

High-speed magnetic-field imaging via N-*V* ensemble and laser raster scanning

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We present a technique based on an ensemble of nitrogen-vacancy (N-*V*) centers in diamond capable of imaging magnetic fields with high spatiotemporal resolution and sensitivity. A focused laser beam is raster scanned using an acousto-optic deflector and N-*V* center fluorescence is read out with a single photodetector, enabling near shot-noise-limited imaging. The method operates in what we term quasi-continuous-wave optically detected magnetic resonance (qCW-ODMR), a regime closely related to pulsed-ODMR schemes used to mitigate power broadening. In this qCW regime, N-*V* centers experience short optical pump pulses for spin polarization and readout while the microwave field continuously drives the spin transitions. We systematically characterize this regime and show that the spin response is governed by a tunable interplay between coherent evolution and relaxation, determined by the temporal spacing between pump laser pulses. Notably, the technique does not require precise microwave pulse control, thus simplifying experimental implementation. To demonstrate its capabilities, we image time-varying magnetic fields from a microwire with submillisecond temporal resolution. This approach enables flexible spatial sampling and, with our diamond, achieves nT/ $\sqrt{\text{Hz}}$ -level per-pixel sensitivity, making it a promising platform for imaging weak, dynamic magnetic fields in biological and other complex systems.

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I. INTRODUCTION

Magnetic imaging utilizing paramagnetic color centers in the solid state is an emerging platform with a broad range of applications, ranging from materials science to life sciences. Nitrogen-vacancy (N-*V*) centers in diamond are a particularly powerful system due to their long electron spin coherence time, operation under ambient conditions, and stability [1,2]. Ensembles of N-*V* centers in diamond with optimized defect concentration and isotopic purity offer exceptional sensitivity together with microscale spatial resolution and large detection bandwidths, tunable through spin-control sequences. Several recent advances have demonstrated their utility for both wide-field imaging and quantum-enhanced performance

[3,4]. Wide-field N-*V* imaging has been applied to the study of current flow and electronic transport in devices ranging from integrated circuits to two-dimensional (2D) materials [5–8], the visualization of magnetic textures, including vortices in superconductors [9,10], and for geological investigations [11,12]. In biological contexts, N-*V*-based wide-field methods have also been employed to image magnetotactic organisms and single cells with internalized nanoparticles [13,14]. Importantly, this wide-field modality also enables the detection of magnetic fields generated by electrical activity in neurons or muscle tissue [15–18].

Despite these successes, imaging biomagnetic processes remains a challenging task. The underlying magnetic signals can range from tens of picotesla to several nanotesla depending on source size, stand-off distance, and the degree of synchronous activity, and they often vary on millisecond timescales, demanding detection bandwidths in the kilohertz range or higher. Capturing these low-amplitude, fast-varying fields with spatial resolution imposes strict requirements on both sensitivity and recording bandwidth [19]. In N-*V*-based magnetic-field imaging, a challenge arises from the fact that the magnetic

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information is encoded as a small change in fluorescence intensity superimposed on a large optical background. Conventional complementary metal-oxide semiconductor and CCD cameras, commonly used for wide-field readout, further exacerbate this issue by imposing trade-offs between temporal resolution, digitization depth, and noise levels, ultimately limiting sensitivity by technical rather than physical constraints [20].

An alternative to camera-based wide-field magnetic imaging is to raster scan the excitation laser beam across the layer containing the ensemble of $N-V$ centers and collect the resulting fluorescence with a photodetector. This approach encodes the spatial information serially in time rather than in parallel on a camera chip. In this case, the achievable detection bandwidth is set by the steering hardware and, ultimately, by the spin dynamics of the $N-V$ centers. Various beam-steering methods can be employed, such as galvanometric mirrors [21] or electro-optic deflectors. In particular, acousto-optic deflectors (AODs) are emerging as a powerful solution, offering beam steering with sub- μ s temporal control. Well established in cold-atom experiments [22,23], AODs are now finding applications in a range of color-center-based techniques, including single-spin control [24], nanoscale NMR spectroscopy [25], and confocal-based imaging [26].

In this work, we implement a laser-scanning imaging scheme based on a two-axis AOD system. A focused excitation beam is raster scanned across the ensemble of $N-V$ centers embedded in the top 25 μ m layer of the diamond crystal, while the resulting fluorescence is recorded with a $p-i-n$ photodiode [Fig. 1(a)]. Among its advantages are, first, digitizing the detector output with a 16-bit data-acquisition system relaxes digitization constraints compared with typical camera-based readout [27], reducing quantization errors and allowing small fluorescence changes to be resolved on top of a large background. Second, the high bandwidth of the scanning device allows for high temporal resolution, with the pixel dwell time limited primarily by the optically induced spin-repolarization time of the $N-V$ centers. This enables fluorescence transients to be resolved with submicrosecond precision—well beyond the capabilities of conventional cameras. Third, the use of a reference photodetector allows for the implementation of common-mode rejection (CMR) in real time, significantly reducing the noise floor in the presence of technical laser noise and enabling operation close to the shot-noise limit. Together, these features provide flexibility to optimize the magnetic imaging setup for sensitivity, spatial resolution, field of view, and temporal resolution; parameters that may be tuned depending on the specific requirements of the magnetic imaging task.

Building on the excitation beam-scanning approach, we implement a hybrid magnetic-field imaging protocol as illustrated by the sequence shown in Fig. 1(b). The $N-V$ center electron spins are continuously driven by the

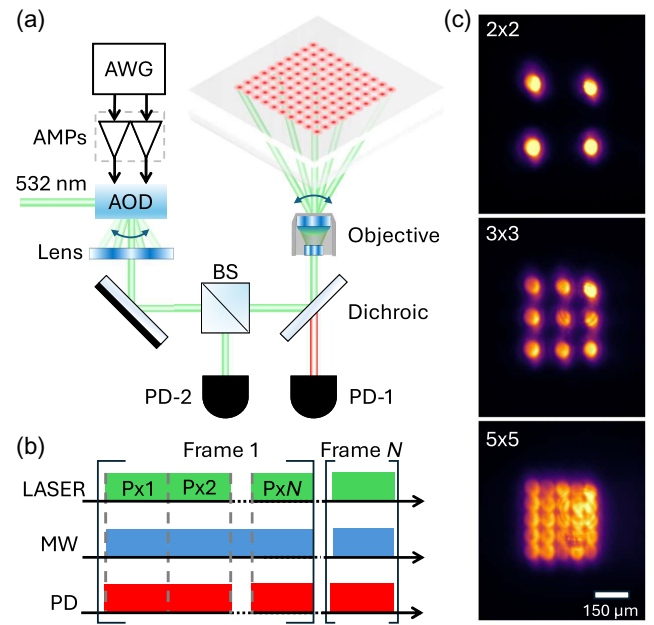


FIG. 1. (a) Schematic of the scanning-based $N-V$ magnetometry setup. The beam of a 532 nm laser is raster scanned across the layer of $N-V$ centers using a 2D AOD, with fluorescence detected by a $p-i-n$ photodetector. A second photodetector provides a reference for common-mode rejection and technical noise suppression. (b) qCW-ODMR diagram: laser scanning (green), continuous microwave excitation (blue), and photodetector readout (red) across successive pixels and frames. (c) Fluorescence images of the diamond captured with a camera from above for different scan patterns.

applied microwave (MW) field while being read out and repolarized with short pulses of the excitation laser. Since the excitation beam is scanned across the sample, each scan spot experiences the excitation as a brief pulse with a duration set by the pixel dwell time. We refer to this regime as quasi-continuous-wave ODMR (qCW-ODMR). Because the excitation is spatially serialized, increasing the number of pixels per frame increases the spacing between consecutive laser excitation pulses at a given location, yielding a modified electron spin evolution and thus impacting sensitivity. To quantify these effects, we vary the pulse spacing and characterize the sensor performance in terms of ODMR contrast, linewidth, and noise floor. Finally, to validate the capability of our technique, we image the time-varying magnetic field induced by a current pulse in a 20 μ m copper wire, resolving spatiotemporal fluctuations of the magnetic field in real time.

Our work establishes AOD-based scanning of the excitation laser beam in combination with photodetection of fluorescence as a viable alternative to camera-based $N-V$ imaging, enabling high-speed, high-sensitivity magnetic imaging.

