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LETTER

Dispersive readout of room-temperature ensemble spin sensors

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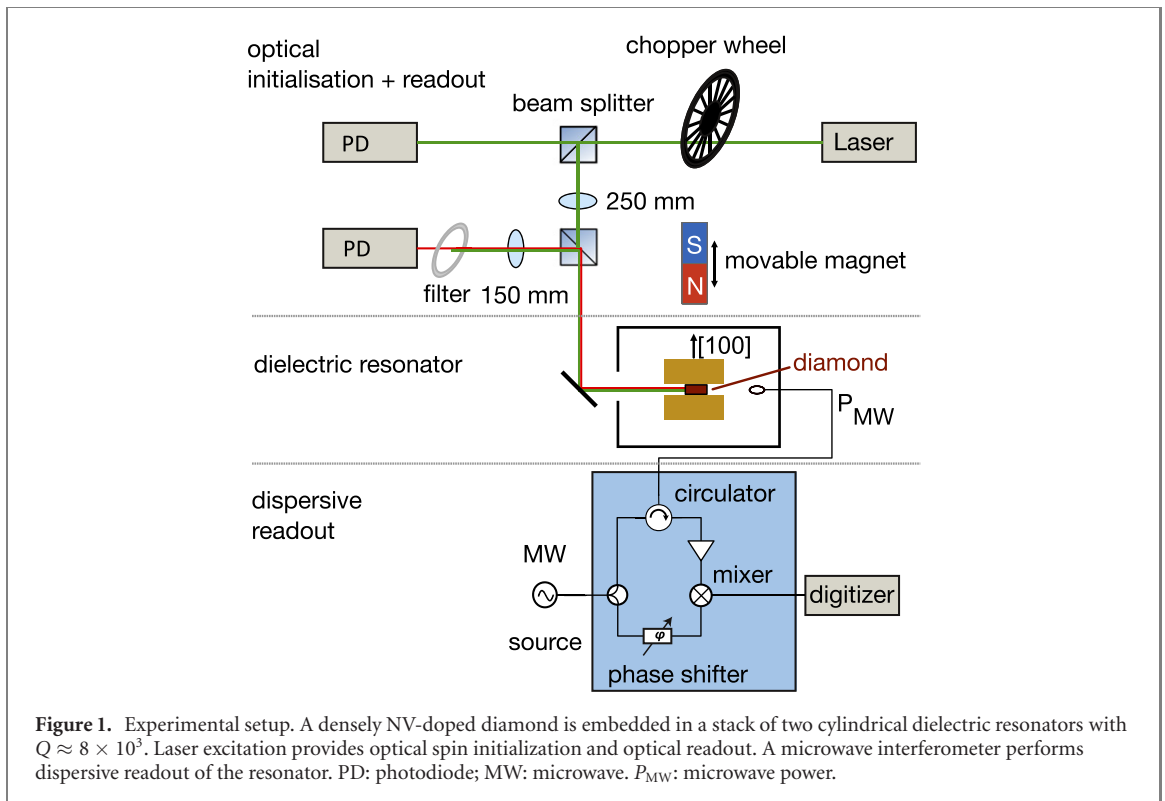
Abstract

We demonstrate dispersive readout of the spin of an ensemble of nitrogen-vacancy centers in a high-quality dielectric microwave resonator at room temperature. The spin state is inferred from the reflection phase of a microwave signal probing the resonator. Time-dependent tracking of the spin state is demonstrated, and is employed to measure the T_1 relaxation time of the spin ensemble. Dispersive readout provides a microwave interface to solid state spins, translating a spin signal into a microwave phase shift. We estimate that its sensitivity can outperform optical readout schemes, owing to the high accuracy achievable in a measurement of phase. The scheme is moreover applicable to optically inactive spin defects and it is non-destructive, which renders it insensitive to several systematic errors of optical readout and enables the use of quantum feedback.

Ensembles of solid-state spin qubits, most prominently nitrogen-vacancy (NV) centers in diamond, are prominent candidates for a new generation of quantum sensors, promising sensitive magnetometers and gyroscopes in a compact device [1–4]. The sensor signal is the expectation value of a spin component (typically $\langle \hat{\sigma}_z \rangle$), that needs to be measured to read out the sensor. For NV spin qubits, spin-dependent fluorescence provides a straightforward way to measure the spin, and has been the workhorse technique for readout in laboratory implementations of ensemble sensors [5]. This optical readout has also been employed in the first generation of integrated sensor devices [6, 7], but it presents a roadblock to further integration, because miniaturization of optics is difficult. The technique is also prone to systematic errors, such as a varying fluorescence background from spin-inactive NV centers in the neutral charge state NV^0 .

