Nanoscale microwave imaging with a single electron spin in diamond

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Abstract
We report on imaging of microwave (MW) magnetic fields using a magnetometer based on the electron spin of a nitrogen vacancy (NV) center in diamond. We quantitatively image the magnetic field generated by high frequency (GHz) MW current with nanoscale resolution using a scanning probe technique. Together with a shot noise limited MW magnetic field sensitivity of 680 nT Hz−1/2, our room temperature experiments establish the NV center as a versatile and high performance tool for MW imaging, which furthermore offers polarization selectivity and broadband capabilities. As a first application of this scanning MW detector, we image the MW stray field around a stripline structure and thereby locally determine the MW current density with a MW current sensitivity of a few nA Hz−1/2.

1. Introduction
Imaging and detecting microwave (MW) fields constitutes a highly relevant element for engineering of future MW devices as well as for applications in atomic and solid state physics. For instance cavity quantum electrodynamics experiments with atoms [1, 2] and superconducting qubits [3, 4] or the coherent control of quantum magnets [5] and quantum dots [6] are based on manipulating quantum systems with MW electric or magnetic fields. Precise control and knowledge of the spatial distribution of the MW near field is thereby essential to achieve optimal device performance. Also, magnetic systems are known to exhibit a large variety of collective magnetic excitations, including spin waves [7] or excitations in frustrated magnets [8, 9]. Imaging such magnetic excitations on the nanoscale is a crucial step towards their fundamental understanding and the development of new spintronics devices, such as magnonic waveguides [10] or domain wall racetrack memories [11]. As a consequence, various techniques have been designed to image MW electric and magnetic fields, including scanning near field microscopy [12–14], micro-Brillouin light scattering [15], superconducting quantum interference devices [16] or imaging with atomic vapor cells [17–19] or ultracold atoms [20]. With only a few exceptions [15], most of these techniques however lack a nanoscale spatial resolution or are restricted to operation in cryogenic or vacuum environments.

MW magnetic field imaging using the electronic spin of a single nitrogen vacancy (NV) center in diamond offers a promising alternative. The NV center is an optically active lattice point defect in diamond with a ground state manifold. Its atomic size, exceptionally long coherence times, optical initialization and readout of the spin state make the NV center an ideal sensor for DC magnetic fields under ambient conditions [21–25]. Recently, magnetometry of MW magnetic fields has been demonstrated using a NV spin in bulk diamond [26], with a resulting MW magnetic field sensitivity of one μT Hz−1/2. However, the bulk NV centers employed in [26] severely restricted spatial resolution in imaging, and in particular do not allow for nanoscale imaging of MW near fields, which remains an outstanding challenge for NV-based MW imaging. In this letter, we address this issue and demonstrate the first nanoscale MW imaging using a scanning NV magnetometer [27]. Our proof-of-
2. MW magnetic field imaging with NV centers in diamond

2.1. Detection principle

Our MW magnetic field detection is based on the ability of the MW field to drive coherent Rabi oscillations between the $|0\rangle$ and $|\pm 1\rangle$ spin-states of the NV center (figures 1(a)–(c)). Selection rules impose that within the rotating wave approximation (RWA), the transition $|0\rangle \rightarrow |\pm 1\rangle$ is only excited by a circularly polarized MW field $\sigma_\phi$. Due to the large NV spin splitting and the comparably weak microwave field amplitudes, the RWA holds to an extremely good extent in the experiments described here. An arbitrarily polarized MW field resonant with either the $|0\rangle \rightarrow |+1\rangle$ or $|0\rangle \rightarrow |-1\rangle$ transition therefore leads to an oscillation of the population between the two involved spin states, at a frequency $\Omega_{\pm, MW} = \gamma_{NV} B'_\pm, MW$, where $B'_\pm, MW$ is the (right-)left-handed circularly polarized component of the MW field in a plane perpendicular to the NV axis and $\gamma_{NV} = 28 \text{ kHz} \mu\text{T}^{-1}$ the NV gyromagnetic ratio. Measuring $\Omega_{\pm, MW}$ by an appropriate experimental sequence (figure 1(b)) thus allows one to directly determine the amplitude of the driving MW magnetic field in a circularly polarized basis (figure 1(c)).