II. METHODS

A. Optical setup and N-*V* center excitation

For N-*V* excitation we use a 532 nm continuous-wave laser delivering around 300 mW of power measured in front of a 100x/0.7 NA objective (Mitutoyo) with 12 mm working distance and focused to a spot diameter of approximately 10 μm in the diamond. The diamond sample is a $2 \times 2 \times 0.5 \text{ mm}^3$ single-crystal diamond with a (100) surface orientation and a 25 μm -thick ^{12}C -enriched layer containing approximately 5 ppm substitutional ^{14}N and about 1 ppm ^{14}N -*V* centers. The diamond is mounted on a planar microwave resonator fabricated on a printed circuit board, which is used to deliver microwave excitation.

Before entering the microscope objective, the laser passes through a two-axis AOD (Isomet) that scans the focused laser beam in the plane of the N-*V*-doped layer in the diamond. In our configuration, the AOD drive signal is centered at 100 MHz with a ± 25 MHz bandwidth and provided by an arbitrary waveform generator (AWG, Tektronix) with a sampling rate of 600 MSa s^{-1} . With the frequency pattern delivered by the AWG, we effectively control the scanning pattern [see Fig. 1(c) for examples], the pixel dwell time τ_d , the number of pixels N , the image size, and the frame rate (FPS). The effective spatial resolution may be adjusted through the laser spot size in the diamond and the thickness of the N-*V*-enriched layer.

Fluorescence from the N-*V* centers is collected through the same objective and spectrally filtered using a long-pass filter (FEL600, Thorlabs) to remove residual 532 nm pump light. Approximately 50 μW of N-*V* fluorescence is detected using a variable-gain linear photodetector (OE-300-SI, FEMTO). For the data presented in this article, the detector operated at a transimpedance gain of 10^5 V A^{-1} , yielding a detection bandwidth of 3.5 MHz.

A beam splitter positioned after the AOD diverts a small portion of the green excitation beam to a second photodetector identical to the one used for fluorescence detection. The outputs of the detectors are digitized independently using a Spectrum Instruments Data Acquisition (DAQ) card with a sampling rate of 20 MSa s^{-1} and 16-bit resolution. The DAQ and AWG are synchronized to ensure precise temporal alignment between the scan and the detected signal, allowing us to implement a CMR scheme in software for the suppression of correlated technical laser noise. Microwave excitation is provided via a signal generator (SG394, Stanford Research Instruments) and an amplifier (ZHL-16W-43-S+, Mini-Circuits; 16 W output), driving the resonator beneath the diamond for N-*V* center electron spin manipulation. A pair of neodymium permanent magnets is positioned across the diamond and used to apply a static magnetic field with a strength $\sim 3 \text{ mT}$ aligned along a [110] crystallographic direction. This field configuration produces two pairs of degenerate N-*V* spin resonances and ensures consistent spin projection

across the ensemble, enhancing both readout contrast and sensitivity to magnetic fields compared with alignment along [111].

B. Scanning and data acquisition

Scanning of the optical excitation beam with the AOD follows a serpentine (bidirectional) raster pattern, in which the beam moves across each row in one direction and then reverses direction for the subsequent row. With the total number of pixels per frame N and the pixel dwell time τ_d , the frame rate (FPS) is simply given by the relation $\text{FPS} = (N\tau_d)^{-1}$. We tested values of τ_d as low as 0.4 μs , limited by the beam diameter in the AOD crystal and the resulting rise time. For images with $N = 11 \times 11$ pixels, this results in frame rates of up to 20 kHz.

We calibrated and dynamically adjusted the AOD drive amplitude for each pixel to compensate for spatial variations in laser intensity and N-*V* density. This procedure ensures a consistent level of detected fluorescence across the entire image.

C. Magnetic-field imaging

To demonstrate the capability of imaging spatiotemporal magnetic fields, we positioned a 20 μm -diameter copper wire directly on the diamond surface and applied a signal generated with a digital-to-analog converter (National Instruments) to induce a spatially and temporally varying magnetic field.

The generated square signal had a total duration of 50 ms, an amplitude of 0.01 V, and inverted polarity halfway through the pulse. The electrical load was measured to be 5 Ω , corresponding to a drive current of approximately 2 mA. The pulses were synchronized with the magnetic-field imaging using a digital marker output from the AWG. The magnetic field induced by the current in the wire was mapped in real time using our scanning N-*V* magnetometry technique. For this experiment, a dwell time of $\tau_d = 1.2 \mu\text{s}$ was used with a 21×21 pixel grid, resulting in a frame rate of 2 kHz. The scanned region covered $\sim 170 \mu\text{m} \times 170 \mu\text{m}$, with a Gaussian beam spot size of 10 μm and a center-to-center pixel spacing of 8 μm , yielding an effective overlap of approximately 15% between adjacent pixels. This degree of overlap provided sub-beam sampling and was consistent with the Nyquist criterion for raster-scanned imaging, preventing undersampling and reconstruction artifacts [28].

We recorded 0.1-s-long time traces for each pixel and averaged them to evaluate noise scaling. The time traces were additionally filtered using narrow-band notch filters to suppress correlated magnetic and electrical pickup at discrete frequencies (e.g., the mains frequency and harmonics).

The optimal microwave frequency for sensing was selected by computing the spatial average of the ODMR

spectra across all pixels and identifying the frequency with the steepest slope. This frequency was then used for subsequent sensing measurements. To suppress pixel-to-pixel amplitude variations arising from spatial differences in optical collection efficiency, N-V density, and local microwave detuning, each time trace was normalized to the response generated by a weak externally applied sinusoidal magnetic field at 727 Hz. This calibration field was produced by a pair of coils positioned sufficiently far from the sensing region so that the resulting magnetic field could be considered homogeneous across the entire scanned area. The procedure equalized the relative signal scaling between pixels but did not alter the intrinsic magnetic sensitivity, which remained limited by the local noise level at each pixel.

III. RESULTS

A. qCW-ODMR

Our magnetic-field imaging protocol combines continuous microwave excitation with spatially and temporally localized optical excitation of N-V centers. The temporal spacing between successive optical excitation pulses is set by the scan time per frame, while the pulse duration is fixed by the pixel dwell time. This scheme is related to

pulsed-ODMR approaches such as in Dréau *et al.* [29], where interleaved microwave and optical readout pulses suppress power broadening and recover the inhomogeneous linewidth. In contrast, our microwaves are left on continuously, and the optical pulses arise naturally from the beam-scanning dwell time rather than explicit pulse gating, producing a qCW regime in which coherent evolution and relaxation occur between successive optical resets. Under our operating conditions the optical pumping rate is high compared with the Rabi frequency ($\Gamma_p > \Omega_R$), such that each optical pulse effectively reinitializes the spin polarization even with the microwave drive continuously applied. To characterize the protocol, we extract the ODMR spectrum at one pixel and determine the magnetic-field sensitivity from the ODMR contrast and linewidth as a function of scan time. For fixed pixel dwell time τ_d , the pulse-spacing time t_{space} is set by the number of pixels per frame; increasing image size or spatial resolution therefore increases t_{space} and modifies the ODMR readout. The measured ODMR contrast and linewidth as a function of pulse spacing are shown in Figs. 2(a) and 2(b), respectively.

