. Spin-coating of HSQ negative resist (150nm) **IV**. Electron beam lithography with the antenna design, and development in TMAH. **V**. Ion beam (Ar) etching of the Cr-Au-Ti multilayer. **VI**. Stripping of the HSQ and Ti layer in diluted hydrofluoric acid (HF). **VII**. Removal from the carrier wafer and possible integration in the PCB.

In order to enhance the surface quality by removing residual mechanical polishing lines and pits and other surface defects, a preliminary non-contact polishing step is applied. This process employs the physical bombardment of the diamond surface with accelerated Ar gas ions (having an energy of 750 eV) at different incident angles. Further details of this process can be found in 18. Following our non-contact polishing, a root mean square (rms) roughness of less than 2 nm is measured over a 10 μm^2 region. We then evaporate 10 nm of Cr, 200 nm of Au and 10 nm of Ti. Both Cr and Ti serve as adhesion layers. Afterward, we spin coat ~ 150 nm Hydrogen silsesquioxane (HSQ XR-1541-006) negative resist, and pattern the antenna design using electron beam lithography. The critical dimensions of the antenna allow us to use a big pixel dimension and electron beam diameter, resulting in a fast exposure time of less than 2 minutes for the entire 3 mm × 3 mm chip. Subsequently, the development is done in Tetramethylammonium hydroxide (TMAH 25%) for 2 minutes. Alternatively, photolithography can be employed to significantly enhance the scalability of the patterning process.

We transfer the pattern from the resist to the Cr-Au-Ti layers using a collimated beam Ar ion etcher (Veeco Nexus IBE350, operation pressure 10^{-4} mbar, base pressure 10^{-7}, Ar^+ ion energy 200 eV). At this energy, the metals are rapidly etched away (Au etching rate ~ 50 nm/min), while the diamond is not damaged. Finally, the remaining HSQ and Ti layers are removed by diluted HF wet etch (1% concentration) and the antenna is removed from the carrier Si wafer.

The optical microscope image of the resulting antenna is shown in Figure 3. To prepare the antenna for testing, we mount it on the 3D printed holder (Figure 4a). Then the antenna is sandwiched between the custom PCB (described in Section 2) and the 3D printed holder using screws (Figure 4b).

To maintain proper electrical contact between the antenna and the PCB, it is important to carry out an ultrasonic cleaning procedure for the CPW antenna on the diamond. This process involves a 1-minute immersion in acetone, followed by a 1-minute immersion in ethanol, and finally, a 1-minute immersion in deionized water.

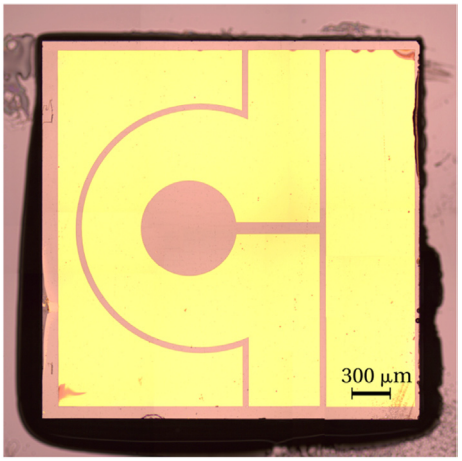


Figure 3. Optical image of the fabricated coplanar waveguide antenna fabricated on a diamond substrate.

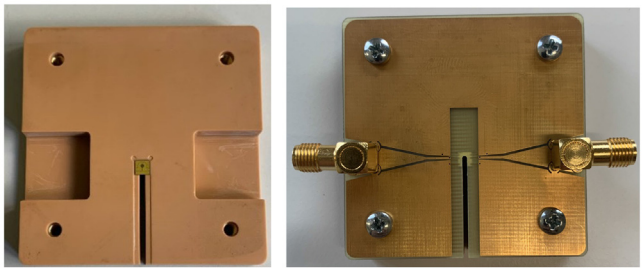


Figure 4. (**a**) 3D printed holder with the patterned diamond chip on top. The holder is designed to securely hold the CPW antenna and allow for easy integration with electronic circuits and optics. (**b**) Assembled device: the diamond with the patterned CPW coil is sandwiched between the PCB and the 3D-printed holder.