The NV spin we employ for MW imaging is located at the apex of an all diamond scanning probe containing the NV spin is scanned at a height $d$ over the PD stripline (yellow). The magnetic field generated by the current $I_{MW}$ which passes through the stripline is detected by the NV magnetometer. The NV spin is optically addressed using a homebuilt confocal microscope. The magnetic field detection is based on the ability of the MW field to drive coherent Rabi oscillations between the $|0\rangle$ and $|\pm 1\rangle$ spin-states of the NV center. The first (second) readout pulse measures the fluorescence $F(B'_\pm, MW)$ (bare fluorescence $F_0$) as described in the text. (c) Optically detected Rabi oscillations of the NV spin, driven by a circularly polarized MW magnetic field $B'_\pm, MW$ in a static magnetic field of 1.6 mT ($\omega_{MW}/2\pi = 2.825 \text{ GHz}$). The black dots are experimental data and the blue solid line corresponds to a rotating wave approximation (RWA) fit with

$$F(B'_\pm, MW) = F_0(1 - C/2) + CF_0/2 \cdot \cos \left(2\pi \gamma_{NV} B'_\pm, MW \tau\right) - \frac{C}{4} \cdot \exp \left(-\frac{\tau}{\tau_b}\right),$$

where $F_0$ is the fluorescence in the $|0\rangle$ state, $CF_0$ is the amplitude and $\tau_b$ the decay time of the Rabi oscillations. (d) Schematic representation of the combined confocal and atomic force microscope. The all-diamond scanning probe containing the NV spin is scanned at a height $d$ over the PD stripline (yellow). The magnetic field generated by the current $I_{MW}$ which passes through the stripline is detected by the NV magnetometer. The NV spin is optically addressed using a homebuilt confocal microscope.

Figure 1. (a) Energy levels of the NV spin in a static magnetic field $B_z$. The $|0\rangle$ state exhibits a higher fluorescence than the $|\pm 1\rangle$ states (bright and dark lightbulbs). (b) Experimental pulse sequence employed for the measurement of NV Rabi oscillation. The first (second) readout pulse measures the fluorescence $F(B'_\pm, MW)$ (bare fluorescence $F_0$) as described in the text. (c) Optically detected Rabi oscillations of the NV spin, driven by a circularly polarized MW magnetic field $B'_\pm, MW$ in a static magnetic field of 1.6 mT ($\omega_{MW}/2\pi = 2.825 \text{ GHz}$). The black dots are experimental data and the blue solid line corresponds to a fit with

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concept imaging experiments were performed on a prototypical MW circuit—a micron-scale MW stripline—and yield nanoscale resolution combined with shot noise limited MW magnetic field sensitivities in the range of a few hundred nT Hz$^{-1/2}$.
300 nm of SiO2 by electron beam lithography and evaporation of 60 nm of Pd. A MW source (Rhode & Schwarz SMB 100A) is used to drive a MW current $I_{\text{MW}}$ with a frequency in the GHz range through the stripline. The right-angled stripline we employ thereby generates a highly inhomogeneous MW magnetic field with a nontrivial field distribution which is largely linearly polarized. This arrangement is therefore ideal to demonstrate spatial resolution and MW magnetic field sensitivity of our imager.

In the following, we demonstrate imaging of the $\sigma^-$-component of the MW magnetic field ($\omega_{\text{MW}}/2\pi = 2.825$ GHz) generated by the stripline. To that end, we tune the sensing frequency $\omega_{s}/2\pi = 2.87$ GHz $-\gamma_B B_z$ of the $|0\rangle \rightarrow |-1\rangle$ transition via a static magnetic field $B_z$ to the frequency $\omega_{\text{MW}}/2\pi$ of the MW field (see figure 1(a)). In analogy, the $\sigma^+$-component of the MW magnetic field can in principle be addressed by changing the external magnetic field $B_z$ such that the $|0\rangle \rightarrow |+1\rangle$ transition of the NV center is resonant with the frequency of the MW field to be imaged. However, we did not perform such an experiment, as for the device under test the MW magnetic field contains equal contributions of circular polarizations and would therefore not provide any polarization contrast in imaging (see footnote 4).

