Eddy-current imaging with nitrogen-vacancy centers in diamond

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We demonstrate microwave-free eddy-current imaging using nitrogen-vacancy centers in diamond. By detecting the eddy-current induced magnetic field of conductive samples, we can distinguish between different materials and shapes and identify structural defects. Our technique allows for the discrimination of different materials according to their conductivity. The sensitivity of the measurements is calculated as $8 \times 10^5 \text{S/m}$/Hz at 3.5 MHz, for a cylindrical sample with radius $r_0 = 1 \text{mm}$ and height $h = 0.1 \text{mm}$ (volume $\sim 0.3 \text{mm}^3$), at a distance of 0.5 mm. In comparison with existing technologies, the diamond-based device exhibits a superior bandwidth and spatial resolution. In particular, we demonstrate a flat frequency response from DC to 3.5 MHz and a spatial resolution of $348 \pm 2 \text{µm}$.

INTRODUCTION

Magnetic induction measurements have proven to be useful in biomedicine,1 security and surveillance,2,3 and materials testing.4 Magnetic-induction imaging works by detecting magnetic fields produced by eddy-currents. When a material is placed in an alternating magnetic field (primary field), electric fields will be induced in the material, causing eddy-currents to flow. These in turn will produce a secondary magnetic field, that can be detected along with the primary field. The secondary field depends on the material’s properties and shape, as well as the skin depth of the primary field. Eddy-current detection has been commercially available with coil-based devices (e.g. Zetec, MIZ-22). Recently it has also been demonstrated using vapor-cell magnetometers.5

Here, we demonstrate eddy-current imaging using magnetic sensing with nitrogen-vacancy (NV) centers in diamond. Compared to other sensors, diamond-based devices operate in a wide temperature range and may have nanoscale-resolution6,7 with high sensitivity8,9 and wide bandwidth.10 The present eddy-current measurements are performed using an all-optical NV magnetometer. The device has a bandwidth of 3.5 MHz and exhibits a spatial resolution of 348 µm.

EXPERIMENTAL SETUP

In Fig.1(a) we present the NV center energy levels. The ground and excited electronic spin-triplet states of the NV are $^3A_2$ and $^3E$, respectively, with the transition between them having a zero-phonon line at 637 nm. Additionally, there are two singlet states. Optical transition rates in the system are spin-independent, however, the probability of nonradiative intersystem crossing from $^3E$ to the singlets is several times higher for $m_s = \pm 1$ than that for $m_s = 0$. As a consequence, under continuous illumination with green pump light (532 nm), NV centers are prepared in the $^3A_2 m_s = 0$ ground state sublevel and in the metastable $^1E$ singlet state. Population in the $^3A_2$ $m_s = 0$ state, then gets excited by the green light and decays back, emitting red photoluminescence (PL).

The setup consists of a microwave-free diamond magnetometer in AC-mode (discussed in detail in the following paragraph), a driving coil to induce eddy currents and a 3D-translation stage to make spatially dependent eddy-current measurements i.e. to create a conductivity image. The setup is shown in Fig.1(b). The diamond used for this sensor is a type Ib, (111)-cut, HPHT grown sample, purchased from Element Six. Its dimensions are

![FIG. 1. (a) Relevant NV center energy levels and transitions. Solid green and red lines indicate excitations, dashed lines indicate radiative transitions, and gray solid lines indicate non-radiative transitions. (b) Schematic of the experimental setup.](image-url)

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(3×3×0.400 mm³. The initial nitrogen concentration of the sample was specified as <110 ppm. The sample was irradiated with 14 MeV electrons at a dosage of 10¹⁸ cm⁻² and then annealed at 700 °C for three hours. Green light is provided to the setup by a diode-pumped solid-state laser (Laser Quantum, gem 532). The power of the laser is stabilized using an acousto-optical modulator (AOM, ISOMET-1260C with an ISOMET 630C-350 driver) controlled with a proportional-integral-derivative controller (PID, SRS SIM960). The light is focused on the diamond using a 50 mm lens. Before being detected with a photodiode (Thorlabs PDA36A-EC), the PL is filtered with a dichroic mirror. The samples to image are attached on to a 24 cm non-conductive rod, which is screwed onto a motorized, computer controlled, 3D-translation stage system (Thorlabs, MTS25-Z8). Using the translation stage, the samples are moved in front of the diamond. The eddy-current inducing magnetic field is produced with a function generator (FG, Tektronix AFG 2021), ranging from 2 Hz to 4 MHz. The signal is supplied to a coil placed around the diamond (RF coil) with five turns and 3.4 mm diameter. It is made from 0.05 mm diameter copper wire. Both the diamond and the coil are placed inside the bore of a custom-made electromagnet (EM). The magnet consists of ~200 turns wound with a rectangular-cross-section (1.4 mm×0.8 mm) wire around a 5 cm-diameter bore. The coil is wound on a water-cooled copper mount, and produces a background field of 2.9 mT per ampere supplied. A current up to 55 A is provided by a Keysight N8737A power supply. A lock-in amplifier (LIA) (SRS, SR865), referenced at the eddy-current frequency, detects the amplitude (R) and phase (θ) of the PL intensity modulation. R and θ are recorded on a computer (PC) along with the position of the 3D-translation stages.