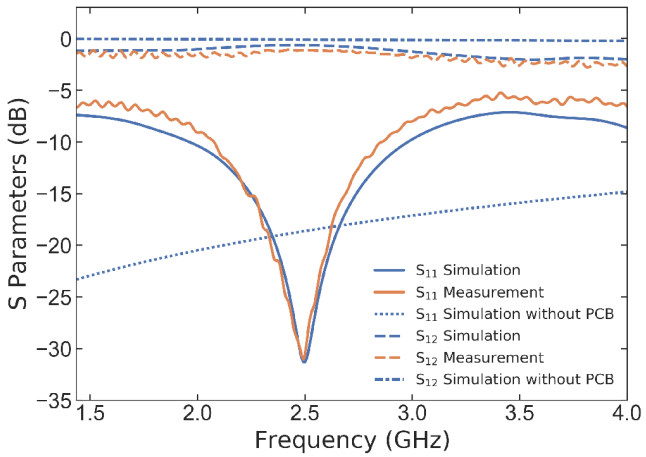


Figure 5. Simulated and measured S-parameters (S_{11} and S_{12}) of the CPW coil without and with being stacked in between a printed circuit board (PCB) and 3D printed holder. The results demonstrate the high transmission efficiency and low reflection coefficient of the proposed design.

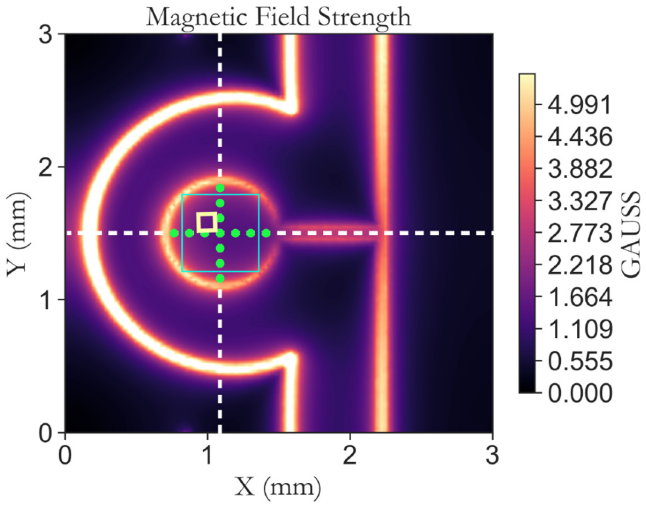


Figure 6. Simulated two-dimensional map of the complex magnitude of the magnetic field (in units of Gauss) at 20 μm inside the diamond for the CPW coil. The dashed white lines represent the cut for plotting x,y,z, and magnitude of the magnetic field in Figure 7. The green circles on the plot represent the optimization points utilized during the simulation and the yellow and cyan squares illustrate the areas to calculate CV and measure Rabi maps, respectively.

4 Results and discussion

To evaluate the performance of the antenna, we examine the scattering parameters (S-parameters), as shown in Figure 5. The simulated results indicate that when the antenna is excited using an RF probe without a PCB, it can achieve high bandwidth with an S_{11} below −10 dB. Moreover, the transmission coefficient is nearly unity, as verified by $S_{21} \approx 0$ dB. The antenna's performance in a stack configuration with the PCB and holder has been studied both experimentally and numerically. Figure 5 compares the measurement results with the simulations, demonstrating good agreement between the two. The reflection coefficient results represent a high bandwidth with $S_{11} < -10$ dB over a range of 1 GHz, and a resonance frequency at 2.5 GHz is also observed.

The proposed CPW coil is designed to generate a strong and homogeneous B_1 field, which can be evaluated by examining the simulated complex magnitude of the oscillating magnetic field over the diamond sample, as presented in Figure 6. The magnetic field distribution is calculated at a center frequency of 2.87 GHz (corresponding to the NV^- zero-field splitting value in the ground state), on a 2D plane positioned at 20 μm inside the diamond, representing the approximate focal point of the laser used to excite the diamond. In all simulations and measurements, the input microwave power is consistently set at 30 dBm, ensuring a fair comparison across different antenna configurations.

Figure 7 presents the simulated results for the complex magnitude of the oscillating magnetic field and its amplitude along the x, y, and z directions defined in Figure 1a. The result is obtained for the CPW antenna without PCB (7a, 7b), to assess the antenna's capability in generating a high and homogeneous B_1 field. The simulation outcomes reveal that the proposed antenna creates a homogeneous field predominantly oriented along the z-axis (perpendicular to the antenna plane) at the center. This is attributed to the grounding principle of the CPW, where the signal conductor and ground plane reside on the same plane. The magnetic field is generated by the surface current flowing through the planar gold structure, resulting in an increase in the magnetic field at the edges while creating a strong and uniform field in the center. The field is uniform with a coefficient of variation of less than 25% in the whole area (represented by a cyan square in Figure 6a), less than 6% in the area of 0.5mm^2, and less than 3.2% in a 100 μm× 100 μm in the center.