We tested $\Omega_R/2\pi$ values of 70 kHz and 140 kHz, respectively, as obtained from Rabi-oscillation measurements, while the optical excitation rate is $\Gamma_p \approx 1$ MHz under our illumination conditions. With zero pulse spacing,

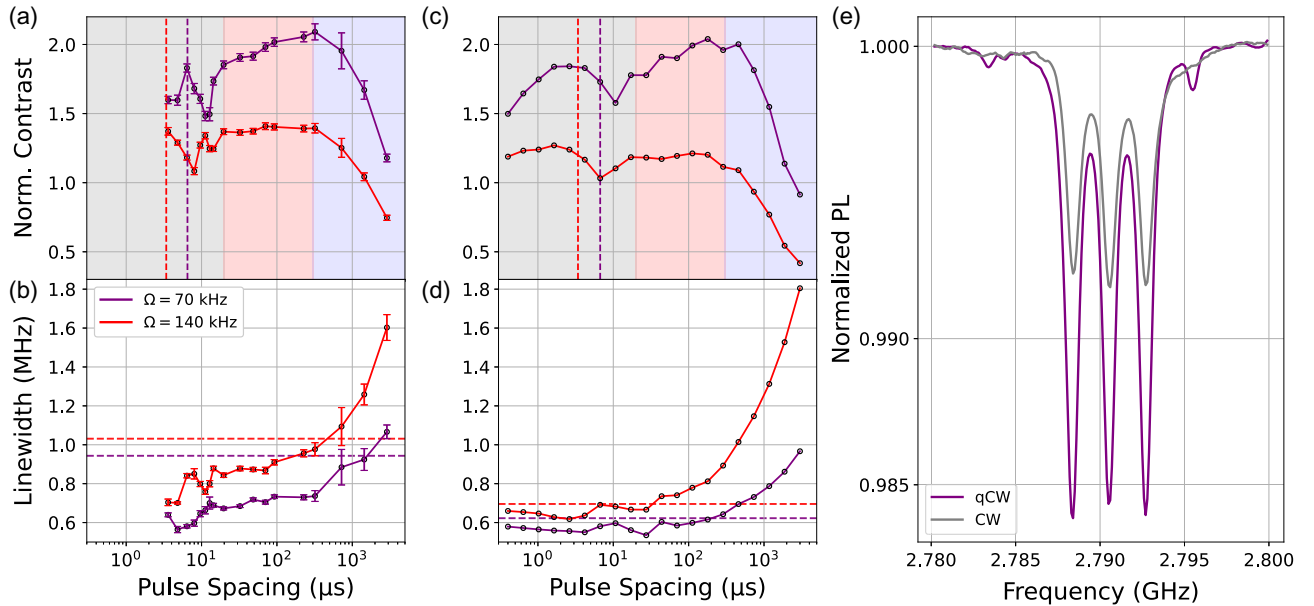


FIG. 2. Quasi-continuous-wave (qCW) ODMR characterization of a single pixel with the magnetic field aligned along the [110] crystal direction. (a) Normalized contrast and (b) linewidth as a function of laser pulse spacing for two Rabi frequencies Ω_R . Pulse spacing defines the time between successive 0.4 μs laser pulses, while the microwave field is applied continuously. In (a), the contrast is normalized to the CW-ODMR contrast at the corresponding Ω_R . Vertical dashed lines indicate the expected π -pulse condition. Shaded regions represent the approximate regimes of coherent Rabi oscillations (gray), dephasing-dominated evolution (red), and relaxation-limited decay (T_1 regime, blue). In (b), dashed horizontal lines indicate the corresponding CW linewidths for each Rabi frequency. (c) Simulated contrast and (d) simulated linewidth obtained from the five-level model under the same driving conditions. (e) ODMR spectra of the $m_s = 0$ to -1 transition acquired under a Rabi drive of $\Omega_R/2\pi = 70$ kHz for a single pixel. The CW (gray) and qCW (purple) spectra are shown; the qCW-ODMR is measured with a pulse spacing of 100 μs , revealing enhanced contrast compared with CW.

both linewidth and contrast are determined by the steady state conditions in the continuous wave (CW) regime. In Fig. 2(a), for a fixed dwell time of 0.4 μs and with increasing pulse spacing, we observe an overall increase in contrast compared with the CW regime. A local maximum occurs for a pulse spacing corresponding to a nominal π -pulse of the spin Rabi frequency Ω_R .

However, the global maximum contrast does not occur at this π -point, but instead appears at a significantly longer pulse-spacing time around 100 μs in our case. This is due to inhomogeneous broadening of the N- V spin transition frequency within the ensemble, which reduces the efficiency of coherent population transfer and shifts the time of maximum readout contrast. This interpretation is supported by numerical simulations (described below and in Appendix A), which reproduce the delayed contrast maximum and show that ensemble frequency broadening modifies the effective rotation rate and damps the oscillation envelope.

Figure 2(b) shows that, as a function of optical pulse spacing, the linewidth (full width at half maximum) is initially narrower than in the CW limit and then broadens with increasing pulse spacing. This observation reflects a transition from coherent to relaxation-dominated dynamics.

We use a five-level model [30,31] to simulate the evolution and readout of the spin states. The dynamics of a single N- V center are described by the density matrix ρ and a Lindblad master equation:

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \mathcal{L}_{\text{diss}}[\rho], \quad (1)$$

where H includes both the energies of the relevant states and the coherent microwave driving of the ground-state spin transition, $\hbar$ is the reduced Planck constant, and $\mathcal{L}_{\text{diss}}$ describes all incoherent relaxation and dephasing processes. The Hamiltonian is given by:

$$H = \hbar \sum_{i=1}^5 \omega_i |i\rangle \langle i| + \hbar \Omega_R \cos(\omega_{\text{MW}} t) (|1\rangle \langle 2| + |2\rangle \langle 1|), \quad (2)$$

where ω_i is the angular frequency of state $|i\rangle$, $|1\rangle$ and $|2\rangle$ denote the ground-state spin sublevels $m_s = 0$ and $m_s = -1$, respectively, Ω_R is the Rabi frequency, and ω_{MW} is the applied microwave angular frequency. The excited triplet and singlet states are not coherently driven. Dissipative dynamics are incorporated through a Liouvillian superoperator:

$$\mathcal{L}_{\text{diss}}[\rho] = \sum_k \left(L_k \rho L_k^\dagger - \frac{1}{2} \{L_k^\dagger L_k, \rho\} \right), \quad (3)$$

where the jump operators L_k represent optical excitation, radiative decay, spin-selective intersystem crossing, singlet relaxation, and ground-state decoherence. The optical

pumping rate for the simulation was chosen to be $\Gamma_p = 1$ MHz motivated by the experimentally observed spin-polarization timescale in the order of 1 μs . The ground-state pure dephasing rate is $\gamma_2^* = 0.01$ MHz, corresponding to $T_2 \approx 32$ μs . This value is consistent with nitrogen-limited coherence for ~ 5 ppm substitutional nitrogen according to the T_2 -scaling reported in Ref. [3], and representative of high-purity ^{12}C -enriched chemical vapor deposition diamond [32]. To reproduce the evolution of spin contrast and linewidth, we need to account for ensemble spin-inhomogeneity. We do this by introducing a Gaussian distribution of detunings with a standard deviation $\sigma_\Delta = 0.17$ MHz, obtained from the experimentally observed minimum ODMR linewidth of approximately 400 kHz (FWHM) via $\sigma_\Delta = \text{FWHM}/(2\sqrt{2 \ln 2})$. Each spin in the ensemble evolves independently according to the master equation under its corresponding detuning, and the fluorescence signal is obtained by averaging over the ensemble. The results of the simulation for qCW-ODMR contrast and linewidth are shown in Figs. 2(c) and 2(d). The model reproduces several key experimental features, including the coherent evolution of the contrast, the delayed maximum arising from inhomogeneous broadening, and the linewidth broadening induced by dephasing and relaxation processes. However, the simulated CW linewidth remains smaller than observed experimentally. We attribute this discrepancy to the measurement geometry: in the experiment the magnetic field is aligned along the $[110]$ direction, resulting in partial spectral overlap of ODMR resonances from two crystallographic N- V orientations. This can introduce variations in the effective Rabi coupling and imperfect overlap of the ODMR dips, thereby increasing the apparent CW linewidth. In addition, the simulation assumes a spatially uniform microwave and optical drive, whereas experimentally the Gaussian intensity profile of the excitation beam and spatial inhomogeneity of the microwave field across the illuminated area can lead to a distribution of effective Rabi frequencies, further contributing to linewidth broadening. These results indicate that, compared with the CW regime, the observed contrast enhancement and linewidth reduction originate from coherent spin dynamics enabled by the qCW protocol. At longer pulse spacings, the contrast decreases as longitudinal spin relaxation reduces the spin polarization before the next optical readout, indicating the onset of a T_1 relaxation-limited regime. Figure 2(e) compares the measured ODMR spectrum of a single pixel acquired under CW and qCW conditions with a Rabi frequency of $\Omega_R/2\pi = 70$ kHz. The qCW spectrum, taken at a pulse spacing of 100 μs , exhibits enhanced contrast consistent with the dynamics described above.

