Fiber-coupled Diamond Magnetometry with an Unshielded 15 pT/√Hz Sensitivity

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Ensembles of nitrogen vacancy centres (NVCs) in diamond can be employed for sensitive magnetometry. In this work we present a fiber-coupled NVC magnetometer with an unshielded sensitivity of (15 ± 5) pT/√Hz in a 10 - 500 Hz frequency range. This sensitivity is enabled by a relatively high green-to-red photon conversion efficiency, the use of a [100] bias field alignment, microwave and lock-in amplifier (LIA) parameter optimisation, as well as a balanced hyperfine excitation scheme. Furthermore, a silicon carbide (SiC) heat spreader is used for microwave delivery, alongside low-strain 12C diamonds, one of which is placed in a second magnetically insensitive fluorescence collecting sensor head for common-mode noise cancellation. The magnetometer is capable of detecting signals from sources such as a vacuum pump up to 2 m away, with some orientation dependence but no complete dead zones, demonstrating its potential for use in remote sensing applications.

I. INTRODUCTION

High sensitivity magnetometry has many applications, from fundamental physics to biology, geoscience and industrial sensing. Over the past decade there has been considerable interest in using solid-state defects for magnetometry, with the negative charge state of the NVC in diamond being the most promising candidate. NVC magnetometers do not require heating, cryogenic cooling, vacuum tubes or magnetic shielding. Ensemble NVC magnetometers can obtain mm-scale spatial resolution with high dynamic range. The properties of diamond and the NVC make them suitable for extreme environments, NVCs being capable of sensing at temperatures up to 600 K and pressures of 60 GPa, as well as for biological and medical applications owing to the low toxicity of diamond. Using ensembles of NVCs increases sensitivity by a factor of 1/√N, where N is the number of sensing spins, at the expense of spatial resolution. Ensembles also enable vector magnetometry, without the need for multiple sensor heads.

Most high sensitivity NVC magnetometers are entirely confined to table-tops, with more portable devices having significantly inferior sensitivity. To improve the functionality of NVC magnetometers, the optoelectronic equipment can be fiber-coupled to a small mobile sensor head. In recent years several fiber-coupled NVC magnetometers with sub-nanotesla sensitivities have been demonstrated. Using a tracking pulsed magnetometry scheme allowed a sensitivity of 103 pT/√Hz in a 1 - 2600 Hz frequency range to be achieved, setting the current record for fiber-coupled NVC magnetometers. This may be compared to the records of 0.9 pT/√Hz and 15 pT/√Hz for non-fiber-coupled NVC magnetometers with and without ferrite flux concentrators respectively. A magnetically shielded room was used for the 15 pT/√Hz magnetometer. High sensitivity NVC magnetometers with portable fiber-coupled sensor heads are more suitable than purely table-top setups for a wide range of applications, from magnetocardiography (MCG) to the detection of corrosion in steel.

In this work we demonstrate a fiber-coupled NVC magnetometer with a sensitivity of 15 pT/√Hz in a 10 - 500 Hz frequency range. The ability of the magnetometer to remotely detect real-life magnetic signals is demonstrated here using a vacuum pump. The vacuum pump consists of a backing pump, the magnetic signals from which can be seen up to 2 m away, and a turbo-pump, with a 1 kHz magnetic signal that could be observed at distances up to 1.8 m.

A continuous-wave optically detected magnetic resonance (CW ODMR) magnetometry scheme, in which the NVC ensemble is addressed simultaneously and continuously with both microwaves and a laser is employed here. A bias magnetic field is applied to split out the magnetic resonances. A LIA is used to pick out the magnetometry signal from the noise and a fixed microwave frequency is applied to the steepest part of a given resonance, the zero-crossing point. A magnetic field from a sample will shift the frequency of the resonance via the Zeeman effect. This leads to changes in the NVC fluorescence, and thus shifts in the LIA voltage output. Using a calibration constant, the magnetic field responsible for the voltage shift can be determined in real-time, assuming the shift is within the bandwidth and dynamic range of the magnetometer.

The Physics of the NVC is explained in appendix A.

For CW ODMR the fundamental photon-shot-noise-limited sensitivity, η, is given by

$$\eta = \frac{4}{3\sqrt{3}} \frac{\Delta \nu}{\gamma C \sqrt{R}}$$

where $\Delta \nu$ is the linewidth, $C$ is the measurement contrast, R the photon detection rate and $\gamma$ is the gyromagnetic ratio of the NVC, equal to 28.024 GHz/T.
As seen in Eq. (11) optimising the sensitivity requires the maximisation of $R$, and thus the fluorescence collection from the NVCs, as well as the $C/\Delta \nu$ ratio. The first of these tasks is made non-trivial by the high refractive index of diamond \cite{19}, as well as the use of a fiber. At the same time, difficulties obtaining high microwave and bias field homogeneity over large ensemble sensing volumes, as well as microwave and laser power broadening complicate improvements to the $C/\Delta \nu$ ratio. Reducing technical noise, for example from laser intensity or frequency variations, is also important for maximising sensitivity as in practice it is typically limited by such noise. Simply increasing the laser power to maximise fluorescence is undesirable, not only due to power broadening of the ODMR linewidth, but also because it leads to increased temperature fluctuations. These fluctuations change the zero-field splitting of the NVC and thus produce noise \cite{50}. Very high laser powers also increase the photo-ionisation of the NVCs \cite{51, 52}.

II. METHODS

The CW ODMR scheme outlined above is implemented using the two sensor head (signal and reference) setup shown in Fig. 1. The NVC ensemble of each sensor head’s diamond is excited using a Laser Quantum 532 nm-Opus laser with a maximum output of 6 W, though to prevent saturation of the photodiodes only 1.8 W of laser power is employed, $\approx 0.3$ W of which is measured at the diamond within the signal sensor head. The laser power is approximately equally split between the two sensor heads. The sensor heads and optoelectronic equipment are both placed on heavy tables, which lack air legs. For each sensor head the laser beam is focused into custom-ordered FG910UEC fibers that are 3 m long with 0.22 N.A., core diameters of 910 $\mu$m and steel FC/PC terminations. The fibers are secured to mitigate modal noise \cite{53}. Only the signal sensor head is employed for magnetometry, with the fluorescence from the magnetically insensitive reference sensor head being focused onto the reference photodiode of a Thorlabs PD450A balanced detector to allow the cancellation of common mode, most notably laser, noise. The fluorescence signals at the photodiodes from each sensor head are equal when the signal sensor head is on a magnetically sensitive resonance and in contrast over a [111] bias field alignment. As NVCs project equally onto all four possible NVC symmetry axis alignments, yielding a factor of four improvement that the magnetometer is sensitive along a vector that is not along a given NVC symmetry axis and in this case the sensitive axis projects equally onto all four possible NVC symmetry axes. Using this alignment means the projection of the magnetic field along their [100] crystallographic orientations of the signal sensor head NVC ensemble. Using this alignment means the projection of the magnetic field along their 4 axial alignments, yielding a factor of four improvement in contrast over a [111] bias field alignment. As NVCs measure the projection of the magnetic field along their [111] symmetry axis and in this case the sensitive axis is not along a given NVC symmetry axis the magnetometer responsivity is reduced by an angle factor of $\cos(109.5^\circ/2) \approx 0.58$. This limits any sensitivity gain relative to a [111] alignment to a factor of 2.3 \cite{5}. From Eq. (2), see Fig. 2, and appendix A, the frequency splitting, $\Delta f$, implies an applied bias field projection along the four

![Figure 1](image_url) Schematic of the experimental setup. PBS is polarising beam splitter, LP is long-pass filter and LIA is lock-in amplifier.
The microwave source and LIA parameters are optimised as outlined in [12, 54]. The optimum parameters with a 500 Hz LIA low-pass filter (LPF) 3 dB point, which is taken as the upper limit of the sensitive frequency range, are 3.003 kHz and 220.23 kHz for the modulation frequency and amplitude respectively. The optimum microwave power is found to occur when \( \approx 0.054 \) W is measured on a vector analyser, placed following the microwave amplifier and circulator. Example ODMR spectra, including the demodulated output of the LIA, taken with these parameters are shown in Fig. 2. Parameter optimisation is further discussed in appendix D.