To validate the simulated results, we perform ODMR and consequently, Rabi measurements using a homemade confocal microscope (see Section 6 for the details of the measurement and methods). The measurements are performed at the center

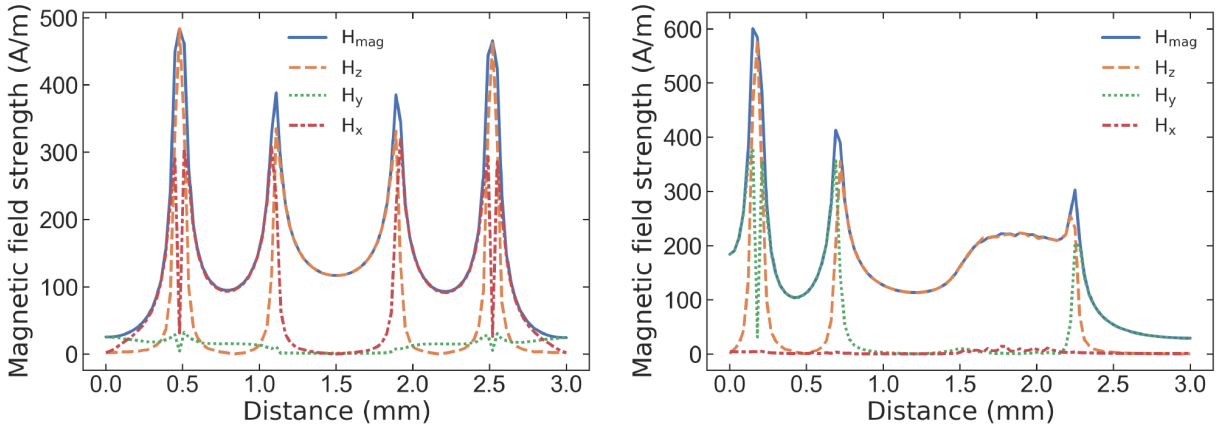


Figure 7. Simulated oscillating magnetic field strength (in units of A/m) along the (**a**) y-axis and (**b**) x-axis at 20μm inside and in the center of the proposed CPW coil . The result is plotted for the x, y, z, and magnitude components of the B_1 field. The results demonstrate the high and homogeneous magnetic field of such a compact structure.

of the planar coil stacked between PCB, 20 μm inside the diamond, along both the x and y axes. The microwave input power is fixed at 1W, and the results are compared to the simulation results, as reported in Figure 8. We observe a great accordance between the experimental and simulated data, with any discrepancies likely attributable to factors such as the assembly of the PCB and CPW. Noteworthy, the Rabi frequency generated by the PCB excitation will be smaller due to impedance mismatching of the feed-line and CPW.

We can determine the relationship between the measured Rabi frequency and the oscillating magnetic field (B_1) by considering that the rate of transition between $m_s = 0$ and $m_s = \pm 1$ depends on the component of B_1 that is perpendicular to the NV axis (see Section 6 for more details).

The simulated and measured magnetic field maps at an offset distance of 30 μm from the center of the CPW coil are shown in Figure 9a and Figure 9b, respectively. These maps are conducted at 20 μm inside the diamond and reveal the spatial distribution and homogeneity of the generated magnetic field by the planar CPW coil. Calculating the coefficients of variations for maps in Figure 9a we demonstrate a notably low value of 5.4% and 6.5% for the simulation and measurement, respectively. To obtain these measurements, a piezo stage from Mad City Labs is used to move the sample across a 100 μm× 100 μm area. At each point, the Rabi frequency is measured, and the data is then converted to the corresponding magnetic field in units of A/m (see Section 6). This process has enabled a direct comparison between the measured magnetic field maps and the simulated maps.

