

Quantum noise in a squeezed-light-enhanced multiparameter quantum sensor

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We study quantum enhancement of sensitivity using squeezed light in a multiparameter quantum sensor, the hybrid dc and rf optically pumped magnetometer (hOPM) [M. Lipka *et al.*, Multiparameter quantum sensing and magnetic communication with a hybrid dc and rf optically pumped magnetometer, *Phys. Rev. Appl.* **21**, 034054 (2024)]. Using a single spin ensemble, the hOPM acquires both the dc field strength (scalar magnetometry) and resonantly detects one quadrature of the ac magnetic field at a chosen frequency (rf magnetometry). In contrast to the Bell-Bloom scalar magnetometer [C. Troullinou *et al.*, Squeezed-light enhancement and backaction evasion in a high sensitivity optically pumped magnetometer, *Phys. Rev. Lett.* **127**, 193601 (2021)], the backaction evasion in the hOPM is incomplete, leading to a nontrivial interplay of the three quantum noise sources in this system: photon shot noise, spin projection noise, and measurement backaction noise. We observe these interactions using squeezed light as a tool to control the distribution of optical quantum noise between S_2 and S_3 polarization Stokes components, and the resulting effect on readout quantum noise and measurement backaction. These results demonstrate quantum-enhanced sensitivity in a continuously operating multiparameter sensor and reveal fundamental trade-offs between sensitivity, backaction, and bandwidth.

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I. INTRODUCTION

Quantum sensing of a single parameter (e.g., the scalar magnetic field strength), described by the theory of quantum parameter estimation [1], has been extensively investigated both theoretically and experimentally [2,3]. Multiparameter quantum sensing, in contrast, aims to simultaneously estimate multiple parameters [4,5], with the potential to provide better precision than when estimating each parameter separately. This potential is supported both theoretically [6–10] and by proof-of-principle demonstrations [11–13].

Many practical quantum sensors operate continuously, relying on nondestructive monitoring of evolving quantum systems [14,15]. In optically detected spin systems such as optically pumped magnetometers (OPMs), three primary quantum noise sources determine the fundamental sensitivity of the sensor: spin projection noise (SPN), photon shot noise (PSN), and measurement backaction (MBA) noise, i.e., the perturbation of the quantum state due to the

measurement itself [16–18]. Approaches to surpass the standard quantum limit (SQL) include optical squeezing [17,19], spin squeezing [20,11], and techniques to evade or mitigate MBA [12,11,21,22].

As we show, the interplay between these quantum noise sources leads to complex quantum limits in continuously operating sensors. In particular, a single, quantum-limited sensor can show a trade-off between sensitivity and bandwidth, and between sensitivity to signals at different frequencies. In this work, we study this interplay using the hOPM [23], a practical platform for multiparameter quantum estimation. The hOPM employs a single atomic spin ensemble to simultaneously perform scalar dc magnetometry and resonant rf magnetometry—that is, it measures both the static magnetic field strength and one quadrature of an ac magnetic field at a chosen frequency. Unlike the Bell-Bloom scalar magnetometer (BBOPM) [17], the hOPM does not evade MBA, making it an ideal testbed for studying the interactions among the three quantum noise sources.

We use polarization-squeezed probe light to control and probe this noise interplay. By adjusting the distribution of quantum fluctuations between the S_2 and S_3 Stokes components of the probe, we influence both the readout noise and the backaction imprinted on the spin ensemble. Beyond serving as a testbed for noise redistribution, this approach allows us to demonstrate quantum enhancement

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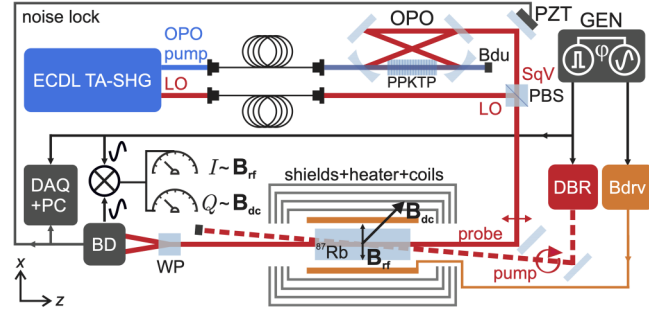