![Graphs showing ODMR spectra](image)

**FIG. 2.** a) and b) show the normalised ODMR and demodulated ODMR spectra respectively. \( B_{\text{NVC}} \) is the projection of the external magnetic field along the NVC symmetry axis for a given alignment. c) shows a zoom of the normalised ODMR with a Lorentzian fit, with the contrast, C, and linewidth \( \Delta \nu \) indicated. d) shows a zoom of the demodulated ODMR spectra, with a linear fit applied at the zero-crossing point of the central resonance feature.

**III. RESULTS**

The sensitivity is determined by applying known test fields along one of the [100] crystallographic orientations of the signal sensor head NVC ensemble to measure the magnetometer response. The test-fields are produced using a Helmholtz coil calibrated using a Magnetics GM07 Hall probe. A linear fit is applied to the data seen in the inset of Fig. 3 to obtain a calibration constant of \( 8.3 \times 10^{-4} \) V/nT. This compares to a calibration constant of \( 1.4 \times 10^{-3} \) V/nT when using the ODMR zero-crossing slope, see Fig. 2, with the ratio of 0.60 between the two values being close to the anticipated value of 0.58.

![Sensitivity spectra graph](image)

**FIG. 3.** Sensitivity spectra, with a mean sensitivity of 15 pT/√Hz from 10 - 500 Hz. The noise floor is also shown when magnetically insensitive (off-resonance), and with no applied laser or microwaves (electronic noise). The noise floor drops at DC due to the use of AC coupling. The shaded region lies beyond the LIA LPF 3 dB point at 500 Hz. The inset shows the magnetometer responsivity as a function of applied magnetic test-field along one of the [100] crystallographic orientations.

To obtain the noise floor, the microwave frequency is set to the zero-crossing point of the demodulated LIA ODMR spectrum. The central resonance with the largest zero-crossing slope (ZCS) is chosen. The magnetometer is then magnetically sensitive and thirty-two 1 s time-traces are taken with a sampling rate of 20 kHz. Such time traces are also taken with the microwave frequency set off-resonance: this renders the magnetometer magnetically insensitive, allowing the level of magnetic noise to be characterised. Time traces are also taken with the laser and microwave source turned off such that the measured signal may be regarded as representing the electronic noise of the system. Using the calibration constant determined above the time traces are converted into power spectral density (PSD) plots before being averaged. The method of determining the sensitivity is expanded upon in appendix F. For the magnetically sensitive case the mean sensitivity is deter-
minded to be \((15 \pm 5) \text{ pT/}\sqrt{\text{Hz}}\) in a frequency range of 10 - 500 Hz, with the 50 Hz peak and its harmonics being masked, as seen in Fig. 8, leaving the predominantly flat noise floor. Significant noise is present at low frequencies, below \(\approx 10\) Hz, and this 1/f noise is attributed to laser power variations and vibrations, as well as magnetic noise in the environment. The characteristic peaks at 50 Hz and its harmonics can be associated with ambient magnetic noise, for example from the mains, as they are not observed when magnetically insensitive. The average noise levels for the magnetically insensitive and electronic noise cases are \((11 \pm 1) \text{ pT/}\sqrt{\text{Hz}}\) and \((4.5 \pm 0.6) \text{ pT/}\sqrt{\text{Hz}}\) respectively.

Equation (1) is used to calculate the photon-shot-noise limit. The red photon detection rate is determined to be \(2.9 \times 10^{15}\) Hz from the fluorescence power measured to be incident upon the balanced detector photodiodes using a Thorlabs PM100D power meter with a S121C head. The ODMR spectrum prior to LIA amplification is used to determine the linewidth and contrast, which are found to be 0.73 MHz and 10% respectively. Using these values and accounting for the 0.58 angle factor, the photon-shot-noise limit is \((6.5 \pm 0.9) \text{ pT/}\sqrt{\text{Hz}}\). It would appear that NVCs distributed throughout the whole volume of the 1 mm\(^3\) diamond are being addressed and contribute to the magnetometry signal. This is discussed further in appendix H.

To demonstrate the ability of the magnetometer to detect signals from remote sources, we use a vacuum pump that consists of a backing and turbo pump. An electric scooter is also investigated as can be seen in appendix M. Figure 4a shows the magnetic signals detected from the vacuum pump compared to a reference state without the vacuum pump. For these measurements, the modulation frequency is set to 10 kHz. The average noise levels are taken for a period of 1 s to ensure that none of the signals are cut-off. Averaging is used, though it is not required to observe the majority of the peaks. Many peaks may be associated with the backing pump, but we focus on a peak at 76 Hz. A peak can also be seen at 1 kHz from the turbo-pump. The amplitudes of both the backing peak 76 Hz and 1 kHz turbo-pump signal are measured as a function of distance from 30 cm to 2 m as seen in Fig. 4b, with the amplitudes following a \(1/d^2\) drop off, where \(d\) is the distance from the diamond [52]. For these measurements the vacuum pump is placed approximately level with the sensor head. The backing pump can be detected at 2 m while still having a signal to noise of 5. No measurements are taken beyond 2 m due to space constraints. The turbo-pump signal could be seen at distances up to 1.8 m. The sensitive axis of the magnetometer lies along a [100] crystallographic orientation. Accordingly the ability to detect signals depends not only on the distance but also on the orientation of the object relative to this axis. However, as there will always be a non-zero field projection along at least one of the four NVC alignments there is not a complete dead zone [50] orthogonal to the sensitive axis as in [42] where a [111] bias field alignment was used. However, the projection and hence response will differ for each NVC alignment if the applied fields are not aligned along [100]. This leads to a complicated overall magnetometer response and the overall response and thus sensitivity is reduced. This is discussed further in appendix L.

**IV. DISCUSSION AND CONCLUSION**

Given our contrast, linewidth, and fluorescence intensity we obtain a photon-shot-noise-limited sensitivity of 6.5 pT/\(\sqrt{\text{Hz}}\), improving upon [42] and approaching [7]. A relatively high ensemble contrast of 4% is obtained by aligning the bias field along a [100] crystallographic...
orientation. This ensures that the entire NVC ensemble population contributes to the magnetometry signal, leading to a factor of 4 enhancement in contrast. Hyperfine excitation is then found to yield a factor of 2.5 increase in contrast, producing a high final contrast of 10% [7, 42, 43, 57]. The power is balanced between the function generator and microwave source to ensure approximately equal microwave intensity within the three hyperfine excitation tones. The use of a SiC, as opposed to Al, antenna substrate has likely resulted in improved microwave power delivery efficiency owing to its superior microwave transmission properties [42, 58]. The SiC may also have enhanced our contrast and microwave field homogeneity relative to Al [42]. The high thermal conductivity of SiC also helps to reduce noise caused by temperature fluctuations within the diamond that change the zero-field splitting of the NVC [51].

