Supplemental material to: Miniature cavity-enhanced diamond magnetometer

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A. NV singlet state population

We can calculate the NV state population from the increase in cavity losses under saturating green pump light. The losses are related to the measurable quantities finesse ($\mathscr{F}$) and the cavity's IR light transmission on resonance to initial IR light ratio ($\frac{I_{\rm tr}}{I_{\rm in}}$). Measuring the losses with (A_2) and without (A_1) green pump light allows us to infer the losses due to NVs in the singlet state ($A_{\rm NV}$). Finally, the increase in losses per roundtrip can be related to the NVs singlet population by the Beer-Lambert law. Assuming ideal loss-free mirrors finesse and transmission are given by:

$$\left(\frac{2\mathscr{F}}{\pi}\right)^2 = \frac{4\sqrt{R_1R_2(1-A)}}{(1-\sqrt{R_1R_2(1-A)})^2} \tag{S1}$$

$$\frac{I_{\rm tr}}{I_{\rm in}} = \frac{4(1-R_1)(1-R_2)(1-A)}{(2-R_1-R_2+A)^2} \tag{S2}$$

where R_1 the reflectivity of the diamond coating, R_2 is the reflectivity of the output mirror and A represents the losses per roundtrip due to the diamond crystal.

According to the company specification, $R_1 = 98.5(5)\%$. R_2 and A_1 can be inferred solving Eq. (S1-S2) with measurements of finesse and transmission. Without green pump light we determine $R_2 = 99.2(8)\%$ and $A_2 = 1.66(1)\%$. Assuming the same reflectivity and adding saturating green pump light we get a new value for losses $A_2 = 3.09(3)\%$. The difference in losses $\Delta A = A_{\rm NV}$ can be attributed to absorption on the singlet transition. These losses can be related to NV population in the singlet state via the Beer-Lambert law. The transmission of the diamond for losses $A_{\rm NV}$ is given by:

$$1 - A_{\rm NV} = e^{-n\sigma l} \tag{S3}$$

Where n is the density of the NVs in the singlet state, σ the absorption cross section of IR light on resonant with the singlet transition and l the path length in the diamond. With a path length $l = 2L_{\rm d}$ (where $L_{\rm d} = 0.39$ mm is the geometric length diamond) and $\sigma = 3\times10^{-18}\,\mathrm{cm}^2$ (Ref.[1]) we calculate the density of NVs in the metastable state as $n = 0.68(1)$ ppm.

B. Cavity finesse

Figure S1 shows the transmission of IR light while scanning the length of the cavity. From our measurements, after fitting we estimate the finesse ($\mathscr{F}$) of our cavity to be $\mathscr{F} = 160(4)$ [the FSR of the cavity is $\sim 30.1(2)$ GHz]. The finesse is measured in the absence of green pump light.

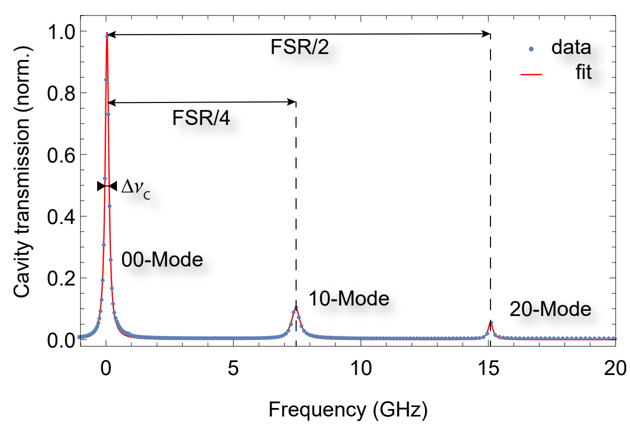

FIG. S1. IR transmission spectrum of the cavity obtained by scanning the cavity length, in the absence of green light. Data are represented with dots (blue) and the fit with a line (red).