5 Conclusion

In conclusion, this paper has presented a novel CPW gold coil patterned on a 3 × 3 mm^2 CVD diamond substrate to address the limitations and challenges associated with earlier antenna designs for NV ensemble magnetometry applications. The proposed CPW coil offers a highly homogeneous magnetic field over a large area of 0.5 mm^2, full integration with a diamond NV center sensor, broad bandwidth from 1.5 to 4 GHz, and ease of testing and operation through the proposed PCB and holder designs. The optimized critical parameters of the coil design, such as the omega-shaped resonator diameter, waveguide width, and gap size, ensure the desired homogeneous magnetic field. Experimental results, including Rabi measurements and S-Parameter analysis, have shown good agreement with simulation results, validating the performance of the proposed CPW coil.

This research has detailed the antenna design and geometry, fabrication process, construction of the PCB stack, and experimental evaluation of the antenna's performance. The proposed CPW coil holds significant potential for advancing the field of NV magnetometry, combining homogeneity, broad bandwidth, and ease of use with the possibility of full integration on a diamond substrate. Future studies may explore additional optimizations or adaptations to further enhance the performance and applicability of the CPW coil in ensemble NV magnetometry applications combined with optimized collection and excitation efficiency.

6 Methods

CW-ODMR measurements are performed to explore the application of our antenna in controlling ensembles of NV centers in diamond. These measurements are carried out in a homemade confocal microscope, more details about this set-up can be found in 19. To this, a biased magnetic field using a permanent magnet is applied to achieve non-degenerately splitting for all NV axes. The NV centers are excited using a 515 nm laser (Cobalt-06-MLD), and the resultant fluorescence signal is captured with an avalanche photodiode (Thorlabs APD430A). Concurrently, a microwave signal sweep calibrated at 1W is applied to the printed circuit board of the CPW coil using a Rohde and Schwarz SMF100A microwave signal generator.

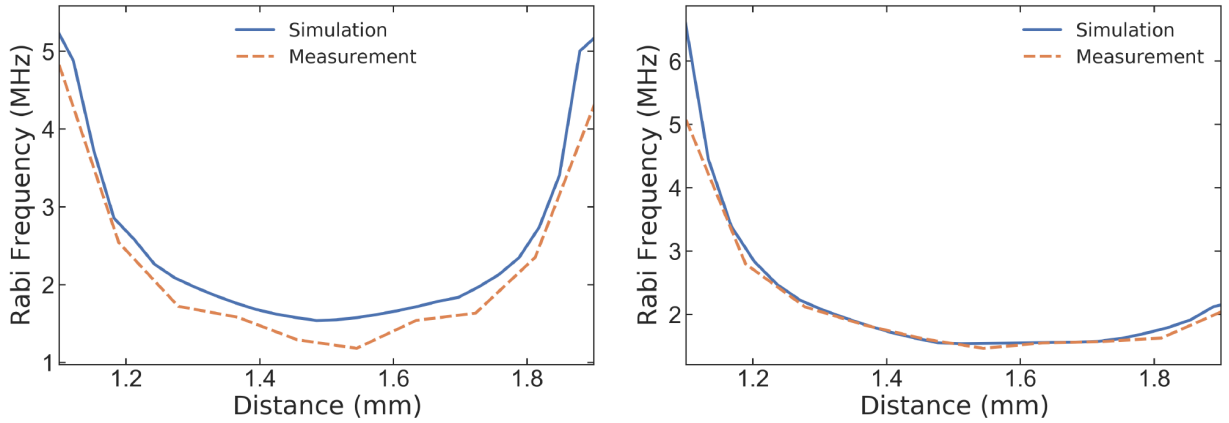


Figure 8. Measured Rabi frequency versus expected simulated Rabi frequency (in units of MHz) along the (**a**) x-axis and (**b**) y-axis at 20 μm inside the diamond and in the center of the co-planar waveguide (CPW) microwave coil stacked between PCB and holder.