The green-to-red photon conversion efficiency is $\approx 0.36\%$. The use of a 910 $\mu$m diameter fiber and aspheric lenses for the collimation and focusing of both the laser and fluorescence light enabled this conversion efficiency, relatively high for a fiber-coupled device [43, 57], though higher efficiencies have been obtained [44]. A comparatively narrow ODMR linewidth, given the NVC concentration, of 0.73 MHz is obtained [42]. The linewidth appears to be modulation-amplitude limited as without frequency modulation the linewidth is found to be 0.63 MHz. Compared to a $T_2^*$-limited linewidth of 0.42 MHz, however, it is clear that the linewidth also suffers from microwave and laser power broadening at the microwave and laser powers employed. Further parameter optimisation is likely possible.

Furthermore, the use of a second sensor head for common-mode noise cancellation provides a factor of eleven improvement in sensitivity. Using a second fluorescence emitting diamond, as opposed to just picking off a portion of the laser beam [42, 44, 46], allows for not only the laser intensity, but also laser frequency noise to be cancelled using the balanced detector. Nonetheless, we remain a factor of 2.3 above our photon-shot-noise-limited sensitivity with magnetic and laser noise being our principal limiting sources of noise, unsurprising in the former case given our lack of magnetic shielding. The laboratory environment is magnetically noisy with numerous coloured peaks appearing, many of which may be associated with the mains. The 1/f noise below 10 Hz is significant and this would be problematic for some applications.

In conclusion, we have presented a fiber-coupled NVC magnetometer with an unshielded sensitivity of (15 ± 5) pT/√Hz in a 10 - 500 Hz frequency range. It was shown to be capable of remotely detecting real-life magnetic fields from machinery. The portable sensor head combined with the high sensitivity make it useful for a wide range of applications.

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APPENDIX A: PHYSICS OF THE NVC

![Figure 5](image)

FIG. 5. Schematic of the electronic structure of the NVC centre in diamond with electric dipole transitions and intersystem crossing (ISC) indicated.

The NVC is a point defect in the diamond lattice consisting of a substitutional nitrogen atom adjacent to a vacancy. The defect has trigonal symmetry, with a (111) major symmetry axis taken as the line between the nitrogen and vacancy, which has four possible alignments [111], [111], [1,1,1], and [1,1,1] for a given diamond crystal [59, 60]. In an ensemble these alignments will typically be equally populated. The negative charge state of the NVC is a spin-1 defect with a spin-triplet ground state that can be optically initialised and read out using ODMR spectroscopy [18, 19]. The energy level structure of the NVC...
is shown in Fig. 5. The NVC can be optically initialised into the $m_s = 0$ sub-level of the $^{3}A_2$ ground state using a 532 nm laser, as if the defect is initially in the $m_s = \pm 1$ sub-levels prior to excitation it has a greater probability of returning to the ground state via the singlet states, which involves non-spin conserving transitions. This pathway is also non-radiative, allowing the spin-state to be read out from the fluorescence intensity. The spin-state can be manipulated and driven from the $m_s = 0$ to $m_s = \pm 1$ sub-levels using microwaves [18, 19].

The zero-field splitting of the $^{3}A_2$ ground state is $\approx 2.87$ GHz at room temperature. Upon the application of an external magnetic field the degeneracy of the $m_s = \pm 1$ sub-levels is lifted via the Zeeman effect, leading to resonances at two different frequencies (for a given NVC alignment) split by $\Delta f = 2\gamma B_{NVC}$,

$$\Delta f = 2\gamma B_{NVC}, \quad (2)$$

where $B_{NVC}$ is the projection of the external magnetic field along the NVC symmetry axis for a given alignment. The $S = 1$ electron spin has a hyperfine interaction with the $I = 1$ nuclear spin of the NVC’s $^{14}N$ atom, splitting each resonance into three, separated by $\approx 2.158$ MHz [6, 59].

**APPENDIX B: DIAMOND PROPERTIES**

An isotopically purified (99.995% $^{12}C$) CVD diamond is used in this work, ensuring a minimal concentration of $I = 1$ $^{13}C$ nuclear spins [61, 62] that would otherwise contribute to decoherence. The diamond has been electron irradiated and then annealed to increase its NVC concentration, which is found to be $(2.8 \pm 0.2)$ ppm via EPR measurements taken using a Bruker EMX spectrometer with a 90 dB microwave bridge and a Bruker super high Q cavity. Pulsed EPR measurements were taken with a Bruker E580 and MD5 resonator to determine the $T_2^*$, $T_2$, and $T_1$ to be 750 ns, 1.3 $\mu$s, and 5100 $\mu$s respectively. Given this $T_2^*$ and using the formula $1/\pi T_2^*$ [19], a minimum ODMR resonance linewidth of 0.42 MHz would be anticipated, though in practice the linewidth is broadened by microwave and laser power broadening. Following this characterisation the diamond sample (which initially had dimensions of $2.97 \times 2.93 \times 0.93$ mm$^3$) was laser cut into nine equal cube pieces, each mechanically polished so that all six faces had an optical grade finish. Two of these $1 \times 1 \times 1$ mm$^3$ diamond samples are employed for the signal and reference sensor heads respectively. For effective noise cancellation it is important that the diamonds used in each of the two sensor heads are as similar to each other as possible. The EPR measurements may be found in the appendix of [42]. The diamond growth, electron irradiation, annealing and polishing were done by Element Six.

**APPENDIX C: SENSOR HEAD**

Figure 6 shows the sensor head design in profile, including both the optics, SiC substrate and microwave antenna. The open 20 mm long Thorlabs SM1L20C lens tube contains a Thorlabs 0.25 N.A. C220TMD-B aspheric lens used for collimating the laser beam output from the Thorlabs 0.22 N.A. 910 $\mu$m diameter FG910UEC fiber. The collimated laser beam is then focused down onto the 1 mm$^3$ diamond sample using a Thorlabs 0.7 N.A. C330TMD-B aspheric lens, contained within the same lens tube. This same lens combination is then used to collimate and focus the fluorescence emitted by the NVC ensemble into the optical fiber.

Figure 7 shows the sensor head showing the microwave transmission line and antenna. The diamond is placed at the centre of a simple 1.1 mm loop antenna. The microwaves are supplied to this antenna by a transmission line. Initially
following the SMA connector this transmission line consists of a Cu contact. Three silver (Ag) wires connect the Cu to the loop antenna and transmission line on top of the SiC substrate, which are both formed from a 100 nm thick Au contact layer with an ≈ 5 nm layer of Ti to allow the Au to stick to the SiC substrate. The SiC substrate with the loop antenna and transmission line are contained within an Al holder, which possesses a Cu base. The dimensions of this holder are shown in Fig. 6 alongside the microwave antenna and transmission line design. The holder acts as a Faraday cage ensuring the microwaves are kept within the sensor head. The thickness of this holder sets the minimum sample to diamond distance at ≈ 2 mm.

In our previous work, an Al substrate with a copper transmission line and antenna loop, was selected due to its high thermal conductivity, which helps to mitigate temperature fluctuations in the diamond that produce noise which looks like a magnetic field. Additionally, in contrast to FR4, Al would not burn under high laser powers. However, the microwave transmission properties of Al are inferior to those of FR4 and thus a material which combined good microwave and thermal properties was desired. SiC has a higher thermal conductivity than Al, 490 W/mK as opposed to 251 W/mK (at best), while the dielectric nature of SiC also ensures the free passage of microwaves, in contrast to metallic Al. This allows us to employ less microwave power and also obtain superior contrasts. Further improvement in microwave power delivery efficiency is likely possible, via the use of superior SMA cables and solder.