FIG. 1. Experimental setup of a quantum-enhanced hybrid dc and rf optically pumped magnetometer (QE-hOPM). WP—Wollaston prism, BD—balanced detector, OPO—optical parametric oscillator, LO—local oscillator, SqV—squeezed vacuum, PM—polarization maintaining fiber, PBS—polarizing beam splitter, DAQ—data acquisition card, Bdrv—low-noise current driver, ECDL—extended cavity diode laser, TA-SHG—tapered amplified second harmonic generator, PPKTP—periodically poled potassium titanyl phosphate nonlinear crystal, Bdu—beam dump, GEN—function generator, PZT—piezoelectric element. Description in the text.

in a multiparameter sensor: reducing total quantum noise below the SQL for both dc and rf measurements, and simultaneously improving magnetic sensitivity and measurement bandwidth. The techniques are compatible with emerging technologies for sensor miniaturization, including integrated OPMs [24] and on-chip squeezed-light sources [25,26], suggesting a pathway toward compact, quantum-enhanced MPQS platforms for real-world applications.

II. QE-HOPM OPERATION

The quantum-enhanced hybrid optically pumped magnetometer (QE-hOPM) is shown schematically in Fig. 1. The hOPM simultaneously performs scalar dc magnetometry and resonant rf magnetometry using a single atomic spin ensemble [23]. The static magnetic field $\mathbf{B}_{dc}$ is inferred from the atomic spin precession (Larmor) frequency ω_L , while one quadrature of an oscillating magnetic field $\mathbf{B}_{rf}$ is inferred from the amplitude of the spin precession.

The sensor operates in the Bell-Bloom regime [27], with periodic optical pumping at frequency $\omega_p \approx \omega_L$. After interaction with the atomic ensemble, the probe polarization undergoes Faraday rotation proportional to the spin component F_z and is detected with a balanced polarimeter. Demodulation at ω_p yields the in-phase (I) and quadrature (Q) components of the signal. The Q quadrature encodes the phase of the spin precession relative to the drive and is used to infer $\mathbf{B}_{dc}$, while the I quadrature is proportional to the spin precession amplitude and responds to one quadrature of the $\mathbf{B}_{rf}$ field [23].

Polarization-squeezed probe light is employed to reduce photon shot noise in the detected Stokes component. The

redistribution of quantum fluctuations between conjugate Stokes components modifies both the optical readout noise and the measurement backaction acting on the atomic spin ensemble, enabling controlled exploration of quantum noise trade-offs in a multiparameter sensor.

III. EXPERIMENTAL SETUP AND OPERATING PARAMETERS

The construction of the hOPM and the generation of squeezed probe light are described in detail in Refs. [23] and [17,28], respectively.

The dc magnetic field $\mathbf{B}_{dc}$ is applied in the $x-z$ plane at 45° with respect to the pumping and probing direction. The rf magnetic field $\mathbf{B}_{rf}$ is aligned along the x axis and oscillates at frequency ω_{rf} , which is set equal to and phase synchronized with the pump repetition frequency ω_p . Optical pumping is implemented using the Bell-Bloom technique [27], in which the collective atomic spin $\mathbf{F}$ is driven periodically at frequency $\omega_p \approx \omega_L$.

Isotopically enriched ^{87}Rb vapor is contained in a magnetically shielded, 3 cm-long glass cell filled with 100 torr of N_2 buffer gas (pressure specified at room temperature). The atoms are heated to 105°C using intermittent Joule heating, yielding an atom number density of 8.2×10^{12} atoms/cm³, which is optimal for scalar magnetometry under these conditions [29]. Magnetic fields are generated by induction coils along the x (TwinLeaf CSUA300) and z (TwinLeaf CSBA-10) axes driven by low-noise current sources, producing a dc bias field of $\mathbf{B}_{dc} \approx 6 \mu\text{T}$, corresponding to $\omega_L \approx 2\pi \times 42$ kHz. The rf field is generated by current modulation of the x axis coil at $\omega_{rf} = \omega_L$.

Optical pumping is provided by a circularly polarized beam with instantaneous power 110 μW from a distributed Bragg reflector (DBR) laser propagating along the z axis. The pump frequency is modulated at ω_p around the ^{87}Rb D_1 transition, sweeping through resonance twice per spin-precession cycle. Pump modulation is generated by a waveform generator (Siglent SDG1025) with phase and frequency synchronized to the rf drive.