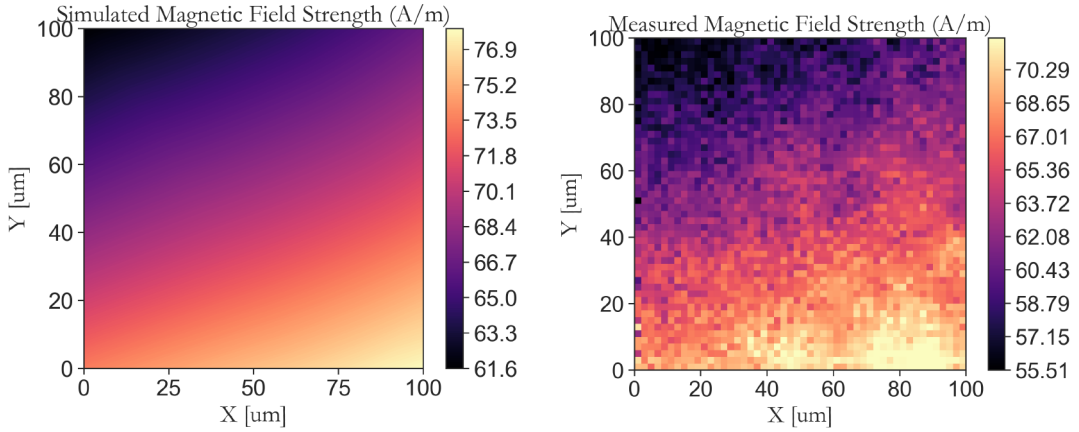


Figure 9. (**a**) Simulated two-dimensional map of the magnetic field (in units of Ampers per meter) at a distance of 30 μm off from the center of the proposed CPW coil (Map is obtained within the yellow square as depicted in Figure 6a). The map shows the spatial distribution of the oscillating magnetic field in the vicinity of the CPW, which is critical for efficient spin manipulation of diamond nitrogen-vacancy (NV) centers. (**b**) Measured two-dimensional map of the magnetic field (in units of Ampers per meter) at a distance of 30 μm off from the center of the proposed CPW coil. The measurement is performed by measuring Rabi frequency at each position on NV centers that have an angle of 55.81° relative to the applied DC magnetic field.

The resulting signal is synchronously captured by a National Instruments data acquisition card (NI 6361) during photon detection. When the microwave frequency matches the spin transition, the NV center undergoes a spin flip, resulting in a decrease in the fluorescence intensity. Figure 10 displays the ODMR signal, which features eight dips corresponding to the four possible orientations of the NV centers within the diamond lattice. The observed ODMR signal can be interpreted using the Hamiltonian approximation given below[1,15]:

$$H = D\left(S_z^2\right) + \gamma_{NV} B_0 \left(\sin(\alpha) S_x + \cos(\alpha) S_z\right) \quad (1)$$

In Equation 1, $\gamma_{NV} = \frac{\mu_B g_S}{h} = 2.8$ MHz/Gauss represents the gyromagnetic ratio, S is the spin matrix, and α is the angle between the NV center axis and the applied DC biased magnetic field, B_0. By analyzing the ODMR signal and solving the Hamiltonian for all four NV axes, it is possible to numerically determine the orientation and magnitude of the applied magnetic field.

The numerical solution script for finding B_0 and its angle relative to all NV axes is provided at the following link: . Our results indicate that for the ODMR presented in Figure 10, the DC magnetic field has a value of 77.41 Gauss. The angles corresponding to the ODMR dip pairs, ordered from the highest to the lowest splitting value, are 55.81°, 115.64°, 106.09°, and 82.45°, respectively.

To evaluate the coupling efficiency of the microwave field generated by the antenna to the NV centers in diamond, we carried out a Rabi measurement. Rabi measurement describes the coherent oscillation between the energy levels of the NV center and is performed within a pulse measurement experiment.

To this, laser pulses with a duration of 100 μs along with applied microwave pulses with a calibrated input power of 1 W to the antenna port are utilized. The time span between two consecutive laser pulses is occupied by a microwave pulse that is in resonance with the chosen NV transition. The duration of the microwave pulses varies linearly. During the period when the laser pulse is applied, the photoluminescence (PL) is averaged out to yield a more accurate readout. The measurements are synchronized using a Swabian pulse streamer instrument. A triggered readout is achieved with the assistance of an NI data acquisition card. By identifying the relevant captured pulse associated with alterations in the distance between laser pulses, we can determine the relative occupation of the spin state transitioning from m_s = 0 to m_s = ±1. This can be found by calculating the ratio between the end of the detected pulse and the beginning of the pulse. The ratio for each time delay, with a range spanning from 0 to 2.5 μs and a spin transition frequency of 2.848 GHz, is depicted in Figure 11. Figure exhibits a Rabi oscillation of 3.9 MHz at the focal plane of the objective, situated 20 μm within the sample. The measured Rabi frequency is fitted with a damped cosine function, as expressed by Equation 2.

$$F(t) = A\cos(2\pi f_R t + \phi_0)e^{-\zeta_D t} + B \quad (2)$$

where f_R is Rabi frequency and ζ_D is the decay rate of the Rabi oscillation.