2.2. Isofield imaging mode

In the first imaging mode, we perform imaging of equi-magnetic field lines of constant amplitude $B'_{-\text{MW}}$. For a fixed MW pulse length $\tau_0$, the accumulated phase (pulse area) in the Rabi oscillation and thus the population difference between $|0\rangle$ and $|-1\rangle$ depends on the local MW magnetic field $B'_{-\text{MW}}$ (figure 1(b)-(c)). While scanning the NV spin at a distance $d$ over the stripline, one can therefore monitor variations of the MW magnetic field via changes in the NV fluorescence $F$ (figure 2).

In order to correct for fluorescence changes arising from potential near field effects [27–29] while scanning, we simultaneously record the bare fluorescence rate $F_0$ of the $|0\rangle$ state to yield the normalized differential fluorescence, $\Delta F = [F(B'_{-\text{MW}}) - F_0]/F_0$.

Figure 2(a) shows $\Delta F$ recorded in the xy-plane in AFM contact (corresponding to a height $d$ of the NV spin above the stripline) with $\tau_0 = 300$ ns. Each bright fringe corresponds to an integer multiple of $2\pi$ of accumulated phase of the NV Rabi oscillations. Consequently, the bright fringes represent isofield lines of $B'_{-\text{MW}}$, which are spaced by $2\pi/\gamma_B \tau_0 = 120 \mu T$. To avoid ambiguities in assigning the correct value of $B'_{-\text{MW}}$ to each measured field line, we separately measured $B'_{-\text{MW}}$ for several reference lines. The references for $B'_{-\text{MW}} = 360, 600$ and $840 \mu T$ are highlighted in yellow, orange and red, respectively in figure 2(a).

The versatility and stability of our microscope allows us to further image MW magnetic fields in all three-dimensions and in particular as a function of distance to the sample. To that end, we release AFM force feedback and record the MW magnetic field image by scanning the sample in a plane orthogonal to the MW current (figure 2(b)). In analogy to figure 2(a), we attribute a MW magnetic field amplitude to each isofield line as shown in figure 2(b).

2.3. Full field imaging mode

While providing a fast and straightforward method for nanoscale imaging of MW magnetic fields, our method for iso-field imaging suffers from limitations in regions of high magnetic field gradients. This is particularly appreciable near the edges of our stripline (figure 2(a)), where individual field lines are hard to distinguish and

\footnote{See supplementary material for further details.}
identification of the measured isofield lines becomes intractable. In order to overcome this limitation, we extended our imaging capabilities to directly determine \( B'_{\text{MW}} \) at each point throughout the scan (figure 3). For this, we measured NV Rabi oscillations at each pixel in the scan range and determined \( B'_{\text{MW}} \) by a sinusoidal fit to each of these traces. Figure 3(a) depicts the resulting image of \( B'_{\text{MW}} \) measured above the corner of the stripline imaged in figure 2(a). From this data, we also extract iso-field lines as highlighted by gray solid lines in figure 3(a). For the quantitative analysis of our results, which we provide below, we further used this imaging method to record linecuts of \( B'_{\text{MW}} \) as depicted in figures 3(b) and (c).