The Faraday rotation of a 560 μW linearly polarized probe beam is detected using a shot-noise-limited polarimeter consisting of a half-wave plate, a Wollaston prism, and a balanced detector (Thorlabs PDB450A). The probe and local oscillator are derived from a frequency-doubled diode laser system with a tapered amplifier (Toptica ECDL TA-SHG 110) operating at a fundamental wavelength of 795 nm. The laser is frequency stabilized 50 GHz blue-detuned from the D_1 line using a fiber interferometer [30]. A fraction of the infrared output serves as the coherent probe or local oscillator, while the remaining light is frequency doubled to 397 nm, spatially mode cleaned, and used to pump a subthreshold optical parametric oscillator, generating vertically polarized squeezed vacuum at 795 nm [17,28].

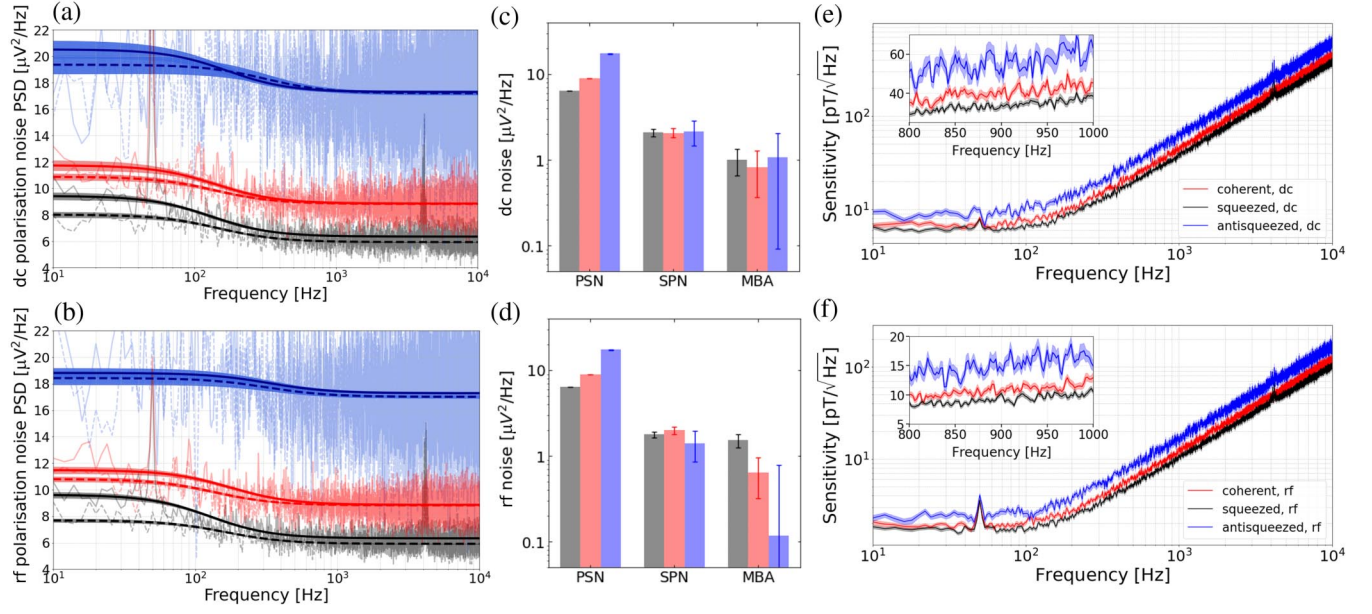


FIG. 2. Observed quantum noise in the dc (a),(c),(e) and rf (b),(d),(f) magnetometer signals for squeezed (black) coherent-state (red) and antisqueezed (blue) probing. (a),(b) Polarization noise after demodulation. Light traces show data, dark traces show maximum-likelihood fits with Eq. (2). Probe power 560 μW throughout. Pump power 110 μW (solid curves), 0 μW (spin-noise spectroscopy, dashed curves). Shaded regions show $\pm 1\sigma$ uncertainty from bootstrapping. (c),(d) best-fit parameters S^{PSN} , S^{SPN} , and S^{MBA} . Error bars show the statistical uncertainties of the extracted PSN, SPN, and MBA amplitudes, obtained from the bootstrap-estimated standard deviations of the fitted parameters. (e),(f) Sensitivity of the hOPM for the dc and rf detection. Shaded regions show $\pm 1\sigma$ uncertainty from bootstrapping.