APPENDIX D: PARAMETER OPTIMISATION

For parameter optimisation ODMR spectra are taken with the bias field aligned along a [100] orientation, as seen in Fig. 2. The ZCS, determined by applying a linear fit to the derivative slope of the higher frequency NVC resonance of the demodulated ODMR spectrum, directly relates the LIA voltage output with a change in fluorescence output induced by a resonance frequency shift. Larger ZCS values indicate greater responsivity and thus sensitivity, however the ZCS does not account for greater susceptibility to noise and thus a larger ZCS does not always imply superior sensitivity.

From Eq. (1) it can be seen that increasing the ratio $C/\Delta \nu$ improves the photon-shot-noise-limited sensitivity. Figure 8 shows both $C/\Delta \nu$ and the ZCS as a function of microwave power. For a given set of parameters ODMR spectra are taken with and without the LIA, using hyperfine excitation. The contrast and linewidth can be extracted from applying Lorentzian fits to the pre-LIA ODMR spectra, taking the fluorescence signal directly from the signal photodiode. The ODMR spectra are taken with a frequency sweep range of 2.88 GHz to 2.92 GHz, a step resolution of 20 kHz, a step dwell time of 3 ms and a sampling rate of 20 kHz (2 MS over 100 s). The LIA 3 dB point is set to 500 Hz, with a filter slope of 48 dB/octave, and the LIA output scaling is set to 100. The reference input phase of the LIA is adjusted to maximise the signal within the X-channel of the LIA. The contrast is determined using

$$C = \frac{I_O - I_R}{I_O},$$

where $I_R$ is the fluorescence signal on-resonance and $I_O$ the fluorescence signal off-resonance. The linewidth is taken from the full-width half maximum (FWHM) of the Lorentzian fit. The optimum microwave power is found to occur when we observe ≈ 0.054 W using an Agilent N9320B vector network analyser. The stated microwave intensity in W is the total power being delivered when exciting all three hyperfine features simultaneously, corresponding to the central peak of the five hyperfine features, the ODMR peak for which the ZCS is determined. For each hyperfine line ≈ 0.018 W of microwave power is being delivered. That this is the optimum value can also be seen from the decrease in ZCS beyond this microwave power. The microwave powers stated above neglect losses following the circulator within the cables, adaptors and transmission line and thus are very approximate and unlikely to reflect the true microwave power being delivered to the diamond sample.

![Figure 8](image_url)

**FIG. 8.** The ZCS and $C/\Delta \nu$ ratio as a function of microwave power. All measurements taken using a modulation frequency of 3.003 kHz and a modulation-amplitude of 220.23 kHz.

The ZCS is found to increase with decreasing modulation frequency as can be seen in Fig. 9. This increase is expected due to the finite repolarisation time of the NVC. However, the noise floors also rise, as susceptibility to noise is increased for modulation frequencies that approach DC.

Accordingly, we measure the mean sensitivity taken over a 10 - 500 Hz frequency range as a function of modulation frequency, as seen in Fig. 9. A modulation fre-
frequency of 3.003 kHz is found to provide the best mean sensitivity over the given frequency range. For the vacuum pump measurements care is also taken to ensure that for a given sampling rate the modulation frequency does not lead to aliased peaks at, for example, 1 kHz, the frequency of the turbo-pump signal.

Figure 10 shows the ZCS and $C/\Delta \nu$ ratio as a function of modulation-amplitude. A modulation-amplitude of 220.23 kHz is found to provide the highest ZCS, with no change being observed in noise floor over the range of modulation-amplitude values. It would appear that further optimisation of the modulation-amplitude may be possible, however, as when frequency modulation is used a linewidth of 0.73 MHz is measured compared to a linewidth of 0.63 MHz when it is off. The $C/\Delta \nu$ ratio continues to increase below the modulation frequency for which the highest ZCS is measured: this suggests that the linewidth broadening caused by the frequency modulation is not the dominant effect influencing the ZCS below 220.23 kHz. From theoretical considerations it is expected that the optimum modulation-amplitude will be equal to $\Delta \nu / 2\sqrt{3}$, which for a linewidth of 0.63 MHz would mean a modulation-amplitude of $\approx 180$ kHz [7].

In this work we use sine as opposed to square wave frequency modulation. Figure 11b shows sensitivity measurements taken with sine and square wave modulation. The noise floor is found to be significantly higher for square-wave modulation, this is likely due to the generation of multiple additional harmonics when using square-wave modulation. Negligible difference in the ZCS is seen between sine and square-wave modulation, this is surprising given that our linewidth ($\Delta \nu = 0.73$ MHz) to hyperfine splitting ($A = 2.158$ MHz) ratio is greater than 1/4, though we are only using a modulation-amplitude of 220.23 kHz [12]. This may be a property of the E8257 microwave source and was not observed using the Agilent N5172B microwave source [12]. Figure 11a shows the hyperfine splitting and linewidth, without hyperfine excitation.

From this parameter optimisation process the optimum modulation frequency, modulation-amplitude, and microwave power are identified to be 3.003 kHz, 220.23 kHz, and 0.054 W respectively. A laser power of 1.8 W, corresponding to an excitation power at the signal sensor head diamond of $\approx 0.3$ W, is used. Higher laser powers cause the photodiodes to saturate or at least enter a non-linear response regime. It is possible that given photodiodes with higher dynamic range, using higher laser powers could yield improvements in sensitivity, with increases to the photon detection rate, $R$. However, increasing the laser excitation power will also change the spin polarisation rate, cause power broadening, and lead to increased noise from temperature fluctuations. Accordingly it would be more desirable to improve the photon detection rate via enhancements in the photon collection efficiency.
FIG. 11. a) ODMR spectrum showing the hyperfine splitting, A and linewidth $\Delta \nu$. Hyperfine excitation is not being used. b) Sensitivity measurements showing the difference in sensitivity between sine and square-wave frequency modulation using the optimum settings. The dotted lines show the mean sensitivity taken for a frequency range from 10 - 500 Hz, with the 50 Hz peak and its harmonics masked. Mean sensitivities of $(15 \pm 5) \ pT/\sqrt{Hz}$ and $(22 \pm 10) \ pT/\sqrt{Hz}$ are found for sine and square-wave frequency modulation respectively. AC coupling is used for these measurements.