The Rabi frequency can also be expressed as $f_r = \frac{1}{\sqrt{2}}\gamma B_1 \sin\beta$, where $\frac{1}{\sqrt{2}}$ accounts for the rotating wave approximation in a spin 1 system and β is the angle between B_1 and the corresponding NV axis[16]. If the CW-ODMR splitting and B_1

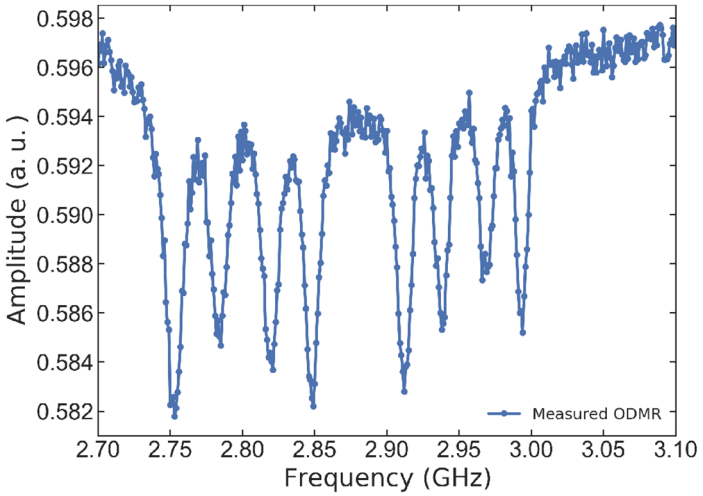


Figure 10. Optically detected magnetic resonance (ODMR) obtained applying the MW field using our antenna and PCB.

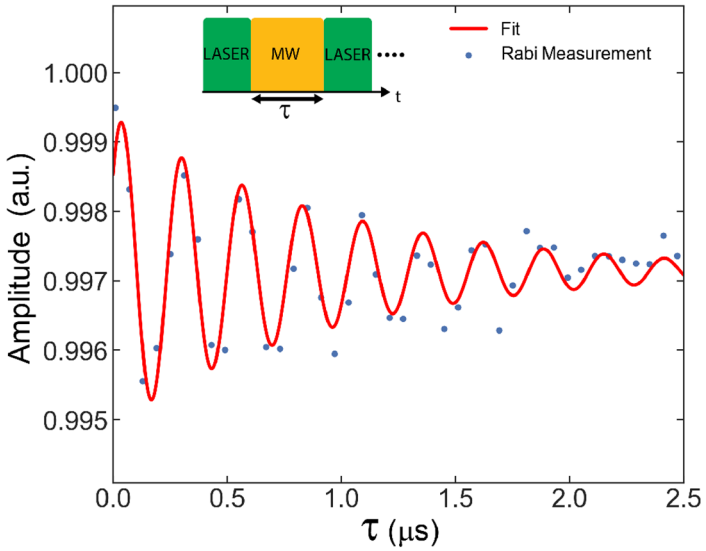


Figure 11. Rabi oscillation measurement for the NV axis at an angle of 55.81° relative to the DC magnetic field within the CPW microwave coil. The Rabi period and lifetime are estimated from the fit as 264 ns and 0.9 μs respectively.

direction from a simulation are known, it is possible to determine B_1 from the Rabi frequency.

Data and software availability

Source code available from: https://github.com/hbabashah/hbabashah.github.io.

Archived source code at time of publication: https://doi.org/10.5281/zenodo.10401685[20].

License: MIT License.

Acknowledgment

We would like to express our gratitude to the Center for Micro-Nano Technology (CMI) facility and its staff at École Polytechnique Fédérale de Lausanne (EPFL) for their invaluable assistance in carrying out this research. Furthermore, We extend our thanks to the EPFL PCB and 3D printing service for prototyping. This work received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 754354 (EPFLInnovator), Wainvam-e, and from EPFL Interdisciplinary Seed Funds.