These limitations have prompted a search for all-electric readout techniques, that directly provide a measurement of the spin state as a current or voltage. Most prominently, spin-dependent photo-ionization of NV centers has been used to induce a spin-dependent photocurrent [8, 9], which has enabled photo-electric spin readout down to the level of a single spin [10]. However, the readout accuracy of this all-electric method is limited by background impurities, dark currents, and fluctuations in electric properties, such as the ionization cross section.

Experiments on spin ensembles at milli-kelvin temperatures frequently employ dispersive spin readout in a superconducting resonator [11], where the spin signal is encoded in the phase of a microwave signal rather than a voltage or current. This technique is also the state-of-the-art solution for single-shot readout of superconducting qubits [12, 13]. Briefly, qubits ($\hat{\sigma}$) are coupled to a microwave cavity (\hat{a}, \hat{a}^\dagger), resulting in



a system described by the Jaynes–Cummings Hamiltonian

$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_0 \hat{\sigma}_z + \frac{\hbar g}{2} (\hat{a} \hat{\sigma}_+ + \hat{a}^\dagger \hat{\sigma}_-), \quad (1)$$

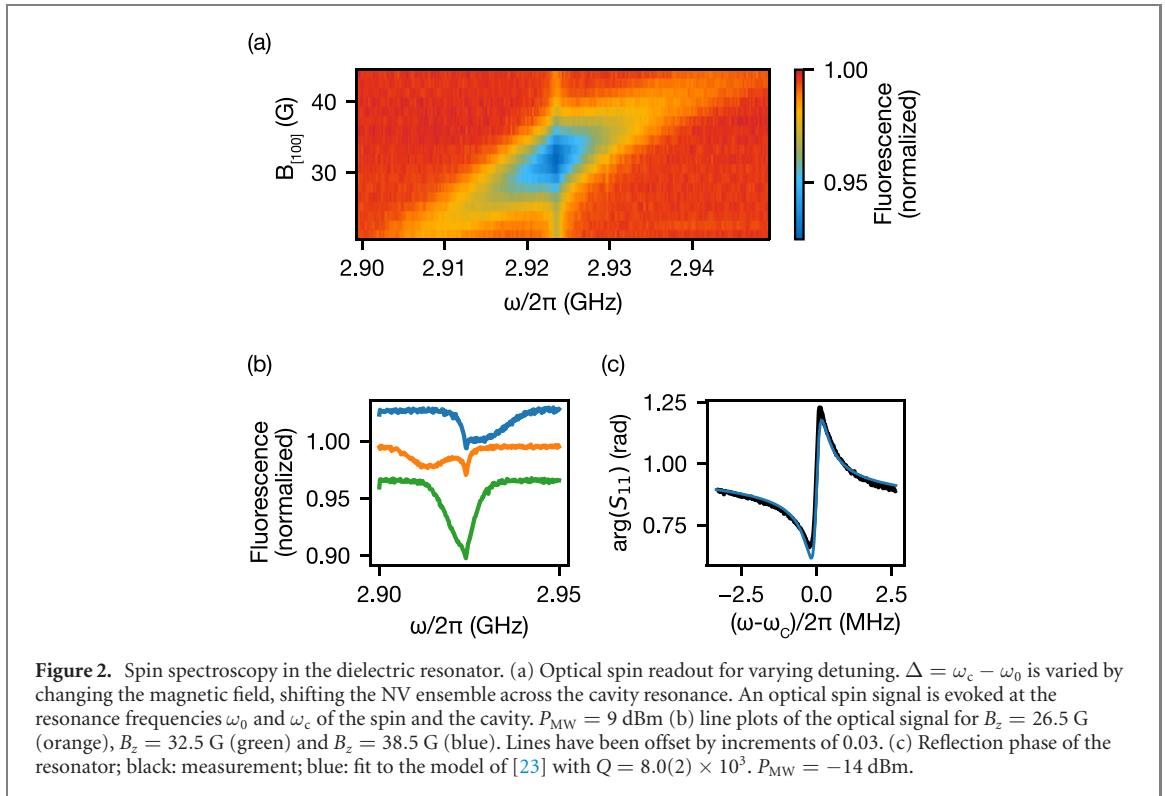
with ω_0 and ω_c denoting the qubit and cavity transition frequencies and g the qubit–cavity coupling. Presence of the qubit imparts a spin-dependent dispersive shift to the cavity. To first order in $g/\Delta = g/(\omega_c - \omega_0)$, this shift is given by