The squeezed vacuum is combined with the horizontally polarized, mode-matched local oscillator on a polarizing beam splitter to produce a polarization-squeezed probe beam. The relative phase between the squeezed vacuum and the local oscillator is actively stabilized using a piezoelectric actuator and feedback loop [17]. The measured polarization squeezing is 2.0 dB before the atomic cell and 1.8 dB at the balanced detector after the atoms. Detector signals and the pump current monitor are digitized using a data acquisition card (National Instruments PCI-4462) for digital demodulation. We note that the present experiment is limited by optical losses, residual phase noise, and the available pump power for squeezed-light generation.

IV. QUANTUM NOISE REDUCTION IN QE-HOPM

The quantum noise dynamics of Bell-Bloom magnetometers have been studied in detail in Ref. [17], and quantum-noise-limited operation of the hOPM has been demonstrated in Ref. [23]. Optical probing measures the Stokes parameter

$$S_2^{(\text{out})}(t) = S_1^{(\text{in})} \sin \phi(t) + S_2^{(\text{in})} \cos \phi(t),$$

which for small polarization rotation angles $\phi(t) = GF_z(t)$ reduces to [23,31]

$$S_2^{(\text{out})}(t) = GF_z(t)S_1^{(\text{in})} + N_{S_2}(t). \quad (1)$$

Here S_α ($\alpha \in \{1, 2, 3\}$) are the Stokes parameters before and after the atoms, G is a detuning-dependent coupling factor, and $N_{S_2}(t)$ denotes the polarization noise of the detected Stokes component.

The measured spin projection $F_z(t)$ oscillates at the pump frequency ω_p and relaxes due to depolarization mechanisms, which also generate broadband spin noise as required by the fluctuation-dissipation theorem [17,32,33]. Expressing the detected signal in terms of slowly varying quadratures yields

$$S_2^{(\text{out})}(t) = I \cos(\omega_p t) + Q \sin(\omega_p t).$$

The demodulation phase is chosen such that $Q = 0$ at resonance ($\omega_p = \omega_L$). Near resonance, Q responds linearly to changes in the dc magnetic field, while I responds linearly to changes in the quadrature amplitude of the rf magnetic field [23].

Single-sided power spectral densities $S_{I,Q}(\omega)$ are computed using a discrete Fourier transform with a Hann window [17,29]. The measured spectra are well described by

$$S_{I,Q}(\omega) = \xi^2 S_{I,Q}^{\text{PSN}} + \mathcal{L}(\omega)(S_{I,Q}^{\text{SPN}} + \xi^2 S_{I,Q}^{\text{MBA}}), \quad (2)$$

where ξ^2 ($\bar{\xi}^2$) is the squeezing (antisqueezing) factor. PSN is frequency independent, while SPN and MBA exhibit a Lorentzian envelope $\mathcal{L}(\omega) = \Delta\omega^2/(\omega^2 + \Delta\omega^2)$, with $\Delta\omega$ the magnetic-resonance linewidth.

Figures 2(a) and 2(b) show the measured polarization noise spectra together with fits to Eq. (2) and with best-fit parameters in Figs. 2(c) and 2(d). The data were averaged over 50–150 iterations. Technical noise peaks near 50 Hz and 4 kHz were excluded from the fitting. Model parameters were extracted following [34] using maximum-likelihood estimation and bootstrapping to compare the response bandwidth, PSN, and low-frequency atomic noise (SPN + MBA) for coherent, squeezed, and antisqueezed probing, and for polarized and unpolarized atomic ensembles.

The polarization noise fits show that the spectra in Figs. 2(a) and 2(b) are dominated by atomic noise (SPN and MBA) at low frequencies and by optical noise (PSN) at high frequencies, as described by Eq. (2). Relative to coherent probing, squeezed light reduces the PSN by approximately 1.59(1) dB, while antisqueezed probing increases the PSN by about 2.91(3) dB, with identical values for the dc and rf channels within experimental uncertainty. The SPN remains unchanged within error for all probe states, as expected. In contrast, the MBA contribution increases under squeezed probing, consistent with enhanced quantum backaction accompanying reduced optical shot noise. For antisqueezed probing, the extracted MBA contribution is lower than for coherent probing, but this reduction is not statistically significant, given the bootstrap uncertainty. Variations in the polarization-noise bandwidth are observed but remain comparable within uncertainties, indicating that squeezing primarily modifies noise amplitudes rather than the dynamical response.