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C. Magnetometer Calibration

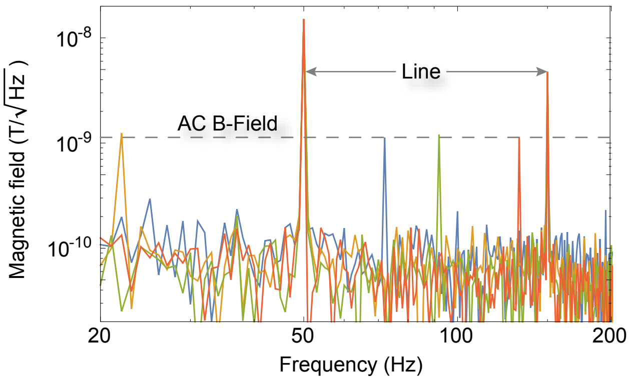

FIG. S2. Magnetic-field noise spectrum for different fields as a function of frequency. The test field is applied for different frequencies of 22 Hz (amber), 72 Hz (blue), 92 Hz (green) and 132 Hz (red).

The sensitivity of the sensor is verified by applying external magnetic fields of a given amplitude and frequency to it. Fig. S2 shows the noise spectrum of the magnetometer in response to a sine-wave-modulated magnetic field of 1 nT RMS amplitude, at different frequencies.

The field is provided by a multi-turn circular current coil. The radius of the coil is r_{coil} ∼2.5 cm and its distance from the sensor is z_{coil} ∼1 cm. The coil is connected in series with a 1 kΩ resistor to decrease induction induced current. The amplitude of the produced magnetic field B_{test} is then compared with the recorded magnetometer signal B_{rec}. B_{test} can be calculated as:

$$B_{test} = \frac{\mu_0 \, N_{turns} \, I_{coil} \, r_{coil}^2}{2[z_{coil}^2 + r_{coil}^2]^{3/2}}.$$

where $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 is the vacuum permeability, $N_{turns} = 11$ are the number of turns of the coil and $I_{coil} = 6.5\,\mu$A the current flowing through the coil. Our measured B_{rec} is consistent with B_{test} within a 2% error.

D. Photon shot-noise behavior

To confirm the photon shot noise behavior of our sensor, in the absence of MWs, we record the output of the LIA ($S_{\rm IR}$) as we detect transmission ($P_{\rm IR,t}$) for a wide range of IR light powers. We then fit the data with a curve $S_{\rm IR} = \sqrt{a^2 + b^2 P_{\rm IR,t} + c^2 P_{\rm IR,t}^2}$, where a signifies laser power independent noise sources (e.g. electronic noise), b relates to IR light shot-noise and c to IR intensity noise sources.

Figure S3 shows the above measurements in dots (blue) at 100 mW of green light. The data is fitted (red) giving fit values $a = 0.23(8)$, $b = 1.16(6)$ and $c = 2\times10^{-3}(2)$ which indicates shot-noise dominated behavior for IR DC levels above ∼0.2 V. The theoretically calculated shot noise is represented by the dashed line. Finally, the asterisk (*) is placed in Fig. S3 to signify the average noise floor between 60-90 Hz under normal operation corresponding to 400 mW of green pump light and a MW field applied to the NVs. The noise floor thus includes environmental and MW-related noise.

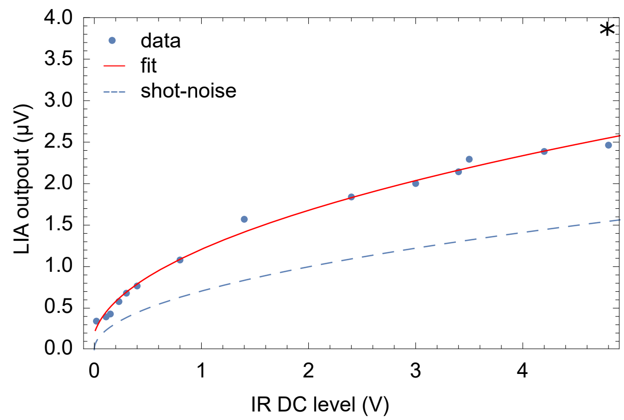

FIG. S3. Measured and calculated RMS noise of cavity transmission. Data show in dots (blue), are fitted with a line (red) . Theoretical calculation for the shot noise is presented with dashed lines and an asterix symbol (*) is placed to signify the noise level under normal operation.

[1] Y. Dumeige, M. Chipaux, V. Jacques, F. Treussart, J.-F. Roch, T. Debuisschert, V. M. Acosta, A. Jarmola, K. Jensen, P. Kehayias, and D. Budker, "Magnetometry with nitrogen-vacancy ensembles in diamond based on infrared absorption in a doubly resonant optical cavity," *Phys. Rev. B*, vol. 87, p. 155202, Apr 2013.