$$\delta_{\omega_c} = g^2/\Delta \quad (2)$$

[14]. It can be probed by measuring the transmission or reflection phase of a microwave resonant with the cavity. This phase varies linearly with Δ within a bandwidth of $\approx \omega_c/Q$ (Q denoting the cavity quality factor) around the cavity resonance $\omega_c + \delta_{\omega_c}$. Sensitive detection of a small shift δ_{ω_c} hence requires a high Q . This is most easily achieved in superconducting cavities, which reach Q values between 10^4 (stripline transmission-line cavity [14]) and 10^{10} (bulk-cavity [15]).

Interestingly, comparably high (10^4 – 10^5) quality factors can be achieved at room temperature, in dielectric resonators made from low-loss high-permittivity ceramics. These devices have already been used for detection of electron paramagnetic resonance [16], based on measurements of absorption or dispersion, although their use is limited by background signals from intrinsic defects in the dielectric material [17], overlapping with many relevant sample spins. This issue is of no concern for spins with an intrinsic zero-field splitting, such as the NV center. Dielectric resonators have already been interfaced with NV centers, to amplify driving pulses [18] and to provide resonant feedback in NV-based masers [19]. Masers have also been proposed as a magnetometry device [20], and recent related work has demonstrated a cavity-assisted magnetometry protocol that does not rely on masing [21]. However, both masers and the novel approach are restricted to continuous-wave operation and do not provide a way for generic spin readout yet.

Here we demonstrate that dielectric resonators enable dispersive readout of the spin state in ensemble-based quantum sensors at room temperature. Our work has been performed in the setup displayed in figure 1. We study a diamond densely doped with NV centres ($[NV] = 2.7 \pm 0.3$ ppm, created by electron irradiation and annealing of a 100 oriented type Ib diamond (Sumitomo)) interfaced to a cavity formed by a stack of two cylindrical dielectric resonators (diameter 16.8 mm, height 5.6 mm, $g/2\pi = 2.4 \times 10^{-2}$ Hz estimated by an analytical model ([22], chapter 4.4)). Stacking is employed to homogenize coupling to the cavity and to tune the resonance frequency close to the NV zero field splitting. This resonator is housed in a shielded enclosure and is probed by a microwave signal, magnetically coupled by a tuneable coupling loop. Probing is performed in a single-sided reflection geometry, where the phase of



the reflected microwave $\arg(S_{11})$ is measured by homodyne detection, and subsequently serves as the readout signal for the sensor. A strong laser (532 nm, 300 mW), focused onto the diamond, is employed to polarize the NV spins. This laser also implements optical spin readout as a complementary signal, recorded by monitoring fluorescence of the NV centers by a photodiode. A tuneable magnetic field is applied along the [100] direction by a moveable permanent magnet. Since its projection along [111] is equal for all four [111] orientations, all four NV orientations experience the same detuning.

This setting allows for a study of NV-cavity coupling for a wide range of detuning $\Delta = \omega_c - \omega_0$ (figure 2). For all values of Δ , we observe that an optical spin signal (figures 2(a) and (b)) is evoked at the two frequencies ω_0 and ω_c of the spins and the cavity. At ω_0 , spins are resonantly driven, resulting in a significant signal despite inefficient off-resonant coupling into the cavity. At ω_c , the drive is resonantly enhanced by the cavity, so that spins can be driven efficiently despite their detuning. We do not see a splitting of the cavity component when tuned into resonance with the spins, which indicates that the spin-cavity system is not in the strong-coupling regime. However, reaching this regime is not required for the demonstration of dispersive readout.

The reflection phase of the cavity varies steeply in vicinity of the resonance (figure 2(c)). We fit this response to the model [23]

$$\arg(S_{11}) = \arctan \left[\frac{4\beta Q\delta}{(2Q\delta)^2 + (1 - \beta^2)} \right] + k\delta + \phi_0, \quad (3)$$

to obtain a quality factor of $Q = 8.0(2) \times 10^3$ and a coupling coefficient of $\beta = 0.28(4)$. $\delta = (\omega - \omega_c)/\omega_c$ denotes relative detuning of the probe microwave to the cavity resonance. NV centers dispersively shift the cavity resonance (figure 2(c)), so that $\arg(S_{11})$ provides a direct electric measurement of the spin state for a microwave tuned to the cavity resonance.