To assess the noise performance of the detection scheme, we first compare the measured noise floor, in the frequency range above 100 Hz, with the expected shot-noise limit [Fig. 3(a)]. For a laser pulse duration of 0.4 μs

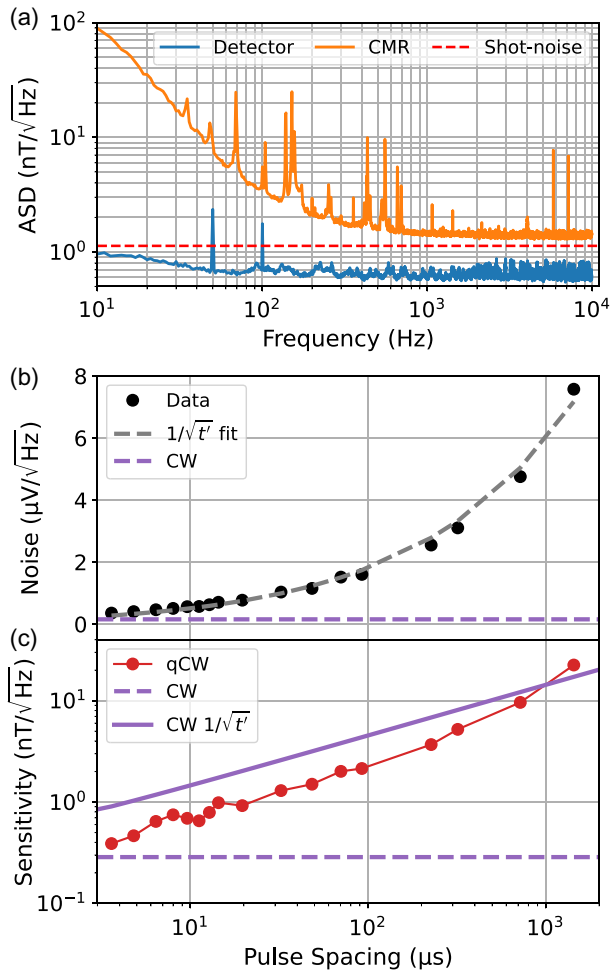


FIG. 3. (a) Amplitude spectral density (ASD) of the magnetic noise floor. The orange curve shows the ASD measured with the laser on after common-mode rejection (CMR), the blue curve shows the combined electronic noise of the two detectors, and the dashed red line marks the estimated shot-noise limit. (b) Noise floor levels (in $\mu\text{V}/\sqrt{\text{Hz}}$) for a single pixel as a function of pulse spacing, with total measurement time fixed at 1 s. As pulse spacing increases, fewer photons are collected, leading to a noise scaling consistent with $1/\sqrt{t'}$. The dashed line shows the CW noise floor. (c) Sensitivity versus pulse spacing. The dashed purple line indicates the experimentally measured CW sensitivity baseline. The solid purple line is a calculated CW reference that accounts only for the reduced photon-collection duty cycle at each pulse spacing (constant contrast and linewidth). The red curve shows the measured sensitivity in the qCW regime.

and a scan pattern corresponding to 121 pixels, we estimate a shot-noise-limited magnetic noise floor of $1.13 \text{ nT}/\sqrt{\text{Hz}}$. The measured electronic noise of the balanced detection system is $0.63 \pm 0.05 \text{ nT}/\sqrt{\text{Hz}}$, which corresponds to the combined noise contribution of the two detectors used in the differential readout (CMR). Combining this detector noise with the estimated shot noise, we calculate a total noise floor per pixel of $1.29 \pm 0.02 \text{ nT}/\sqrt{\text{Hz}}$. The experimentally measured noise floor under laser illumination is

$1.4 \pm 0.5 \text{ nT}/\sqrt{\text{Hz}}$, which is within 10% of this prediction, indicating operation close to the shot-noise-limited regime.

We next quantify the magnetic sensing performance over a variable number of pixels by extracting noise floor levels from 1 s time traces as a function of the pulse-spacing time t_{space} [Fig. 3(b)]. For a total acquisition time T , the effective fluorescence integration time is $t' = DT$, where the duty cycle is $D = \tau_d/(\tau_d + t_{\text{space}})$. The observed $1/\sqrt{t'}$ scaling reflects the reduction in collected photons at longer spacings. The corresponding sensitivity trends are summarized in Fig. 3(c). The dashed purple line at $300 \text{ pT}/\sqrt{\text{Hz}}$ marks the experimentally measured CW sensitivity of a single pixel. The solid purple curve is a calculated reference obtained by rescaling this CW value by the effective integration time t' , which isolates the sensitivity variation expected solely from the reduced photon-collection duty cycle. For pulse spacings shorter than 1 ms, the measured qCW sensitivity degrades more slowly than the CW reference, indicating an enhanced spin response under continuous MW drive that outweighs the photon-loss penalty. At longer spacings, the qCW sensitivity degrades more rapidly due to dephasing and reduced spin polarization between pulses.

B. Imaging of magnetic fields from a microwire

Having established the behavior and performance of the qCW-ODMR protocol at the single-pixel level, we now demonstrate its applicability to imaging by mapping the spatiotemporal magnetic field generated by a current-carrying $20 \mu\text{m}$ copper wire. Using the wire-stimulation setup described above, we recorded time-resolved maps of the magnetic-field projection along the effective sensing axis ($B_{[110]}$) during the application of square pulses with a polarity reversal, as indicated by the black dashed line in Fig. 4(a). The measurements were performed using our AOD-based scanning scheme with 21×21 pixels, giving a mean per-pixel sensitivity of $\sim 10 \text{ nT}/\sqrt{\text{Hz}}$ in the 100 to 1000 Hz band.

Figure 4(a) shows the magnetic time traces from all 441 pixels averaged over 50 min. Individual pixels exhibit clear magnetic-field responses, whereas the spatial average (orange) remains comparatively small—a direct consequence of the strongly varying field produced by the wire, underscoring the necessity of spatially resolved detection. The fluorescence image in Fig. 4(b), acquired from above the diamond with a camera, shows the relative position of the wire across the $\sim 170 \times 170 \mu\text{m}^2$ scanned area (orange).

Magnetic-field maps at two representative times in the current cycle are shown in Fig. 4(c). The maps display the expected dipolar structure and the polarity reversal between the positive and negative phases of the pulse. Two representative pixels, A and B, located on opposite sides of the wire, are highlighted. Their time traces [Fig. 4(d)]