The measured distributions of \( B'_{\text{MW}} \) depends on the orientation (\( \varphi, \theta \)) and the position \( \vec{r} = (x, y, z) \) of the NV spin with respect to the MW current \( I \) (see also figure 1). Assuming an infinitely thin stripline \( (t \ll w) \) in vacuum with a homogenous MW current density \( J \) oriented parallel to the stripline, the MW magnetic field profiles in figures 3(b) and (c) can be described by an analytical function \( B'_{\text{MW}}(d, J, \varphi, \theta) \), with \( d, J, \varphi, \theta \) as free parameters. We note that our assumption of a homogeneous current distribution is justified by the fact that the skin-depth of Pd at 2.825 GHz is larger than the stripline-width and is further corroborated by our numerical simulations. The resulting fits (blue lines in figures 3(b) and (c)) are in excellent agreement with the experimental data (dark gray dots in figures 3(b) and (c)). In addition, we have numerically computed in a finite element simulation the MW magnetic field amplitude, assuming a MW current in a stripline (width \( w = 2.5 \text{ \mu m} \), thickness \( t = 60 \text{ nm} \)) on 300 nm of SiO\(_2\). The best fit to the experimental data (green lines in figure 3(b) and (c)) was obtained with parameters \( d, J, \varphi, \theta \) (green insets) that are almost identical to the analytical fit parameters (blue insets). Finally, we also numerically determined the full two-dimensional distribution of the MW magnetic field in a finite element simulation (figure 3(d)), using the distance and orientation of the NV spin determined in figure 3(b). For most of the scanned area, the experimental data (figure 3(a)) is in excellent agreement with the simulation (figure 3(d)), which further establishes the reliability of our method.

3. Spatial resolution and MW field sensitivity

The accurate determination of the NV-to-sample distance \( d = 25 \pm 5 \text{ nm} \) that our method provides is relevant for various aspects of our work and NV-based sensing in general. First and foremost, \( d \) determines the spatial resolution in imaging the sources of magnetic fields [27, 30], which we thus estimate to be \(~25 \text{ nm}\). Moreover,
the distance links the MW current in the stripline to the MW magnetic field seen by the NV spin and therefore sets the sensitivity with which one can detect a MW current in the sample. With \( d \sim 25 \text{ nm} \) and the magnetic field sensitivity determined below, we find a MW current sensitivity of our NV magnetometer of \( \sim 300 \text{ nA Hz}^{-1/2} \) for an infinitely thin, current-carrying wire. Note that for the data set presented in figure 3(c), we find \( d = 64 \pm 5 \text{ nm} \), significantly larger than the value of \( d = 25 \pm 5 \text{ nm} \), which we determine for all the other data presented in this work. We attribute this discrepancy to contaminations on the diamond tip that has accumulated throughout the course of our experiments\(^ 3 \)—removing these contaminants or working with a fresh tip should restore \( d \) to its original value.

We now estimate the photon shot noise limited sensitivity of the NV spin determined by \( \eta_{\text{photon}} = \sqrt{2e\left(\tau_0 C \sqrt{F_0 T_0}\right)} \), with \( F_0 \), \( C \) and \( \tau_0 \) as defined earlier (see figure 1 and 4). For the NV spin used in our experiments, we find \( \eta_{\text{photon}} = 680 \text{ nT Hz}^{-1/2} \) at 2.825 GHz\(^ 4 \). It should be noted that in general the decay time of the Rabi oscillation \( \tau_0 \) is itself a function of the Rabi frequency (and thus of \( B'_e \text{MW} \)) \(^ {31} \). While a general expression for \( \eta_{\text{photon}} \) is therefore difficult to obtain, it is instructive to consider the two limits of low and high Rabi frequencies with respect to \( 1/T^2 \), where the decay time is given by \( \tau_0 = T^2 \) and \( T_1 \), respectively. For typical values of NV centers in ultrapure diamond (\( T^2 \) \( \sim 1 \mu s \) and \( T_1 \sim 1 \text{ ms} \)) one then finds \( \eta_{\text{photon}} \sim 1.4 \mu \text{T Hz}^{-1/2} \) and \( \eta_{\text{photon}} \sim 40 \text{ nT Hz}^{-1/2} \) respectively. Additionally, we note that while coherent detection of MW fields through Rabi oscillations is limited by \( \tau_0 \), incoherent detection of these fields is limited by \( T_1 \) only. Performing such incoherent MW imaging (also referred to as relaxation-imaging \(^ {32, 33} \)) would thus allow us to reach the highest sensitivities also in the limit of low Rabi frequencies. The sensitivity could be further enhanced by improving the Rabi decay time \( \tau_0 \) using isotopically enriched diamond \(^ {21, 34} \) and by optimizing the photon collection efficiency using alternative tip geometries \(^ {35} \) or scanning probes made from \(^ {111} \) oriented diamond material \(^ {36} \). In addition, the MW magnetic field sensitivity can be estimated from the full, quantitative field measurement (figure 3) and is given by \( \eta_{\text{meas}} = \delta B'_e \text{MW} \sqrt{T} \), where \( \delta B'_e \text{MW} \) is the smallest measurable MW magnetic field, i.e. the fitting error to the Rabi fits, and \( T \) the measurement time for each data point. For the values extracted from figure 3 we obtain a sensitivity of \( \eta_{\text{meas}} = 15 \mu \text{T Hz}^{-1/2} \), which is larger than the shot-noise limited sensitivity quoted above. This discrepancy is explained by the fact that for the measurement shown in figure 3, we recorded full Rabi oscillations for each point of the scan, i.e. most of the data was taken for evolution times \( \tau \), which do not yield optimal measurement sensitivities\(^ 4 \).