We employ this readout scheme for time-dependent tracking of the spin state (figures 3(a) and (b)). Here, the laser is modulated by a mechanical chopper wheel, resulting in alternating bright and dark cycles of 2 ms duration. As spins polarize into their ground state under illumination, the dispersive phase shifts by up to 4 mrad within $T_{1,\text{Laser on}} = 427(5) \mu\text{s}$. In the dark phase of the cycle, this spin polarization is lost by thermal relaxation and excitation by the probe microwave, resulting in a recovery of the dispersive phase shift within $T_{1,\text{Laser off}} = 740(10) \mu\text{s}$. The unperturbed spin relaxation time T_1 can be obtained by performing the MW after a delay τ without any drive applied. This measurement (figure 3(d)) yields $T_1 = 2.68(4)$ ms, in agreement with previous measurements on comparable samples (2.9(1) ms [24]). The dispersive shift grows for small detunings Δ and changes sign with Δ , as expected from the expression $\delta_{\omega_c} = g^2/\Delta$. At the point of maximum spin contrast ($t = 2.2$ ms, figure 3(c)), the data is well described by a

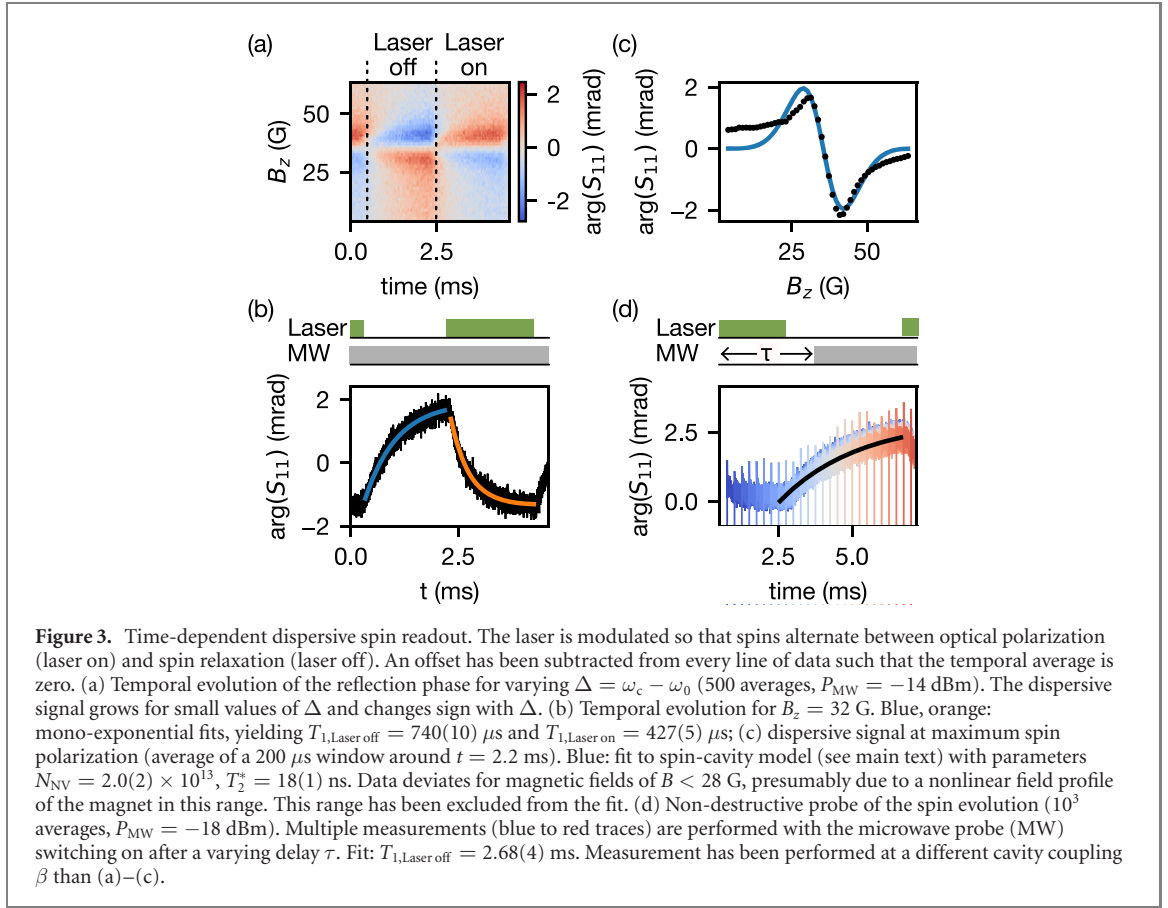


Table 1. Parameters of the current setup and an optimized device.