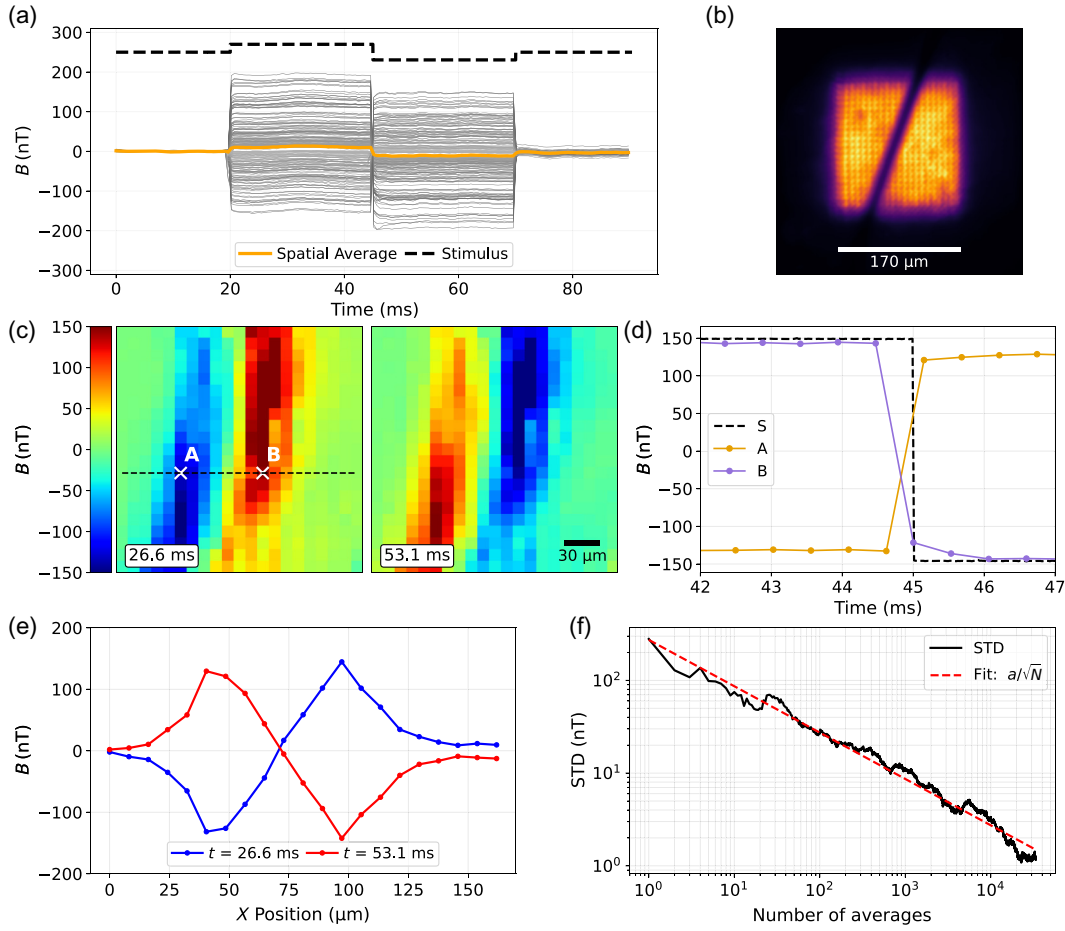


FIG. 4. Magnetic imaging of a current-carrying microwire. (a) Time traces from all 441 pixels in the 21×21 scan (gray). The orange curve represents the spatial average of all traces, and the black dashed curve shows the recorded biphasic current stimulus. (b) Microscope image showing the microwire relative to the N- V sensing region. The oblique dark line indicates the wire position; scale bar: $170 \mu\text{m}$. (c) Magnetic-field maps at two selected times (26.6 ms and 53.1 ms), corresponding to the positive and negative phases of the applied stimulus. Pixels A and B (white X marks) lie on a horizontal cut (dashed line) used for subsequent analysis. (d) Time traces of pixels A (gold) and B (purple), overlaid with the applied stimulus (black). The two traces show opposite magnetic polarity due to their positions on opposite sides of the wire. (e) Horizontal line profiles across the sensing plane at the same two timestamps as in (c), revealing the characteristic dipolelike magnetic field generated by the microwire. (f) Noise performance for a representative single pixel. The standard deviation is calculated over the first 20 ms of the reconstructed magnetic-field time trace and follows the expected $1/\sqrt{N}$ scaling with the number of averages N .

exhibit opposite magnetic polarity, and both faithfully follow the rapid transitions of the 10 kHz sampled stimulus, demonstrating preserved temporal response during abrupt reversal of the polarity in the applied signal.

To quantify the spatial field structure, horizontal linecuts extracted at the two times indicated in Fig. 4(c) are shown in Fig. 4(e). The profiles exhibit sharp extrema at the wire location, consistent with the steep gradient predicted by the law of Biot-Savart for a thin conductor. The narrowness of these features confirms that the system's spatial resolution—set by the $10 \mu\text{m}$ optical spot and $8 \mu\text{m}$ pixel spacing—is sufficient to clearly resolve the phase in the induced magnetic-field distribution.

Finally, Fig. 4(f) shows the noise scaling for a representative single pixel. For each number of averages N ,

the standard deviation is calculated over the first 20 ms of the reconstructed magnetic-field time trace, before the transient magnetic signal appears. The observed $1/\sqrt{N}$ scaling indicates stable averaging behavior and the absence of long-term technical drifts over the measurement time.

IV. DISCUSSION

We have demonstrated a scanning N- V magnetometry technique based on acousto-optic beam deflection and qCW-ODMR, enabling high-speed magnetic imaging with nT-level sensitivity and operation close to the shot-noise limit. Software-based common-mode rejection suppresses laser-intensity noise, improving measurement stability.

The qCW protocol combines continuous microwave excitation with spatially localized optical readout and repolarization. This approach removes the need for precise microwave timing control and avoids the use of gated microwave pulses or fast arbitrary waveform generators. Instead, the interpulse spacing—set directly by the scan configuration—governs the spin dynamics. As shown experimentally and through numerical modeling, the system transitions from coherent microwave-driven evolution to a relaxation-dominated regime as the pulse spacing increases.

Because the number of scan points determines the interpulse spacing, the imaging approach introduces an inherent trade-off between spatial resolution, image size, and sensitivity. Increasing the pixel number reduces the frame rate and increases the effective pulse spacing, which modifies the ODMR contrast and linewidth (Fig. 2) and therefore the sensitivity. Importantly, this trade-off is fundamentally set by the detected photon counts and N- V spin physics, rather than by any additional instrumental limitation specific to the scanning approach. Additional spatial inhomogeneities arise from variations in strain, microwave amplitude, optical intensity, and detuning, since all N- V s are driven by a single global microwave frequency. We mitigate these effects by choosing the microwave drive frequency based on spatially averaged ODMR spectra and by normalizing each pixel to a homogeneous calibration field generated by external coils.

As a functional demonstration of the system's capabilities, we imaged the magnetic field induced from the current in a microwire. The measured spatiotemporal maps reproduced the expected polarity and temporal evolution of the field, while the linecuts revealed sharp spatial features consistent with the predicted gradient near the wire. The pixel-level traces followed the rapid current reversals, confirming preserved temporal response, and the averaging analysis showed stable noise reduction. Together, these results validate the practical imaging performance of the platform.

This capability is directly relevant to biomagnetic sensing, where magnetic fields arise from electrical currents in excitable tissue. While N- V magnetometry has enabled proof-of-principle measurements of biomagnetic processes in controlled preparations, current N- V sensitivities are not sufficient yet for single-neuron, single-shot imaging in mammalian tissue, where expected magnetic-field amplitudes are in the picotesla range at typical stand-off distances. However, the sensitivity and bandwidth demonstrated here are compatible, in principle, with imaging signals from compound activity in muscle or nerve bundles in the hundreds of picotesla to nanotesla range, particularly in configurations where response timing is controlled and repeatable.

To benchmark our technique, we compare its sensitivity to ideally shot-noise-limited state-of-the-art scientific

camera detectors. The table included in Fig. 5 summarizes the relevant camera performance metrics, including the per-pixel CW-ODMR sensitivity η_{px} and the effective macropixel sensitivity η_{eff} obtained by averaging camera pixels over an AOD sampling area. The table also includes the estimated saturation powers per pixel $P_{\text{px}}^{\text{sat}}$ and over the full field of view $P_{\text{FOV}}^{\text{sat}}$. The saturation powers are evaluated at the peak quantum efficiency of each sensor, and the sensitivity estimates assume a CW-ODMR regime with contrast of 2.5% and a linewidth of 700 kHz. For the AOD system, the comparison is performed using the experimentally characterized operating point of Fig. 3, namely a scan configuration of 11×11 pixels with a pixel dwell time of 0.4 μs .

The plot in Fig. 5 reports η_{eff} as a function of full-frame readout rate for the camera set, together with the measured AOD sensitivity and the corresponding shot-noise-limited estimate. The detailed assumptions and calculations underlying this comparison are provided in Appendix B. Under the upper-bound assumptions above, the most sensitive camera in our set is the heliCam C4, owing primarily to its large full-well capacity and high full-frame rate: we estimate $\eta_{\text{px}} \approx 20 \text{ nT}/\sqrt{\text{Hz}}$ on a single pixel and $\eta_{\text{eff}} \approx 0.7 \text{ nT}/\sqrt{\text{Hz}}$ when spatially averaged to an AOD-sized macropixel.

However, achieving this shot-noise-limited bound in camera-based N- V imaging is not trivial. It requires delivering sufficient fluorescence to simultaneously operate all pixels at full well with submillisecond exposure times across the entire field of view.