4. Conclusion and outlook

In conclusion, we have established scanning NV center spins as a valuable resource to sensitively detect and image MW magnetic fields on the nanoscale. Our results indicate an imaging resolution of \( \sim 25 \text{ nm} \) together with a shot noise limited MW magnetic field sensitivity of \( 680 \text{ nT Hz}^{-1/2} \), resulting in a sensitivity to the generating currents of few nA Hz\(^{-1/2} \) all at frequencies \( \sim 3 \text{ GHz} \). Extending the bandwidth of detection to the range above 20 GHz can be achieved by placing our microscope in a sufficiently strong magnetic field \(^ {37} \) and would have profound impact for applications in MW device characterization, as currently available field imaging techniques cannot operate in this frequency range \(^ {38} \). It should be noted that detection of microwave fields through Rabi oscillations has also been implemented for \(^ {25} \text{Rb} \) vapor cells \(^ {17–20} \). Such devices operate with tens of \( \mu \text{m} \) spatial resolution over a mm to cm detection window \(^ {39} \), compared to our nanoscale spatial resolution over a tens of \( \mu \text{m} \) detection window, and thus provide a complementary wide field imaging tool to our NV scanning magnetometers. Finally, recent experiments have demonstrated that spin wave excitations in nanomagnetic systems can be addressed via MW NV magnetometry \(^ {40} \). There external DC magnetic fields are used to bring the spin wave excitation frequency into resonance with the NV spin transition and thus enables a detection of the spin wave amplitude via the NV Rabi frequency. Combining this detection scheme with our ability to image MW magnetic fields at nanoscale resolution would therefore form an exciting avenue that could allow for real space imaging of spin wave excitation in nanomagnets \(^ {41} \) or skyrmion core dynamics \(^ {42} \).