MAGNETOMETRY

The magneto-metric scheme we followed for this measurements enables all-optical detection of AC fields. Figure 2(a) presents normalized PL measurements as a function of the background magnetic field at different alignments of the magnetic field relative to the NV axis. Figure 2(b) shows the corresponding amplitude of the PL oscillation due to the oscillating magnetic fields, R as measured with a LIA component from the lock-in amplifier. The traces display several features discussed in the literature. We investigated three different areas: α) the slope from 0 to ~25 mT, β) the cross-relaxation features around 50 mT and γ) the ground-state level anti-crossing (GSLAC) feature at 102.4 mT. To perform the measurements, we apply a bias field and maximize R for the different features. While R is maximized due to the quadratic shape of the feature, we are not sensitive to small changes in the bias field. However because we are demodulating at the frequency of the eddy current using a lock-in amplifier, we are sensitive to AC field changes.

As it is shown in Fig. 2(b) the maximum R is obtained at the GSLAC for the red trace. However, as demonstrated in the literature, this feature is sensitive to misalignment. To make the sensor more robust to misalignment, we perform the measurements, at area α. Even though area α is less sensitive it allows for robustness which will be useful in a portable device. Instead of requiring a highly homogeneous magnetic field, a standard permanent magnet could bias the field. The smaller field value additionally facilitates implementation in a miniaturized sensor and requires less power dissipation if an EM is used.

![Figure 2](image-url)

FIG. 2. (a) Fluorescence as a function of magnetic field at different alignments (up to ~5°) between the NV and magnetic field axis. The smallest misalignment is represented by the red trace and the biggest by the green. The data is normalized to the PL at 80 mT. (b) Lock-in amplifier R component for the same alignments between the NV and the magnetic field axis, with an applied magnetic field modulation of 60 kHz and an amplitude of 50 µT. The shaded areas α, β, γ represent magnetic field values at which we performed AC magnetometry measurements.

For eddy-current detection measurements a broad bandwidth is important because the frequency of the primary field determines its penetration depth into the sample under study. The penetration depth in turn provides information about the geometry, thickness, and material of the sample. Hence, to optimize images of different thickness materials, a wide frequency range is beneficial. Furthermore, higher frequencies enhance the response and make it possible to image materials with lower con-
SPATIAL RESOLUTION

One of the advantages of NV-based sensors is their spatial resolution. For eddy-current imaging, for a constant conductivity, the smaller a material is, the smaller the amplitude of the secondary field it produces. As a test of spatial resolution, we image fifteen 1 mm-diameter 35 μm thick dots made out of aluminum. The amplitude and phase response of the magnetic field sensor caused by these dots is shown in Fig. 4. Both the dots and the distance between them, which is sub-mm, are clearly visible. Note that covering the pattern with aluminum foil adds an offset but does not significantly alter the eddy-current image patterns shown in Fig. 4a and c.

Figure 3 shows the average cross section of the fifteen 1 mm dots imaged in Fig. 4. Using the average detected cross section data we deconvolute them with a square function, searching for a Gaussian function kernel that would recreate the experimental result. The kernel provides information about the dots’ width. In Fig. 3 the red plot signifies the dots’ width of 1 mm as a square function, the blue dots are the experimental data, the green trace represents the Gaussian function kernel and the convolution result of the red and green traces. All the traces amplitudes are normalized to unity for representation in the figure. The Gaussian kernel full-width-half-maximum is 348 ± 2 μm which we use as a measure for the spatial resolution of the sensor. The spatial resolution is mostly limited by the distance between sample and sensor. The diamond thickness sets the minimum distance to the sample. To decrease the distance between the sensor and the imaged sample a thinner diamond sample or a diamond with a shallow implanted NV layer could be used. A close proximity would improve measurement contrast and therefore the spatial resolution and allow the imaging of smaller objects.