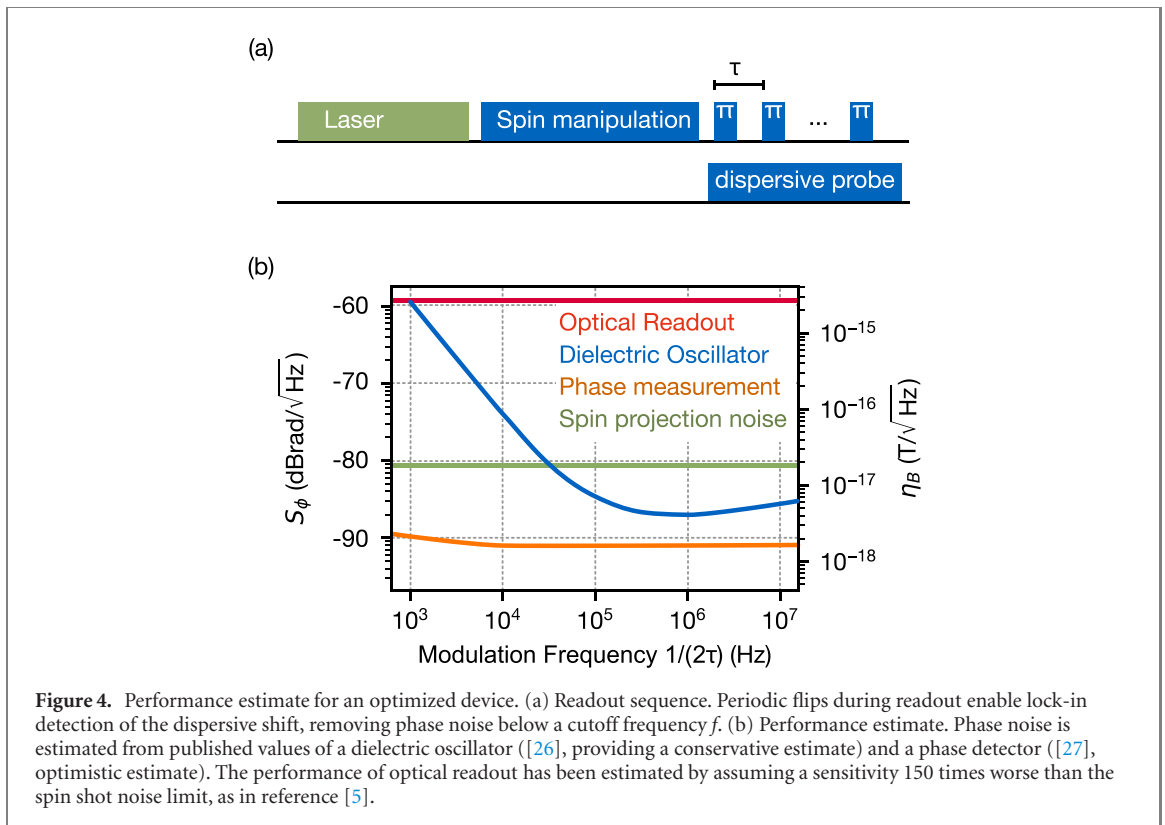
Parameter	This work	Optimized
$g/2\pi$ (Hz)	2.4×10^{-2}	3×10^{-1}
$\omega_0/2\pi$ (GHz)	3	10
Q	8×10^3	10^4
$\Delta/2\pi$ (MHz)	10	10
T_2 (ms)	Not measured	1
N	2×10^{13}	10^{14}

numerical model computing the shift of equation (2) for an ensemble of NV centers with a Gaussian distribution of transition frequencies with a width of $\sigma_\omega = 1/T_2^*$ and $T_2^* = 18(1)$ ns.