References

1. Barry JF, Schloss JM, Bauch E, *et al.*: **Sensitivity optimization for NV-diamond magnetometry.** *Rev Mod Phys.* 2020; **92**(1): 15004.
Publisher Full Text
2. Savvin A, Dormidonov A, Smetanina E, *et al.*: **NV- diamond laser.** *Nat Commun.* 2021; **12**(1): 7118.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
3. Barton J, Gulka M, Tarabek J, *et al.*: **Nanoscale Dynamic Readout of a Chemical Redox Process Using Radicals Coupled with Nitrogen-Vacancy Centers in Nanodiamonds.** *ACS Nano.* 2020; **14**(10): 12938–12950.
PubMed Abstract | **Publisher Full Text**
4. Doherty MW, Manson NB, Delaney P, *et al.*: **The nitrogenvacancy colour centre in diamond.** *Phys Rep.* 2013; **528**(1): 1–45.
Publisher Full Text
5. Eichler C, Sarma VV, Englund D, *et al.*: **Broadband microwave control of diamond nitrogenvacancy centers using an integrated waveguide.** *Physical Review Applied.* 2021; **15**(3): 034047.
6. Rose W, Haas H, Chen AQ, *et al.*: **High-resolution nanoscale solid-state nuclear magnetic resonance spectroscopy.** *Phys Rev X.* 2018; **8**(1): 011030.
Publisher Full Text
7. Mamin HJ, Kim M, Sherwood MH, *et al.*: **Nanoscale nuclear magnetic resonance with a nitrogen-vacancy spin sensor.** *Science.* 2013; **339**(6119): 557–560.
PubMed Abstract | **Publisher Full Text**
8. Le Sage D, Arai K, Glenn DR, *et al.*: **Optical magnetic imaging of living cells.** *Nature.* 2013; **496**(7446): 486–489.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
9. Lozov RK, Baranov AA, Ermak SV, *et al.*: **Comparison of orientational error of an optically pumped quantum sensor in on-board equipment of galileo and gps satellite systems.** IOP Publishing, In: *J Phys: Conf Ser.* 2019; **1236**: 1012077.
Publisher Full Text
10. Pelliccione M, Jenkins A, Ovartchaiyapong P, *et al.*: **Scanned probe imaging of nanoscale magnetism at cryogenic temperatures with a single-spin quantum sensor.** *Nat Nanotechnol.* 2016; **11**(8): 700–705.
PubMed Abstract | **Publisher Full Text**
11. Wolf T, Neumann P, Nakamura K, *et al.*: **Subpicotesla diamond magnetometry.** *Phys Rev X.* 2015; **5**(4): 041001.
Publisher Full Text
12. Waldherr G, Beck J, Neumann P, *et al.*: **High-dynamic-range magnetometry with a single nuclear spin in diamond.** *Nature Nanotech.* 2012; **7**(2): 105–108.
Publisher Full Text
13. Childress L, Gurudev Dutt MV, Taylor JM, *et al.*: **Coherent dynamics of coupled electron and nuclear spin qubits in diamond.** *Science.* 2006; **314**(5797): 281–285.
PubMed Abstract | **Publisher Full Text**
14. Magaletti S, Mayer L, Roch JF, *et al.*: **A quantum radio frequency signal analyzer based on nitrogen vacancy centers in diamond.** *Commun Eng.* 2022; **1**(1): 19.
Publisher Full Text
15. Bayat K, Choy J, Baroughi MF, *et al.*: **Efficient, uniform, and large area microwave magnetic coupling to nv centers in diamond using double split-ring resonators.** *Nano Lett.* 2014; **14**(3): 1208–1213.
PubMed Abstract | **Publisher Full Text**
16. Sasaki K, Monnai Y, Saijo S, *et al.*: **Broadband, large-area microwave antenna for optically detected magnetic resonance of nitrogen-vacancy centers in diamond.** *Rev Sci Instrum.* 2016; **87**(5): 053904.
PubMed Abstract | **Publisher Full Text**
17. Roman Opaluch O, Oshnik N, Nelz R, *et al.*: **Optimized planar microwave antenna for nitrogen vacancy center based sensing applications.** *Nanomaterials (Basel).* 2021; **11**(8): 2108.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
18. Mi S, Toros A, Graziosi T, *et al.*: **Non-contact polishing of single crystal diamond by ion beam etching.** *Diam Relat Mater.* 2019; **92**: 248–252.
Publisher Full Text
19. Babashah H, Shirzad H, Losero E, *et al.*: **Optically detected magnetic resonance with an open source platform.** *arXiv preprint arXiv:2205.00005, 2022.*
Reference Source
20. Babashah H: **hbabashah/hbabashah.github.io: Physics Quantum Lab (QuantumNVLab1).** *Zenodo*. [Code], 2023.
http://www.doi.org/10.5281/zenodo.10401685

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Version 1

Reviewer Report 16 August 2024

https://doi.org/10.21956/openreseurope.18234.r39818

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✔ **Bing Chen**
Hefei University of Technology, Hefei,, Anhui, China