APPENDIX E: OPTICS

The green-to-red photon conversion efficiency is $\approx 0.36\%$, enabling a red photon detection rate of $2.9 \times 10^{15} \ Hz$ for $\approx 0.3 \ W$ of laser excitation power. This has been achieved via a series of incremental improvements in both the sensor head and table-top optics. Firstly, the replacement of a 400 μm diameter, 5 m long 0.22 N.A. FG400AEA fiber with a 910 μm diameter, 3 m long 0.22 N.A. FG910UEC fiber is found to improve the observed fluorescence signal for a given laser power. It is easier to couple both the laser beam and fluorescence into the larger diameter fiber and the reduced length allows them to be better secured to minimise modal noise. Larger diameter fibers are also anticipated to be less susceptible to modal noise due to them possessing a higher number of modes and thus a reduced speckle contrast. Using a Thorlabs CS165CU/M Zelux™ colour CMOS camera the standard deviation of the fiber output speckle pattern is measured to be 0.42 and 0.39 for the FG400AEA and FG910UEC fibers respectively. However, the 910 μm fiber is more rigid and we have been unable to procure a ceramic FC/PC termination for the sensor head end of the fiber. The first of these factors would be inconvenient if scanning the sensor head across a sample, while the use of a steel FC/PC termination is a source of magnetic noise. Introducing padding should help to reduce the effects of vibrations on the sensor head and help with 1/f noise. Given our narrow linewidths and [100] bias field alignment, relative motion, from vibration for example, between the sensor head and permanent NdFeB magnet are likely to be a not insignificant source of low-frequency noise. Excitation and collection efficiency could also be improved by better securing the optical fibers; movements and misalignment of the fibers are found to cause large drops in fluorescence. This not only contributes to noise, not readily cancelled using the balanced detector, but also leads to inefficient collection and excitation as the skew in the light launched into the fiber produces a "dount-shaped" beam output. Some improvement in fluorescence collection may also be the result of the highly reflective SiC substrate upon which the diamond is placed.

As discussed in appendix C the sensor head optics are contained within a 25.4 mm diameter SM1 open lens tube 20 mm in length. This arrangement allowed us to observe what happened to the fluorescence emitted by the diamond. We found that it rapidly diverged before it could be effectively collimated and focused by the lenses. Using a single lens tube allowed us to then bring the lenses closer together and to control the relative positions of both the fiber, C220TMD-B and C330TMD-B lenses in the z-direction. Using a Thorlabs CXY1 XY translating lens mount it was possible to obtain x and y control in addition to z-control, though we found that the fiber, lenses and diamond were already well-centered without this additional degree of freedom. The 0.25 N.A. C220TMD-B aspheric lens is used both for collimation in the sensor head and for coupling the laser beam into the fiber on the table-top optics side. This N.A. closely matches that of the 0.22 N.A. fiber.

For the table-top optics Thorlabs BB111-E02 > 99% reflectance Zerodur broadband dielectric mirrors are used, helping to minimise laser and fluorescence losses. Thorlabs DMS605 shortpass dichroic mirrors, which possess a 99% reflectance at 650 nm, are used to separate the green laser and red fluorescence light. Imaging with the CS165CU/M Zelux™ colour CMOS camera allowed us to ensure the fluorescence beam diameter matched the 0.8 mm diameter of the balanced detec-
tor photodiodes. 15 mm diameter, 12 mm focal length, Thorlabs ACL1512U aspheric condenser lenses are used, in combination with 25 mm focal length aspheric lenses, to achieve this beam diameter. A tighter focus onto the photodiodes would be undesirable as it could lead to non-linear effects.

The use of two sensor heads necessitates the use of more laser power than for a single sensor head configuration. The 1.8 W of laser power is split approximately equally between the two sensor heads using a Thorlabs PBS12-532-HP high-power PBS and a Thorlabs WPH05M-532 zero-order half-wave plate, held within a Thorlabs RSP1/M rotation mount. When on a magnetically sensitive resonance and using a Thorlabs PM100D power meter with SI21C head the laser power prior to the fibers is found to be \( \approx 0.6 \text{ W} \) and 0.75 W for the signal and reference sensor heads respectively. Given a measured \( \approx 80\% \) transmission efficiency through the optical fiber, and further losses from the sensor head lenses, in part due to their B (650 - 1050 nm) coatings that are selected to maximise fluorescence even at the expense of green laser power, \( \approx 0.3 \text{ W} \) of laser excitation power is directed upon the diamond. For the reference sensor head this number is \( \approx 0.4 \text{ W} \). On the magnetically sensitive resonance \( \approx 0.9 \text{ mW} \) of fluorescence is measured just prior to the signal and reference photodiodes, suggesting the optics alignment for the reference channel could be improved. Considering only the laser power going to the signal sensor head the green-to-red photon conversion efficiency is found to be \( \approx 0.36\% \) or 0.18\% for whether or not the laser power losses prior to the diamond are included respectively. A lower total laser power could be employed via the use of AB coated, as opposed to B-coated, optics. Additionally, the optical isolator is found to be responsible for \( \approx 0.2 \text{ W} \) of laser power loss. The coupling of the laser beam output of the fibers into the sensor heads could also likely be improved. Small changes in the positioning of the fiber are found to yield large changes in the laser power measured at the diamond as well as in the fluorescence signal measured at the photodiodes. If the fiber is moving around during measurements changes in the coupling efficiency could be a substantial source of noise, alongside modal noise.

APPENDIX F: SENSITIVITY DATA ANALYSIS

In this work, to determine the sensitivity 1 s time traces are taken using a Picoscope 5442D at a sampling rate of 20 kHz and these are converted into PSD plots via Matlab. The time trace in volts (V) is converted into nT by dividing through by a calibration constant with units of V/nT. This calibration constant is found via either the test-field or ZCS method. In the test-field approach a field from a Helmholtz coil, as explained in the main text, is applied along [100] while sitting on a magnetically sensitive resonance. The shift in voltage due to the applied field is measured as the current through the Helmholtz coil is increased in steps. The Helmholtz coil has been calibrated using a Magnetics GM07 Hall probe that measures the total field. As temperature changes and laser power fluctuations can also cause voltage shifts the magnetic field is turned off between each increase in the test-field magnitude. Examples of the step signals observed when applying the test-fields can be seen in the inset of Fig. 12. The calibration constant in V/nT can then be found by applying a linear fit to the data seen in Fig. 3 of the main text. The alternative, ZCS method involves applying a linear fit to the zero-crossing point of the ODMR resonance to obtain a slope in V/MHz. This slope can then be converted into an appropriate calibration constant using the gyromagnetic ratio of the NVC, \( \gamma = 28 \text{ Hz/nT} \). A ratio of \( \approx 0.58 \) is found between the calibration constant determined using the test-field and ZCS methods respectively. This is due to the projective nature of NVC magnetometers, with the actual field measured along each of the four NVC alignments being a factor of 0.58 smaller than the total field measured with the Hall probe. The ZCS method is not employed for this work, as with the bias field aligned along [100] the sensitive axis is now along [100] as opposed to a \langle 111 \rangle NVC symmetry axis. The calibration constant determined using this method would be as if the total magnetic field had been completely projected along each of the four NVC alignments symmetry axes simultaneously: a situation that would never occur in practice.
Initially fast-Fourier transforms (FFT) in dBu were taken alongside the time traces using the Picoscope 5442D. Then these FFTs were extracted and converted into volts using the conversion formula $0.775 \times 10^{L/20}$ where $L$ is the FFT noise floor in dBu. However, we stopped making use of the FFTs from the Picoscope as we found that the total energy in the time traces and FFTs did not agree with Parseval’s theorem.