In practice, the available fluorescence power is often limited by collection efficiency and permissible laser power, and increasing photon flux can modify the ODMR slope through power broadening and contrast changes. In addition, technical laser-intensity noise must also be suppressed below shot noise over the measurement bandwidth. Digitization noise and camera readout noise are neglected in this comparison; when operating away from the full-well regime, these noise sources can dominate over shot noise and further degrade the achievable sensitivity. A further practical distinction is dynamic-range tunability: in a photodiode readout, the effective transimpedance gain can be adjusted to keep the detector operating near its saturation-limited optimum over a wide range of fluorescence levels, whereas a camera pixel's full well and digitization range are generally fixed. As a result, changes in experimental conditions such as the diamond sample, optical alignment, or field of view often shift the detected fluorescence level and move the camera operation away from full-well-limited regime without an equivalent mechanism for reoptimization.

Looking ahead, several improvements could further enhance the performance of the platform. Sensitivity may be increased by implementing lock-in detection schemes based on modulation of the laser and the microwave drive,

Camera	$\eta_{px}(\text{nT}/\sqrt{\text{Hz}})$	$\eta_{\text{eff}}(\text{nT}/\sqrt{\text{Hz}})$	P_{px}^{sat} (pW)	$P_{\text{FOV}}^{\text{sat}}$ (μW)	$n_{px,eq}$
1.ORCA Fusion BT	865.5	4.2	0.4	2.3	41692
2.ORCA Fire	659.4	2.3	0.8	8.6	82427
3.ORCA Quest 2	1091.1	4.0	0.3	2.9	74120
4.pco.edge 26 CLHS	1291.0	2.8	0.3	8.0	205887
5.Evolve 128 EMCCD	97.1	8.6	36.0	0.6	129
6.CP70-1-M/C-1000	236.6	2.3	9.9	13.0	10294
7.Phantom S641	216.5	1.2	11.2	46.0	32170
8.Cyclone-1HS-3500	119.2	1.3	71.7	78.9	8646
9.heliCam C4	20.0	0.4	1018.7	282.7	2180
10.Phantom S711	70.4	0.8	186.9	191.4	8042

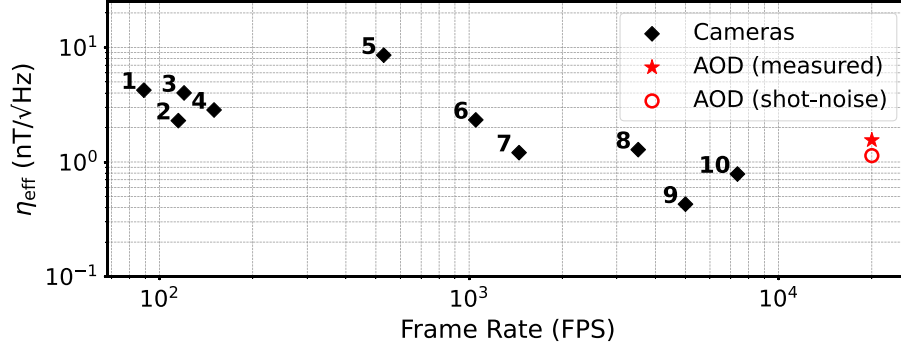


FIG. 5. Shot-noise-limited upper-bound sensitivity estimates for representative camera detectors and comparison with the AOD scanning approach. Top: Table summarizing the estimated per-pixel magnetic sensitivity η_{px} for each camera, assuming shot-noise-limited operation at the maximum full-frame rate and full-well capacity. To enable a direct comparison with the AOD system at matched spatial resolution, the effective macropixel sensitivity η_{eff} is obtained by averaging the camera pixels contained within one AOD pixel area ($n_{px,eq}$). The optical power required to reach full well is reported both per pixel (P_{px}^{sat}) and for the full field of view ($P_{\text{FOV}}^{\text{sat}}$), calculated using the manufacturer-specified peak quantum efficiency. Bottom: η_{eff} versus frame rate for the cameras listed above. The red star indicates the experimentally measured sensitivity of our AOD-based scanning system under the operating conditions described in Sec. III, while the open circle represents the corresponding shot-noise-limited estimate.

which would suppress low-frequency noise and improve long-term stability. Double-quantum readout, enabled by a dual-frequency microwave drive, would offer an additional gain in magnetic sensitivity and reduced common-mode noise [33]. Further gains in sensitivity could be achieved by improving optical collection efficiency, optimizing beam shaping, or adopting adaptive scan strategies that allocate longer dwell times to regions of interest. Finally, extending the approach to multibeam scanning could increase the effective measurement bandwidth by enabling parallel interrogation of multiple spatial locations. Together, these developments would push the technique toward higher sensitivity, larger fields of view, and higher frame rates.

V. CONCLUSION

Our work introduces a scanning N-V magnetometry platform that combines fast AOD beam steering, high-speed photodetection, and a qCW-ODMR protocol, enabling near-shot-noise-limited magnetic imaging

at frame rates above 10 kHz with nT-level per-pixel sensitivity. By scanning a focused laser beam across an ensemble of N-V centers under continuous microwave excitation, each pixel experiences a brief, localized optical reset. This configuration enables access to a tunable spin regime in which the contrast and sensitivity are modulated by the pulse spacing between successive excitations.

We show that the qCW regime enables flexible optimization of sensitivity and bandwidth, and supports frame rates exceeding 10 kHz across a significant number of pixels. The microwire measurement provides a proof-of-principle demonstration of the platform, showing that the sensor preserves both spatial precision and kHz-band temporal response under realistic experimental conditions. In the specific operating regime demonstrated here, using a 21×21 pixel scan, the system achieves a mean per-pixel sensitivity of $10 \text{ nT}/\sqrt{\text{Hz}}$ in the 100–1000 Hz band.

Overall, our platform provides a versatile and flexible framework for high-speed magnetic imaging in environments where weak, time-varying signals must be captured with both spatial and temporal precision.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: SIMULATION OF qCW-ODMR USING A FIVE-LEVEL MODEL

To simulate spin dynamics in the qCW-ODMR regime, we implemented a five-level model [30,31] including two ground spin states, two corresponding excited states, and an intermediate singlet shelving state. The model includes optical excitation, radiative decay, intersystem crossing, and ground-state coherence.

Microwaves are applied continuously, while the optical excitation is pulsed periodically with a variable interpulse spacing. Each simulation run integrates the system dynamics across a sequence of laser pulses. After approximately 10 pulses, the system reaches a steady-state cycle, and we compute the fluorescence signal by integrating the excited-state populations during subsequent pulses. In our model, fluorescence is modeled as

$$P_L = \alpha \rho_{33} + \beta \rho_{44}, \quad (\text{A1})$$

where ρ_{33} and ρ_{44} are the populations of the excited triplet states, and α , β are weighting factors accounting for the respective emission probabilities. By scanning the microwave detuning Δ , we construct simulated ODMR spectra and extract contrast and linewidth for comparison with experimental data. To account for ensemble inhomogeneous broadening, we average the simulated response over a Gaussian distribution of detunings, with $\sigma_\Delta = 0.17$ MHz. Each ensemble member therefore evolves with a slightly different resonance frequency, and the resulting ODMR response is obtained by averaging the fluorescence signal over this detuning distribution. Following the Lindblad master equation described in Sec. III, the equations

governing the populations and coherences are

$$\begin{aligned} \dot{\rho}_{11} = & -\Gamma_p \rho_{11} + k_{31} \rho_{33} + k_{41} \rho_{44} \\ & + k_{51} \rho_{55} - \frac{k_{21}}{2} (\rho_{11} - \rho_{22}) - \frac{i}{2} \Omega_R (\rho_{12} - \rho_{21}), \end{aligned} \quad (\text{A2})$$

$$\begin{aligned} \dot{\rho}_{22} = & -\Gamma_p \rho_{22} + k_{32} \rho_{33} + k_{42} \rho_{44} \\ & + k_{52} \rho_{55} - \frac{k_{21}}{2} (\rho_{22} - \rho_{11}) + \frac{i}{2} \Omega_R (\rho_{12} - \rho_{21}), \end{aligned} \quad (\text{A3})$$

$$\dot{\rho}_{33} = \Gamma_p \rho_{11} - (k_{35} + k_{32} + k_{31}) \rho_{33}, \quad (\text{A4})$$