Using the high bandwidth and spatial resolution of the device we are able to image intricate structures on printed circuit boards (PCBs). Figure 6 shows a miniature coat-of-arms of the city of Mainz as imaged by the eddy-current based method. The coat-of-arms is printed on a PCB, made out of copper with a 35 μm thickness.

SENSITIVITY

To calculate the sensitivity of the device we have to make assumptions about the sample to be imaged. We assume a primary field of \( B_{\text{prim.}} = 91 \, \mu \text{T} \) with frequency of 3.5 MHz, a cylindrical material with radius \( r_0 = 1 \, \text{mm} \) and height \( h = 0.1 \, \text{mm} \) (volume \( \sim 0.3 \, \text{mm}^3 \)). The sensor is placed at a distance \( d = 0.5 \, \text{mm} \) from the material. We calculate the minimum conductivity \( \sigma \) that the material should have in order to produce a field strong enough to be detected with our magnetic field sensor (current sensitivity \( \sim 10 \, \mu \text{T/√Hz} \)).

The secondary magnetic field can be calculated using the expression for the electromotive force (EMF)

\[
U = -\frac{\Delta \Phi}{\Delta t} = -2E \pi r,
\]

where \( \Delta \Phi \) is the magnetic flux and \( 1/\Delta t = \omega = 2 \pi f \), \( f \) being the modulation frequency of \( B_{\text{prim.}} \), \( E \) is the electric field and \( r \) is the distance from the center of the imaged sample. Using Biot-Savart’s law, the field produced by the eddy-currents (i.e. secondary field, \( B_{\text{sec.}} \)) and the minimum \( \sigma \) able to be detected can be calculated. For the example presented it would be \( \sim 8 \times 10^9 \, \text{S/m/√Hz} \). Enough to detect small pieces of materials like copper and aluminum,
FIG. 4. a),c) Lock-in Phase and Lock-in R amplitude for a PCB containing fifteen aluminum dots imaged with eddy-current b) photograph of the PCB with the corresponding length of 1 mm noted for scale.

FIG. 5. Determining spatial resolution. The blue dots signify the average cross section of fifteen 1 mm dots imaged by our sensor, the red plot signifies the dots’ width as a square function, the green trace represents a Gaussian function needed as a kernel to recreate the experimental data and blue trace represents the convolution result of the red and green trace.

\( \sigma_{\text{copper}} = 5.96 \times 10^7 \text{ S/m}, \quad \sigma_{\text{aluminium}} = 3.77 \times 10^7 \text{ S/m} \)

will be visible with our sensor.

**DISCUSSION**

We have demonstrated eddy-current imaging using NV centers in diamond. The magnetic sensitivity is achieved with an all-optical method that is robust to misalignment and makes use of the NV-NV cross-relaxation feature in the PL as function of the magnetic field. The bandwidth extends to 3.5 MHz. The spatial resolution is 348 \( \mu \text{m} \pm 2 \mu \text{m} \). The sensitivity of the device is calculated as \( 8 \times 10^5 \text{ S/m} \sqrt{\text{Hz}} \) at 3.5 MHz, for a cylindrical sample with radius \( r_0 = 1 \text{ mm} \) and height \( h = 0.1 \text{ mm} \) (volume \( \sim 0.3 \text{ mm}^3 \)) at a distance of 0.5 mm. Combining the above characteristics our device can be used, to distinguish between different materials, detect structural defects, and image complex structures on PCBs. The technique can be further improved by closer proximity to the imaged sample, which can be achieved using a thinner diamond or one with a shallow implanted NV layer. Compared to measurements with atomic vapor cells, the current NV-based method has superior bandwidth and spatial resolution. Comparing with coil-based commercial devices, it features superior bandwidth (e.g. Zetec, MIZ-22, bandwidth 50 Hz to 2 MHz) and sensitivity (5 \( \times 10^5 \text{ S/m} \)).

With its high bandwidth and spatial resolution, if combined with state-of-the-art NV sensors\(^9\text{-}^{10}\) the sensitivity (on the order of 10 pT/\( \sqrt{\text{Hz}} \)) would be sufficient for applications in biomedicine to distinguish between different tissues, or even healthy and unhealthy tissues, because of their different conductivities (ranging from 0.5 mS/cm to 13.7 mS/cm\(^\text{19}\)). The device’s robustness to misalignment and small size would allow it to be implemented on a hand-held, small and portable endoscopic sensor.

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FIG. 6. a),c) Lock-in θ and R of a PCB depicting the symbol of the city of Mainz imaged with eddy-current. b) photograph picture of the PCB with the corresponding length of 6 mm noted for scale.

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