$$E = \int_{-\infty}^{\infty} x(t)x^*(t) dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(\omega)X^*(\omega) d\omega \quad (4)$$

that the energy of the signal should be conserved between the time and frequency domain. In Eq. $\text{4}$, $E$ is the energy of the signal, $x(t)$ is the signal in the time domain and $X(\omega)$ is the signal in the frequency domain. Using the time traces directly is found to improve our sensitivity value by a factor of 2 relative to the value found using the Picoscope FFTs. As a result our previously published sensitivity of $310 \text{ pT/Hz}$ in $\text{[12]}$ may be more accurately reported as $155 \text{ pT/Hz}$. For the FFTs taken both in Picoscope and directly from the time traces in Matlab a Blackman window is used. The difference between taking the FFT in Matlab and Picoscope appears to result from the fact that the absolute FFT of the time trace is taken in order to determine the PSD, and thus the negative values of the FFT are rejected. The absolute value of the FFT is then squared to obtain the PSD plot. As the negative part of the FFT has been ignored it is then necessary to multiply the squared quantity by $2/F_{\text{res}}$, where $F_{\text{res}}$ is the bin width, to conserve energy. This can be written in the following form:

$$\text{PSD} = \frac{1}{F_{\text{res}}} |\text{FFT}|^2,$$

whereas it would seem that the Picoscope software is using $\text{PSD} = \frac{1}{2F_{\text{res}}}|\text{FFT}|^2$. The inclusion of the $2/F_{\text{res}}$ prior to squaring the term to obtain the PSD produces a factor of 2 difference in the sensitivity measured in $\text{nT/Hz}$. When determining the mean sensitivity the $50 \text{ Hz}$ peak and its harmonics at $100 \text{ Hz}$, $150 \text{ Hz}$, $200 \text{ Hz}$, $250 \text{ Hz}$, $300 \text{ Hz}$, $350 \text{ Hz}$, $400 \text{ Hz}$, and $450 \text{ Hz}$ are treated as signals, given their known origin, and masked. Others peaks between $10 - 500 \text{ Hz}$ are not masked. The standard deviation of the mean of the sensitivity spectrum in a $10 - 500 \text{ Hz}$ frequency range is taken as the error.

It should be noted that for all our measurements the higher frequency ODMR resonance is used, as this is the resonance for which the microwave power has been optimised. The difference in ODMR contrast and linewidth between the two ODMR resonances that can be observed in Fig. $3a$ and Fig. $3b$ in the main text are a consequence of the amount of microwave power differing between the two frequencies, as is observed using an Agilent N9320B vector network analyser. Sensitivity measurements are taken using the same LIA and microwave settings as their corresponding ODMR spectra, with a $100 \text{ LIA output}$ scaling.

**APPENDIX G: BALANCED DETECTION**

![Figure 13](image-url)  
**FIG. 13.** Sensitivity measurements taken with and without the use of "red-red" balanced detection. Mean sensitivities of $(15 \pm 5) \text{ pT/Hz}$ and $(170 \pm 30) \text{ pT/Hz}$ are found with and without balanced detection respectively. No AC coupling is used for these measurements.

In this work a second reference sensor head containing a diamond is employed to provide fluorescence for balanced detection as opposed to picking off a portion of the laser beam, in other words "red-red" noise cancellation. As discussed in appendix B this is also a $1 \text{ mm}^3$ diamond cut from the same original sample. It is important for the two sensor heads to be as identical to one another as possible. The optics arrangement used for the signal and reference paths are very similar, though it is clear there is some difference in the excitation power and collection efficiency for each of the sensor heads. When on a magnetically sensitive resonance the rotation mount containing the waveplate is adjusted until the balanced output is set to zero, at which point the fluorescence signals from each sensor head are equal. Initially we had balanced the two fluorescence signals when off-resonance which not only leads to inefficient noise cancellation but also meant the amount of fluorescence coming from the signal sensor head when on-resonance was artificially reduced. Figure $13$ shows the effect of using the balanced output as opposed to the main signal output without any noise cancellation. "Red-red" noise cancellation is found to provide a factor of eleven improvement in sensitivity. Without common-mode noise cancellation the sensitivity is limited by laser noise and also other sources of noise common to each sensor head. Nonetheless, as the sensitivity measurements in Fig. $3b$ of the main text show laser noise remains a significant part of our overall noise floor. Further improvement in noise cancellation is likely possible via attempts to equalise the laser power being delivered to each sensor head, as increased laser excitation power in one sensor head will lead to dif-
fering levels of temperature fluctuation and thus noise for example. Additionally, noise associated with the optical fibers likely differs for each of the two sensor heads.

Gradiometry or differential magnetometry would allow magnetic noise to be cancelled, assuming it is common to each sensor head [67–70]. Effective cancellation of magnetic noise could enable us to get down to the magnetically insensitive noise floor of \((11 \pm 1) \text{ pT/}\sqrt{\text{Hz}}\). Gradiometry could be implemented using the current setup by supplying microwaves to the reference sensor head. The reference sensor head, at \(\approx 180^\circ\) to the signal sensor head, is presently aligned such that the bias field is also along a [100] orientation and the sensor heads show close to identical performance, necessary for the effective cancellation of magnetic noise. It would be convenient to use two separate microwave sources to address each sensor head, however, if a single microwave source could be employed alongside a microwave splitter it would also allow for the common microwave phase noise to be cancelled, though this does not appear to be a limiting source of noise at present.

APPENDIX H: POWER SATURATION

![Power Saturation Curve](image)

**FIG. 14.** Power saturation curves showing the fluorescence intensity at the photodiodes as a function of laser excitation power for both signal and reference sensor heads.

Figure 14 shows power saturation measurements for both the signal and reference sensor heads. It is clear we are far from saturating the NVC ensembles in either sensor head. Indeed, given the dynamic range of the photodiodes (a 10 V maximum output voltage) we would not be able to saturate the NVC ensemble before the photodiodes. The saturation that appears in the signal sensor head saturation data is likely due to the response of the photodiode. This can be seen from the fact that the reference sensor head data does not display the same saturation behaviour, even with the higher laser excitation power. The signal and reference sensor heads differ in fluorescence intensity in part due to the fact that these are the off-resonance fluorescence intensities and thus the photodiode signals are inbalanced. It is also apparent that the green-to-red photon conversion efficiencies differ between the two sensor heads (\(\approx 0.27\%\) for the reference as opposed to \(\approx 0.36\%\) for the signal sensor head) from power meter measurements of the red fluorescence taken when on a magnetically sensitive resonance. Accordingly, more laser power is required to obtain the same fluorescence intensity for the reference sensor head.

It is probable that the NVCs contained within the sensing volume directly illuminated by the focused laser beam are fully saturated at an excitation laser power of \(\approx 0.3\) W. Saturation is not observed from the power saturation measurements. This is likely because as the laser excitation power is increased more photons are scattered through the diamond and thus excite fluorescence from NVCs outside of the immediate sensing volume. This means the sensing volume has been increased greatly, perhaps to encompass the entire diamond sample, which could be negatively impacting performance depending upon the microwave and bias field homogeneity over the entire diamond sample. Increasing the laser power in an effort to saturate the NVC ensemble will exacerbate these homogeneity issues.

APPENDIX I: HYPERFINE EXCITATION SCHEME

Figure 15 shows the ODMR spectrum taken, with the bias field aligned along one of the [100] orientations, with and without hyperfine excitation. Hyperfine excitation is found to improve the contrast from 4% to 10%, a factor of 2.5 improvement. However, the linewidth is also broadened from 0.70 MHz to 0.73 MHz due to increased microwave power broadening. Further parameter optimisation may be possible. We use an external Mini-Circuits ZX05-U432H-S+ up-converter, and the output of the microwave source and the RSPro AFG21005 arbitrary function generator are sent into the local oscillator and intermediate frequency inputs of the up-converter respectively. The RF output is then sent to a 43 dB Mini-Circuits ZHL-16W-43-S+ microwave amplifier, followed by a Pasternack PE83CR005 2-4 GHz circulator, and thence onto the sensor head.