$$\dot{\rho}_{44} = \Gamma_p \rho_{22} - (k_{45} + k_{42} + k_{41}) \rho_{44}, \quad (\text{A5})$$

$$\dot{\rho}_{55} = k_{45} \rho_{44} + k_{35} \rho_{33} - (k_{52} + k_{51}) \rho_{55}, \quad (\text{A6})$$

$$\dot{\rho}_{12} = -(\gamma'_2 + i\Delta) \rho_{12} + \frac{i}{2} \Omega_R (\rho_{22} - \rho_{11}), \quad (\text{A7})$$

$$\dot{\rho}_{21} = -(\gamma'_2 - i\Delta) \rho_{21} - \frac{i}{2} \Omega_R (\rho_{22} - \rho_{11}), \quad (\text{A8})$$

where $\gamma'_2 = k_{21}/2 + \gamma_2^* + \Gamma_p/2$, Γ_p is the optical excitation rate during the laser pulse, Ω_R is the Rabi frequency of the applied microwave drive, and Δ is the detuning frequency. The density-matrix elements ρ_{11} and ρ_{22} denote the ground-state populations, ρ_{33} and ρ_{44} denote the excited-state populations, and ρ_{12} and ρ_{21} denote the ground-state coherences. The simulation used the following parameters and relations:

$$K_3 = k_{31} + k_{32} + k_{35}, \quad (\text{A9})$$

$$K_4 = k_{41} + k_{42} + k_{45}, \quad (\text{A10})$$

$$K_5 = k_{51} + k_{52}, \quad (\text{A11})$$

$$\alpha = \frac{k_{31} + k_{32}}{K_3}, \quad (\text{A12})$$

$$\beta = \frac{k_{41} + k_{42}}{K_4}, \quad (\text{A13})$$

$$\begin{aligned} k_{21} &= \frac{1}{2 \text{ ms}}, & k_{31} &= \frac{1}{16 \text{ ns}}, & k_{32} &= 0.01 \cdot k_{31}, \\ k_{42} &= \frac{1}{15 \text{ ns}}, & k_{41} &= 0.01 \cdot k_{42}, & k_{35} &= \frac{1}{95 \text{ ns}}, \\ k_{45} &= \frac{1}{13 \text{ ns}}, & k_{51} &= \frac{1}{330 \text{ ns}}, & k_{52} &= \frac{1}{380 \text{ ns}}, \\ \tau &= 0.4 \text{ } \mu\text{s}, & \Gamma_p &= 1 \text{ MHz}, & \gamma_2^* &= 0.01 \text{ MHz}. \end{aligned}$$

The microwave Rabi frequency was tested at two values, $\Omega_R/2\pi = 70$ kHz and 140 kHz. These parameters were chosen to match experimental conditions and previously reported N-*V* center dynamics. An example of the resulting population dynamics and corresponding fluorescence signal as a function of time is shown in Fig. 6.

To further investigate the role of inhomogeneous broadening in the qCW regime, we performed simulations in

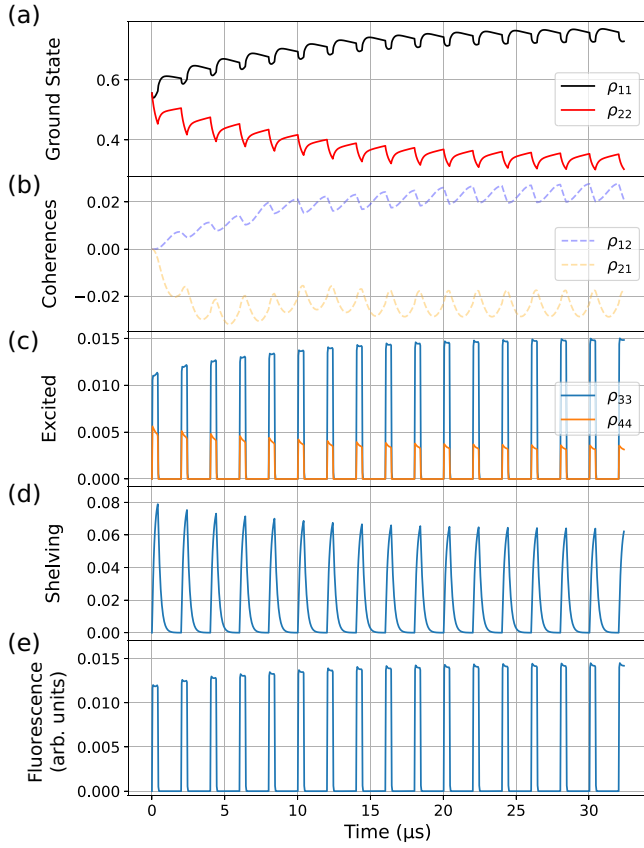


FIG. 6. Example of simulated qCW-ODMR population dynamics for a fixed laser pulse duration of $0.4 \mu\text{s}$, pulse spacing of $2 \mu\text{s}$, and a microwave Rabi frequency of $\Omega_R/2\pi = 70 \text{ kHz}$. (a) Ground-state populations ρ_{11} and ρ_{22} corresponding to the $m_s = 0$ (black) and $m_s = -1$ (red) spin states. (b) Ground-state coherences ρ_{12} and ρ_{21} . (c) Excited-state populations ρ_{33} and ρ_{44} corresponding to the $m_s = 0$ (blue) and $m_s = -1$ (orange) spin states. (d) Population of the metastable shelving state ρ_{55} . (e) Simulated fluorescence signal obtained from the radiative decay of the excited states.

which only the width of the detuning distribution, σ_Δ , was varied while keeping all other parameters fixed. The resulting contrast and linewidth as a function of pulse spacing are shown in Fig. 7. With increasing σ_Δ , the contrast peak near the nominal π -pulse condition at $7 \mu\text{s}$ decreases in amplitude and shifts toward shorter pulse spacings, whereas the delayed maximum at longer pulse spacing ($\sim 100 \mu\text{s}$) becomes relatively more pronounced, even though the overall contrast decreases. In addition, the linewidth in the small pulse-spacing regime approaching the CW limit is much more sensitive to σ_Δ than the linewidth at longer pulse spacings.

APPENDIX B: CAMERA SENSITIVITY COMPARISON

To benchmark our AOD-based scanning platform against camera-based wide-field N- V magnetometry, we

estimate the best-case, shot-noise-limited magnetic sensitivity of representative high-end scientific cameras under idealized operating conditions for CW-ODMR imaging. Throughout this camera comparison, we use the same ODMR linewidth $\Delta\nu$ and contrast C (taken from our operating point) for all cameras in order to isolate detector-readout properties from N- V -dependent parameters. Specifically, we assume (i) the camera can be operated at its quoted maximum full-frame rate f_{max} while (ii) each pixel collects a number of photoelectrons equal to the full-well capacity FWC in each exposure. Here f_{max} denotes the highest achievable frame rate at the camera's maximum spatial resolution (full sensor readout); higher frame rates available only in reduced readout modes (binning, reduced bit depth) are not considered in this benchmark to ensure a consistent full-resolution comparison across devices. Under these assumptions, the photoelectron rate is maximized ($R_e = \text{FWC}f_{\text{max}}$), providing an upper bound on camera performance. Furthermore, we assume the detector operates in the shot-noise-limited regime and therefore neglect readout noise and digitization noise; these effects can be included as additional noise terms but are omitted here because the purpose is to establish a shot-noise upper bound. The same shot-noise-limited assumption is used for the lock-in camera (HeliCam C4) considered below; i.e., the lock-in operation is not assumed to provide an intrinsic sensitivity gain in this regime. The camera parameters used for the sensitivity estimates and comparison are summarized in Table I.

The following constants are used throughout: the gyro-magnetic ratio $\gamma = 28 \times 10^9 \text{ Hz T}^{-1}$, ODMR linewidth $\Delta\nu = 0.7 \text{ MHz}$, contrast $C = 2.5\%$, AOD pixel area $A_{\text{AOD}} = 10 \mu\text{m} \times 10 \mu\text{m}$, and total imaging FOV $A_{\text{FOV}} = 170 \mu\text{m} \times 170 \mu\text{m}$. The quoted quantum-efficiency (QE) values are manufacturer-specified peak QE, typically reported near the visible green, depending on the sensor. We do not attempt to use the QE at the N- V red fluorescence wavelengths ($\sim 650\text{--}800 \text{ nm}$), which are generally lower and not always tabulated consistently across vendors. Using peak QE therefore makes the required optical power to reach FWC an optimistic lower bound.