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References

[1] Kaluzny Y, Goy P, Raimond J and Haroche S 1983 Phys. Rev. Lett. 51 1175
[2] Raimond J, Bruine M and Haroche S 2001 Rev. Mod. Phys. 73 565
[3] Walraff A, Schuster D, Blais A, Frunzie L, Huang R S, Majer J, Kumar S, Girvin S and Schoelkopf R 2004 Nature 431 162
[4] You J and Nori F 2011 Nature 474 589
[5] Thiele S, Balestro F, Ballou R, Klyatskaya S, Ruben M and Wernsdorfer W 2014 Science 344 1135
[6] Koppens F, Buizert C, Tielrooij K, Vink I, Nowack K, Meunier T, Kouwenhoven L and Vandersypen L 2006 Nature 442 766
[7] Sparks M 1964 Ferromagnetic-Relaxation Theory (New York: McGraw-Hill)
[8] Schollwoeck U, Richter J, Farnell D J and Bishop R F 2004 Quantum Magnetism (Berlin: Springer)
[9] Balents L 2010 Nature 464 199
[10] García-Sánchez F, Borys P, Soucaille R, Adam J P, Stamps R L and Kim J V 2015 Phys. Rev. Lett. 114 247206
[11] Parkin S, Hayashi M and Thomas I. 2008 Science 320 190–4
[12] Agrawal V, Neuzil P and van der Weide D W 1997 Appl. Phys. Lett. 71 2343–5
[13] Lee S C, Feenstra B J, Schwartz A, Steinhauer D E, Wellstood F C and Anlage S M 2000 Appl. Phys. Lett. 77 4404–6
[14] Rosner B and van der Weide D W 2003 Rev. Sci. Instrum. 73 2503
[15] Sebastian T, Schultheiss K, Obry B, Hillebrands B and Schultheiss H 2015 Frontiers Phys. 335
[16] Black R C, Wellstood F C, Dantsker E, Miklich A H, Koelle D, Ludwig F and Clarke J 1995 Appl. Phys. Lett. 66 1267
[17] Boehi P and Treutlein P 2012 Appl. Phys. Lett. 101 181107
[18] Horsley A, Du G, Pellaton M, Affolderbach C, Mileti G and Treutlein P 2013 Phys. Rev. A 88 063407
[19] Affolderbach C, Du G X, Bandi T, Horsley A, Treutlein P and Mileti G 2015 IEEE Trans. Instrum. Meas. PP 1
[20] Boehi P, Riedel M, Haensch T and Treutlein P 2010 Appl. Phys. Lett. 97 051101
[21] Rondin L, Tetienne J P, Hingant T, Roch J F, Maletinsky P and Jacques V 2014 Rep. Prog. Phys. 77 056503
[22] Degen CL 2008 Appl. Phys. Lett. 92 243111
[23] Taylor J, Cappellaro P, Childress L, Jiang L, Budker D, Hemmer P, Walsworth R, Yacoby A and Lukin M 2008 Nat. Phys. 4 810
[24] Maze J et al 2008 Nature 455 644
[25] Balasubramanian G et al 2008 Nature 455 648
[26] Wang P, Yuan Z, Huang P, Rong X, Wang M, Xu X, Duan C, Ju C, Shi F and Du J 2015 Nat. Commun. 6 6631
[27] Maletinsky P, Hong S, Grinolds M S, Haussmann B, Lukin M D, Walsworth R L, Loncar M and Yacoby A 2012 Nat. Nanotechnology 7 230
[28] Tetienne J-P, Rondin L, Spinicelli P, Chipaux M, Debusschert T, Roch J and Jacques V 2012 New J. Phys. 14 103033
[29] Anger P, Bharadwaj P and Novotny L 2006 Phys. Rev. Lett. 96 113002
[30] Hingant T, Tetienne J, Martinez L, Garcia K, Ravelosona D, Roch J F and Jacques V 2015 Phys. Rev. Appl. 4 014003
[31] Slichter C 1996 Principles of Magnetic Resonance (Berlin: Springer)
[32] Pelliccione M, Myers B A, Pascal L M A, Das A and Bleszynski Jayich A C 2014 Phys. Rev. Appl. 2054014
[33] Tetienne J-P, Hingant T, Rondin L, Cavailles A, Mayer L, Dantelle G, Gacoin T, Wrachtrup J, Roch J and Jacques V 2013 Phys. Rev. B 87 235436
[34] Balasubramanian G et al 2009 Nat. Mater. 8 383–7
[35] Momenzadeh S, Stoehr R, de Oliveira F, Brunner A, Denisenko A, Yang S, Reinhard F and Wrachtrup J 2015 Nano Lett. 15 165–9
[36] Neu E, Appel P, Ganzhorn M, Miguel-Sánchez J, Lesik M, Mille V, Jacques V, Tallaire A, Achard J and Maletinsky P 2014 Appl. Phys. Lett. 105 153108
[37] Stepanov V, Cho F H, Ayebwardana C and Takahashi S 2015 Appl. Phys. Lett. 106 063111
[38] Sayil S, Kerns D and Kerns S 2005 IEEE Trans. Instrum. Meas. 54 2082
[39] Horsley A, Du G and Treutlein P 2015 Widefield microwave imaging in alkali vapor cells with sub-100 μm resolution, (accepted)
[40] van der Sar T, Casola F, Walsworth R and Yacoby A 2015 Nat. Commun. 6 7886
[41] Spinelli A, Bryant B, Delgado F, Fernandez-Rossier J and Otte A 2014 Nat. Mater. 13 782–5
[42] Nagaosa N and Tokura Y 2013 Nat. Nanotechnology 8 899