The three microwave tones can be observed using an Agilent N9320B vector network analyser. It is thus possible to vary the amplitude of the sine-wave and microwave power to identify combinations which yield three microwave tones of approximately equal intensity, an example of which can be seen in Fig. 16. This corresponds to a total microwave power of \(\approx 0.054\) W on the vector analyser for the central-most hyperfine feature, distributed across the three microwave tones each of which has
FIG. 15. a) and b) show the ODMR spectra with and without hyperfine excitation. c) and d) show the demodulated ODMR spectra with and without hyperfine excitation.

≈ 0.018 W of power, which is identified to be the optimum microwave power via the parameter optimisation process described in appendix D. For the non-hyperfine case a single microwave tone of ≈ 0.018 W of microwave power is used. Increasing the microwave power to ≈ 0.054 W for a single microwave tone does not yield the contrast improvement seen from hyperfine excitation but does lead to considerable linewidth power broadening. The ratio of the peaks observed in Fig. 15 is 1:1.7:2.3:1.7:1, being taken relative to the first of the five hyperfine excitation ODMR features. The contrast increase of 2.3 relative to the first peak when using hyperfine excitation as opposed to when comparing the contrast to single excitation suggests a discrepancy in the microwave intensity of a single tone between the two sets of measurements in Fig. 15. These results are in closer agreement to theoretical predictions than our previous work and have enabled a further improvement in contrast and thus sensitivity \[42\]. None-the-less, the linewidths of each of the five ODMR peaks still differ from around 0.66 MHz for the single tone outer peaks to 0.73 MHz for the central peak corresponding to three tone excitation. It is apparent that there remains a non insignificant difference in the microwave intensity of each tone. Further improvement in the hyperfine excitation scheme should be possible given additional optimisation of the power balance between the microwave source and function generator. Additionally, the balance of the tones is observed via the vector analyser and this may be misleading as it would not account for microwave power losses and other effects that may occur on the path to the diamond. Working through the large parameter space of microwave power and sine-wave amplitude combinations would be required to optimise the performance further.

FIG. 16. The three microwave tones used for hyperfine excitation as observed using a vector analyser. A BNC cable used to connect the SMA cable to the vector analyser is found to cause ≈ 8.5 dB in microwave losses. These losses are accounted for when determining the microwave intensity of each tone.

APPENDIX J: FREQUENCY RANGE

The upper limit of the sensitive frequency range is taken to be the 3 dB point of the LIA LPF, which is set to 500 Hz with a filter order of 48 dB/octave. The lower limit is selected to be 10 Hz due to the 1/f noise, which appears to be associated primarily with environmental magnetic noise, below this point. A 3 dB point of up to 2.8 kHz is employed for the backing and turbo-pump measurements, however, in order to ensure the filter response does not cut-off any of the magnetic signals from the machinery. The use of a larger 3 dB point necessitates the use of a higher modulation frequency of 10.003 kHz due to increases in the noise floor as large, only weakly suppressed signals may be seen at 3.003 kHz and associated frequencies for this larger frequency range. In prin-
ciple the maximum frequency range that can be obtained with this magnetometer would be limited by the modulation frequency, and ultimately the response of the NPCs, in terms of the repolarisation rate \( \frac{\delta f}{\gamma} \). At present we are limited by the frequency response of the LIA LPF. The sampling rate would not limit our ability to detect signals in this case given it is set to 20 kHz, and thus the Nyquist frequency is significantly higher than both our modulation frequency and the frequencies of the machinery signals of interest.

**APPENDIX K: DYNAMIC RANGE**

One of the main benefits of NVC magnetometers is their potential for high dynamic range \( \approx \pm \mu \text{[72]} \). The dynamic range of the NVC magnetometer (\( \delta B \)) is given by \( \delta B = \delta f / \gamma \), where \( \delta f \) is the linewidth of the NVC resonance. From this and using a linewidth of 0.73 MHz the dynamic range is determined to be \( \pm 13.1 \mu \text{[73]} \). This agrees with results obtained when applying a test-field along [100] using the Helmholtz coil. Figure 12 shows the voltage shift as a function of the applied magnetic test field, with the polarity of the Helmholtz coil being switched to apply fields along both the +1 and -1 directions of a [100] orientation (along and against the bias field). A slight disparity is observed in the slope between the two polarities suggesting the test-fields are not quite aligned along [100]. The test-field is increased in magnitude until the resonance frequencies ceased to lie on the central ODMR dispersion feature.

Improvements in linewidth and thus sensitivity are at the expense of a decrease in dynamic range. This is problematic for the backing pump measurements as if the device is brought closer than \( \approx 20 \text{ cm} \) the DC magnetic field from the pump’s steel components begins to negatively impact the ODMR spectra in terms of contrast and linewidth, as well as causing voltage shifts out of the linear region that render the magnetometer magnetically insensitive. This could be accounted for by adjusting the bias field alignment. More practically, however, feedback control has been implemented for NVC magnetometers, allowing the microwave frequency to be continuously adjusted to remain on-resonance \( \approx \pm 100 \text{ nT} \). This allows for dramatic improvements in dynamic range such that the magnetometers are principally limited by the microwave source frequency sweep range, the bias field magnitude and the NVC energy level anti-crossing point at \( \approx \pm 100 \text{ nT} \).

**APPENDIX L: ORIENTATION DEPENDENCE**

NPCs only measure the projection of external magnetic fields along their symmetry axis, as opposed to the total magnetic field. As a result the magnetometer responsivity is weaker for magnetic fields applied orthogonally to a given NVC symmetry axis. This means the ability of the magnetometer to detect magnetic signals depends not only on distance but also on the orientation of the sample relative to the diamond (and thus NVC ensemble). In our case the sensitive axis is not one of the (111) NVC symmetry axes, but instead a vector along a [100] crystallographic orientation that projects equally onto each of the NVC symmetry axes. Accordingly, we are most sensitive to fields applied along this orientation and as noted previously the NPCs will not experience the total field, but the projection of this total field along each of their symmetry axes and thus a field applied along [100] will always be reduced by the angle factor of 0.58 from the perspective of each NVC alignment. In contrast to the [111] bias field alignment case, however, there is no complete dead zone orthogonal to the sensitive axis, as the whole NVC population is being employed and there will always be some non-zero projection along one of the possible NVC symmetry axis alignments. However, the voltage response to the field is more complicated when the test-field is not applied along [100], as the projection differs for each of the four NVC alignments. If the projection of an applied magnetic field can be measured for each possible NVC symmetry axis alignment it is then possible to obtain vector information. Figure 17a shows the magnetometer response observed when a test field is applied along various directions. The stated angles are relative to the typical [100] orientation we used, which is taken to be \( 0^\circ \) and \( 180^\circ \) for the two polarities of the Helmholtz coil. The exact orientation of the diamond lattice relative to the applied field is unknown. Figure 17b shows the mean sensitivity as a function of angle, using calibration constants determined from the magnetometer response plots of figure 17a. This demonstrates the lack of dead zones in which the magnetometer is entirely insensitive. Even when the test field is applied orthogonal to the typical [100] direction a sensitivity of \( \langle 140 \pm 50 \rangle \text{ pT/}\sqrt{\text{Hz}} \), in a 10 - 500 Hz frequency range, is still observed.