The paper presents a coplanar waveguide (CPW) gold coil patterned on a 3 × 3 mm2 diamond substrate, offering full integration, enhanced stability, and broad bandwidth suitable for various NV sensing applications. The authors include more comprehensive details about the CPW on diamond.
1. What is the difference between CPW and double split-ring antenna.
2. Will plating electrodes directly on the diamond cause the metal to penetrate into the diamond?
3.Why is the resonant point of this coplanar waveguide not 2.87GHz.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: quantum sensing using NV center in diamond

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 14 August 2024

https://doi.org/10.21956/openreseurope.18234.r39824

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Suvechhya Lamichhane
University of Nebraska Lincoln, Lincoln,, Nebraska, USA

This study has effectively implemented a coplanar waveguide (CPW) directly onto the diamond substrate, showcasing a uniform field distribution across a wide area. This uniform microwave field significantly enhances sensitivities for ensemble NV magnetometry, rendering the work noteworthy in the NV sensing community. The experiments and simulations are well conducted to demonstrate the efficacy of their design. However, certain aspects require clarification for result reproducibility and interpretation.

1. The reason behind utilizing Ti atop the Au layer remains unclear. Additionally, specifics regarding the electron beam's acceleration voltage and exposure dose are indispensable. Are there any concerns regarding charge accumulation during e-beam exposure?
2. Discrepancies between the simulated magnetic field strength (~1.6 Gauss in Figure 6) and the field estimation from Rabi data (~0.95 Gauss in Figure 9) necessitate clarification. It would be nice to have the explanation for this inconsistency.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: NV magnetic sensing

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 23 April 2024

https://doi.org/10.21956/openreseurope.18234.r39504

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?

Jixing Zhang
University of Stuttgart, Stuttgart, Germany

This research article introduced an integrated coplanar waveguide coil on diamond. The study meticulously details the design, fabrication process, and experimental evaluation of the proposed antenna, showcasing its potential for enhancing magnetic field homogeneity and broad bandwidth in NV magnetometry applications. The authors' thorough analysis, supported by simulation and experimental results, demonstrates the effectiveness of the CPW coil in achieving desired performance metrics.
While the design of CPW and its application for NV centre in diamond is a well-explored field, this paper lacks significant innovation in CPW design. However, it still holds value for society by providing a detailed fabrication process. Therefore, I recommend that the authors include more comprehensive details about the fabrication of CPW on diamond to ensure reproducibility by others.
Moreover, the direct printing of CPW on diamond offers improved heat dissipation but also raises concerns about diamond heating. Given that the zero field splitting of NV centres is sensitive to temperature fluctuations, it would be beneficial to discuss this effect further.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: nitrogen vacancy center based quantum sensing

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 22 April 2024

https://doi.org/10.21956/openreseurope.18234.r38631

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Wojciech Gawlik
Jagiellonian University, Krakow, Poland

The article by H.Babashah, E. Loser, and Ch. Galland describes the design of a waveguide coil for NV magnetometry on the surface of a bulk diamond crystal. In addition to the discussion of the main design criteria, the authors verified their predictions in the experiment and discussed the results obtained.

The creation of a homogenous, intense, and broadband microwave field is a crucial issue for practical magnetometry with NV diamonds, so there is a need for successful designs that meet as much as possible of the above criteria. The described construction largely satisfies these requirements. It produces a reasonably strong field in a broad frequency band. Although the area of homogeneity is not very impressive, the important advantage is that the constructed coil is placed directly on the diamond crystal, so it is fully integrated with a diamond crystal, which is very advantageous from the point of view of cooling and compactness of the device.

Discussion of the system performance based on S-parameter analysis of the S parameters is very detailed and accurate. I was pleased with the careful elimination of the higher-order mode by a careful and well-thought-out discussion of the coil dimensions. Figures 7-11 illustrate that the constructed coil meets expectations, so it can be recommended as a useful and convenient design.

When reading the paper, I noticed some problems referring to Figure 6a in Sect.2, page 4. Apparently, Figure 6a does not exist. Perhaps the authors meant Figure 7, when they referred to ‘green circles’, but I only found green dots there, rather than green circles. Also, there were no labels (a), (b) associated with two figures 7, so this part of the text required some effort to follow.

In conclusion, the article discusses criteria important for the construction of an NV magnetic sensor and presents a successful design that can be recommended for applications by other researchers.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Atomic and laser physics, spectroscopy research on warm and cold atoms and colour centers in diamonds

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.