We finally turn to a quantitative analysis of the ultimate performance that can be reached by the dispersive readout scheme. We assume the technical parameters of table 1. The coupling strength is increased by an order of magnitude over the present work, which appears realistic by the use of a higher-frequency resonator with a smaller mode volume. The number of spins is increased by one order of magnitude to the level of reference [19]. This improvement requires more efficient laser illumination to polarize more spins. With improved excitation optics, polarization can also be achieved in more dilute NV ensembles, pushing the coherence time to $T_2 = 1$ ms [25], $T_2^* = 1$ μ s. The optimized cavity thus operates at the border of strong-coupling ($\sqrt{g^2 N} \gtrsim \omega_c/Q, 1/T_2^*$). In a sensor, it will be desirable to choose the detuning large against all these parameters (e.g. to a value of $\Delta/(2\pi) = 10^7$ Hz), in order to preserve sensitivity to magnetic fields. Still, the dispersive shift induced by the spins could be as large as

$$\arg(S_{11}) = \frac{\pi Q N g^2}{\omega_0 \Delta} = 3 \text{ rad.} \quad (4)$$

The sensitivity of a sensor will be limited by the measurement accuracy on $\arg(S_{11})$, which will be limited by electronic phase noise and intrinsic noise of the dielectric resonator. Both of these mechanisms become stronger for decreasing frequencies, so that a naive implementation would be hampered by low-frequency noise such as thermal drift of the resonator. This problem can be overcome by lock-in schemes (figure 4(a)), where the spin is modulated to create an oscillating signal. Such a modulation could be implemented by



mere T_1 decay (as in our present work), or by a sequence of periodic control pulses. Readout sensitivity would then be limited by the phase noise $S_\phi(f)$ at the modulation frequency f .

$$\eta_B = \frac{\hbar}{g\mu_B T_2} \frac{\omega_0 \Delta}{\pi Q g^2 N} S_\phi(f). \quad (5)$$

The phase noise $S_\phi(f)$ can be estimated from similar existing devices (figure 4). Dielectric oscillators present a conservative estimate, because their phase noise includes contributions from measurement, feedback, and intrinsic noise of the resonator. An optimistic estimate can be obtained from phase measurement circuits, which do not contain the latter two sources. In both cases, readout sensitivity can reach the limit of spin projection noise, which is currently out of reach for optical spin readout in ensembles. However, the worst-case scenario requires modulation at a frequency of several 10 kHz or higher. We note that the microwave power required for a measurement at the spin shot noise limit would be still much less than the Rabi frequency required to drive spin flips. Readout would require a minimum flux of N/T_2 microwave photons. N photons are required to overcome photon shot noise. They have to pass the resonator within T_2 , because this is the lifetime of the spin signal under dynamical decoupling (figure 4(a)). This microwave signal will populate the resonator with an average $NQ/[\omega_c T_2] \approx 10^{10}$ photons, corresponding to a Rabi frequency of $\Omega_R/2\pi \approx 3 \times 10^4$ Hz, which is much smaller than Δ .

The sensitivity of microwave readout (equation (5)) is linear in the number of spins N , in contrast to the square root dependence of fluorescence readout [1]. This implies that dispersive readout is most advantageous for large ensembles. A phase-noise-optimized implementation of our current experiment—retaining one order of magnitude lower g and N compared to the optimized scenario—would thus reach, but not surpass, the performance of fluorescence readout.

In summary, we have demonstrated a dispersive approach to spin readout in quantum sensors. Similar to related work [21], our approach promises a higher detection efficiency than optical readout, potentially down to the limit of spin projection noise. Future implementations of the scheme will have to address one key challenge: dispersive readout requires a narrowband cavity, where fast pulsed control is not easily implemented. Combining both requirements would be most straightforward in a dual-port cavity with the ability of rapid Q -switching [28]. Alternatively, optimal control schemes could be employed to enable spin manipulation in a narrowband cavity [29].

The technique has several complementary advantages over optical readout beyond sensitivity. It is applicable to a wider range of spin species, as there are spins that can be optically polarized, but cannot be efficiently read out optically (such as the silicon-vacancy in silicon-carbide [30]). Cavity readout is

moreover non-destructive, so that spin states can be weakly probed during their evolution, as demonstrated here for the measurement of spin relaxation times. This is a crucial requirement for the implementation of quantum feedback schemes [31, 32]. It also mitigates several problems of optical readout, such as a background of luminescent but spin-inactive centers in the neutral charge state NV^0 . These would contribute fluorescence background but no dispersive signal. Finally, the mere technical simplicity of the scheme will enable straightforward integration into compact devices as it is required for large-scale application of quantum technologies.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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