In practical terms, this orientation dependence means that for example, with the turbo-pump directly in front of the sensor head it is possible to detect the 1 kHz signal at distances up to \( \approx 1.8 \text{ m} \) away, but when the turbo-pump is placed very roughly orthogonal, and below, the sensor head the 1 kHz signal can only be seen at up to \( \approx 50 \text{ cm} \) away. There could be some potential benefits to this orientational or directional dependence to magnetic signals as the sensor head would be less sensitive to interference from certain noise sources. Though you would have little control over the relative direction of magnetic fields within the environment and thus it would be more desirable to be able to measure the total magnetic field in general. For NVC ensemble magnetometers this is possible to achieve using a single diamond sample, if the bias field is aligned such that all eight possible ODMR resonances do not overlap. This would entail a reduction in contrast compared to a [100] orientation, but would enable you to measure the projection of the sample magnetic field along the four different NVC alignments and
from this it would be possible to determine the x, y, and z magnetic field components and from these the total magnetic field. Vector magnetometry of this kind has been demonstrated successfully \[31, 44, 74\]. It would be possible to measure the projection of the magnetic field along each NVC symmetry axis alignment with a [100] bias field, however, the applied field would need to be sufficiently large to separate out the resonances of each NVC alignment so that they are no longer completely overlapped.

**APPENDIX M: ELECTRIC SCOOTER MEASUREMENTS**

FIG. 18. Sensitivity measurement taken with and without the electric scooter being turned on. AC coupling is not used for these measurements. The sampling rate is set to 10 kHz.

Electric scooters have grown in popularity over recent years, being relatively environmentally friendly, low in cost, and increasingly accessible \[73\]. Using our NVC magnetometer it is possible to detect various signals from the spinning back wheel, that contains the motor, of a Voi electric scooter as can be seen in Fig. 18. In this case the scooter’s back wheel (and motor) is \( \approx 94 \) cm from the diamond located within the sensor head. Unlike the vacuum pump measurements, the scooter is not level with the sensor head and is instead placed on the ground.

These results, alongside the vacuum pump measurements, suggest the potential use of NVC magnetometers for the condition monitoring of vehicles and more generally for remotely monitoring the usage and condition of machinery, even through thick walls. Failure modes could be identified from changes to the magnetic signals that appear in the FFT when compared to a working condition, reference signal set. This form of fault detection can be automated and does not require a detailed understanding of the device being investigated \[74, 77\].

**APPENDIX N: LASER NOISE**

Due to limited space and the consequently small size of the laser head heat sink, it is necessary to cool the laser using active measures such as a fan. The fan is turned off when taking measurements and with the current laser power the laser is not in a thermally stable regime. This may be responsible for at least some of the noise at low, sub-10 Hz, frequencies, the elevated and changing temperature of the laser head causing the laser to oscillate...
between different modes producing large changes in laser output power. The use of a larger heat sink, or a lower noise active solution, would enable the laser to operate at higher laser powers (important for pulsed magnetometry) and in a more stable thermal regime. The fan, as can be seen in Fig. 19, causes significant noise especially at lower frequencies due to the vibration of the optics, the kicking up of dust that passes through the laser beam, the effect of temperature on components such as the PBS as well as the fan’s magnetic signal.

Another factor to consider is the use of optics such as the PBS and optical isolator. It appears that the polarisation of the laser output is unstable and the use of such polarisation maintaining optics may be causing large changes in the total amount of laser power being delivered to the diamonds and in the case of the PBS changing the ratio of power delivered between the signal and reference sensor heads respectively. The noise caused by the latter effect cannot be cancelled using the balanced detector. Laser performance issues in non-temperature controlled environments are likely to be problematic for the practical implementation of high-sensitivity NVC magnetometers.

**APPENDIX O: FUTURE IMPROVEMENTS AND POTENTIAL APPLICATIONS**

Gradiometry could be implemented by delivering microwaves to the reference sensor head. This should allow magnetic noise to be cancelled, assuming it is common to both sensor heads. This would be especially effective at reducing the impact of coloured mains noise, such as the 50 Hz peak, and potentially also the 1/f noise. Gradiometry has been employed in several other NVC magnetometers [67, 70] and the possibility of implementing gradiometry for our setup is expanded upon in appendix G.

The relatively low photon-collection efficiency, compared to non-fiber coupled devices, remains an issue [75, 78]. Directly coupling the fiber to the diamond [43], or placing the diamond within the fiber may allow for improvements in photon collection efficiency. This would also allow for reductions in the size of the sensor head, allowing it to be brought closer to objects of interest. Hollow-core fibers could be useful for this, though such fibers available commercially typically have relatively high losses [80, 83].

Ferrite flux concentrators have been employed in several NVC magnetometers to concentrate magnetic flux from samples into a diamond, yielding up to a factor of 254 improvement in sensitivity [46, 84]. However, they limit spatial resolution and it would be relatively difficult to implement ferrite flux concentrators with our current sensor head design. Dual-resonance magnetometry could also be employed to ensure the NVC magnetometer is less susceptible to noise, caused by temperature fluctuations, which is problematic for the target applications [31, 46, 50, 74, 85].

Pulsed schemes typically yield around an order of magnitude improvement in sensitivity over CW for a given excitation volume [7, 19, 49], while also enabling the implementation of spin bath driving and double quantum magnetometry techniques [86, 87]. However, high microwave and optical excitation homogeneity is critical for fully exploiting pulsed schemes, and it would likely be necessary to use a microwave resonator to efficiently drive all the NVCs with comparable dynamics, which would limit the bandwidth of our NVC magnetometer [88, 91]. A more uniform intensity could be obtained across the excitation volume using a tophat beam shaper to convert the Gaussian laser output to be super-Gaussian [92, 93]. Fully exploiting the benefits of pulsed magnetometry would also require the saturation of the NVC ensemble, and thus significantly higher laser power for the current diamond sample. Alternatively a smaller diamond, with a correspondingly smaller NVC ensemble, would be more readily saturated at lower laser powers. Using a smaller diamond sample would also help with obtaining high microwave and bias field homogeneity. However, a smaller NVC ensemble would lead to a lower photon detection rate, \( R \). Further discussion of the saturation behaviour of the NVCs appears in appendix H.

The magnetometer’s sensitivity and portable sensor head design make it useful for a wide range of applications. As an example, here the machinery measurements demonstrate the capacity of NVC magnetometers for use in remote sensing and potentially even condition monitoring applications. In principle the system would be capable of detecting machinery even through thick walls. Machinery such as engines, air conditioning units, and electric motors are widely used in domestic, commercial and industrial applications. Such machinery typically produces clear and characteristic magnetic signals over a
A wide range of frequencies [94, 95]. High-sensitivity magnetometers can be used to non-invasively detect and monitor these signals and NV centers are also capable of remaining operational in harsh environments [13, 76, 77, 94]. If monitored in working condition for a long period of time, then shifts in the frequencies of these characteristic peaks could be used by operators to identify damage. High magnetic sensitivities enable detection even with large separations between the sensor and target. Vector magnetometry could be used to obtain additional information and to remove the orientation dependence [31, 44, 74]. Remote condition monitoring is also discussed, alongside measurements taken using an electric scooter, in appendix M. With further improvements in sensitivity, the magnetometer could potentially be used for MCG, for which the portable sensor head is convenient as it can be brought into close contact with the chest. For MCG reducing 1/f noise would be crucial given the magnetic signals of the heart are to be found in the range 1 - 40 Hz [33, 47, 97–99]. Many sensor heads could be employed to allow for rapid mapping of the entire heart [100]. Magnetoecephalography (MEG) would be a possible application if femtotesla sensitivites could be obtained [101, 102]. Other applications include axion-like particle detection [4] and battery monitoring [103].

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