Consider a sensor with $N_x \times N_y$ pixels mapped to a field of view of dimensions $w \times h$ in object space. The pixel density in object space is

$$\rho_p = \left(\frac{N_x}{w}\right) \left(\frac{N_y}{h}\right). \quad (\text{B1})$$

The equivalent number of camera pixels that fall within one AOD pixel area is

$$n_{\text{px,eq}} = \rho_p \cdot A_{\text{AOD}}. \quad (\text{B2})$$

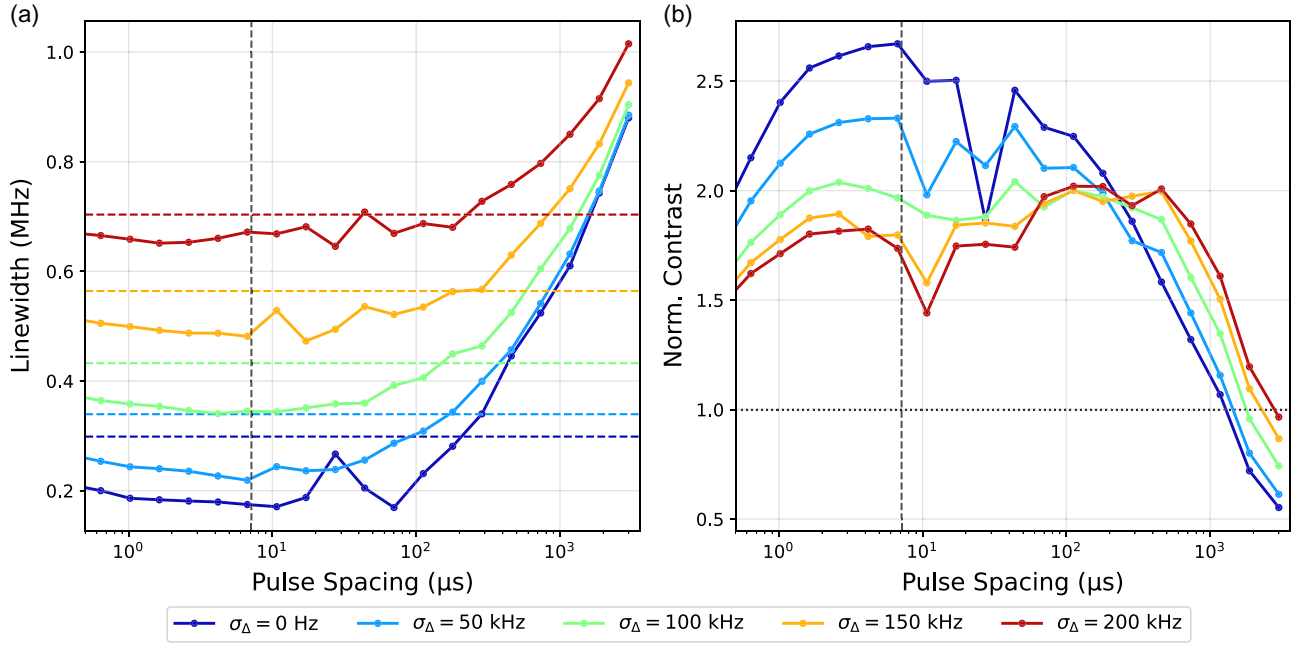


FIG. 7. Simulated ODMR linewidth and contrast as a function of pulse spacing for a fixed Rabi frequency $\Omega_R/2\pi_R = 70$ kHz and different values of the inhomogeneous broadening σ_Δ . (a) Simulated linewidth. The dashed horizontal lines indicate the corresponding CW linewidth obtained from the same model parameters. (b) Simulated contrast normalized to its CW value. The vertical dashed line marks the nominal π -pulse condition. The horizontal reference line at 1 (CW limit) is included for visual guidance.

Assuming Poisson statistics and operation at full-well capacity, the rms shot noise per pixel in electron units is

$$\sigma_e = \sqrt{\text{FWC}}. \quad (\text{B3})$$

In this upper-bound model, the mean detected photoelectrons per pixel per frame is $S = \text{FWC}$. For cameras digitized with n_{bits} analog-to-digital converter (ADC) bits, we define an electron-to-ADC conversion factor

$$k_{\text{ADC}} = \frac{\text{FWC}}{2^{n_{\text{bits}}}}, \quad (\text{B4})$$

such that the noise in ADC units is

$$\sigma_{\text{bits}} = \frac{\sigma_e}{k_{\text{ADC}}}. \quad (\text{B5})$$

For white noise, the single-pixel noise floor expressed per $\sqrt{\text{Hz}}$ is obtained by normalizing the rms noise by the square root of the full-frame rate:

$$S_{\text{noise}} = \frac{\sigma_{\text{bits}}}{\sqrt{f_{\text{max}}}}. \quad (\text{B6})$$

TABLE I. Camera parameters used in the shot-noise-limited sensitivity estimates. The values were taken from the manufacturers' specifications.

Camera	Manufacturer	Sensor (px)	Pixel size (μm)	QE _{peak} (%)	FWC (e ⁻ /px)	ADC (bit)	Max FPS (full frame)
ORCA Fusion BT	Hamamatsu	2304 × 2304	6.5	95	15 000	16	89
ORCA Fire	Hamamatsu	4432 × 2368	4.6	86	20 000	16	115
ORCA Quest 2	Hamamatsu	4096 × 2304	4.6	85	7000	16	120
pco.edge 26 CLHS	Excelitas	5120 × 5120	2.5	60	4000	10	150
Evolve 128 EMCCD	Photometrics	128 × 128	24	90	200 000	16	530
CP70-1-M/C-1000	Optronis	1280 × 1024	6.6	55	17 000	12	1051
Phantom S641	Phantom	2560 × 1600	10	58	14 714	12	1450
Cyclone-1HS-3500	Optronis	1280 × 860	13.7	30	20 000	10	3518
heliCam C4	Heliotis	542 × 512	12	75	500 000	10	5000
Phantom S711	Phantom	1280 × 800	20	33	27 417	12	7360

Here σ_{bits} is the per-frame rms noise expressed in ADC units; dividing by $\sqrt{f_{\text{max}}}$ converts this per-sample rms noise into an amplitude spectral density (white-noise floor) in units of ADC counts per $\sqrt{\text{Hz}}$. The ODMR contrast expressed in ADC units is

$$C_{\text{bits}} = C \cdot 2^{n_{\text{bits}}}, \quad (\text{B7})$$

and the slope in ADC units per unit frequency is approximated as $C_{\text{bits}}/\Delta\nu$. The per-pixel magnetic sensitivity (in $\text{T}/\sqrt{\text{Hz}}$) follows as

$$\eta_{\text{px}} = \frac{S_{\text{noise}}}{\gamma \left(\frac{C_{\text{bits}}}{\Delta\nu} \right)}. \quad (\text{B8})$$

Notably, by substituting the definitions above into the expression for η_{px} , all ADC-related factors cancel; the resulting shot-noise-limited sensitivity depends only on the photoelectron rate per pixel, which in the present upper-bound model is set by $\text{FWC}f_{\text{max}}$. This yields the same shot-noise-limited scaling as derived by Wojciechowski *et al.* [20]:

$$\eta_{\text{px}} = \frac{\Delta\nu/\gamma}{C\sqrt{R_e}}. \quad (\text{B9})$$

Finally, to compare to a scanning approach with spatial binning corresponding to one AOD pixel, we assume that camera pixels within the AOD pixel area are averaged, giving an effective sensitivity

$$\eta_{\text{eff}} = \frac{\eta_{\text{px}}}{\sqrt{n_{\text{px,eq}}}}. \quad (\text{B10})$$

This scaling assumes uniform illumination and uncorrelated noise between pixels, such that averaging over $n_{\text{px,eq}}$ pixels reduces the noise by $\sqrt{n_{\text{px,eq}}}$. This provides a direct camera-vs-scanning comparison at matched spatial resolution.

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