V. SENSITIVITY OF QE-HOPM FOR DC AND RF DETECTION

Magnetic sensitivity of the hOPM is measured as in Ref. [23]. The responsivity, defined as $R_{\mathcal{I}}(\omega) \equiv d\mathcal{I}(\omega)/dB_{\text{rf}}(\omega)$ [$R_{\mathcal{Q}}(\omega) \equiv d\mathcal{Q}(\omega)/dB_{\text{dc}}(\omega)$] is measured in two steps. First, at a range of frequencies ω we apply a small harmonic perturbation to B_{rf} (B_{dc}) and observe the resulting $S_{\mathcal{I}}(\omega)$ [$S_{\mathcal{Q}}(\omega)$]. This gives $R_{\mathcal{I}}^2(\omega)$ [$R_{\mathcal{Q}}^2(\omega)$] up to a global calibration factor, which we obtain by quasistatically acquiring $\mathcal{I}$ versus B_{rf} with $\delta B_{\text{dc}} = 0$ ($\mathcal{Q}$ versus B_{dc} with $B_{\text{rf}} = 0$) and making a linear fit around the operating point to find $R_{\mathcal{I}}^2(0)$ [$R_{\mathcal{Q}}^2(0)$]. The equivalent magnetic noise is then calculated as

$$S_{B_{\text{rf}}}(\omega) = S_{\mathcal{I}}(\omega)/R_{\mathcal{I}}^2(\omega), \quad (3)$$

$$S_{B_{\text{dc}}}(\omega) = S_{\mathcal{Q}}(\omega)/R_{\mathcal{Q}}^2(\omega). \quad (4)$$

This method automatically accounts for frequency dependence of the signal chain and data analysis.

TABLE I. Window-averaged magnetic-field sensitivities for the dc and rf channels using squeezed (sq), coherent (coh), and antisqueezed (asq) probing. Values in parentheses give the relative noise reduction or penalty in dB with respect to the coherent case. BW is 3 dB bandwidth.

State	10–80 Hz		850–950 Hz		BW (Hz)
	$\mathcal{S}$ (pT/ $\sqrt{\text{Hz}}$)	dB	$\mathcal{S}$ (pT/ $\sqrt{\text{Hz}}$)	dB	
rf _{sq}	1.717(2)	−0.88(1)	9.210(8)	−1.42(1)	198
rf _{coh}	1.901(2)	0	10.842(8)	0	180
rf _{asq}	2.509(4)	+2.41(2)	15.106(23)	+2.88(2)	144
dc _{sq}	6.112(7)	−1.05(1)	33.544(23)	−1.61(1)	164
dc _{coh}	6.897(11)	0	40.359(36)	0	154
dc _{asq}	9.167(15)	+2.47(2)	55.011(72)	+2.69(2)	118

The hOPM is then operated at the nominal operating point with no applied test signal, and the residual noise power spectral density $S_{\mathcal{I}}(\omega)$ [$S_{\mathcal{Q}}(\omega)$] is recorded in the same way. In the presence of squeezed light, this sensitivity is modified by ξ^2 and $\bar{\xi}^2$, affecting the noise spectrum as given in Eq. (2), leaving responsivity unchanged. The measured sensitivity is shown in Figs. 2(e) and 2(f). The noise spectra here were averaged over 50–150 iterations and smoothed for clarity using frequency bins whose widths scale proportionally with frequency (logarithmic binning). The sensitivity enhancement provided by squeezed-light probing is seen across both low- and high-frequency bands, see Table I. We note that the hOPM is operated in a regime optimized for resolving quantum noise contributions rather than for absolute sensitivity, leading to slightly higher noise floor compared with the sensitivities reported in Ref. [23]. The sensitivity of the dc (rf) readout in the PSN dominated region is improved by 1.42(1) dB [1.61(1) dB] for the squeezed-light probing, and reduced by 2.88(2) dB [2.69(2) dB] for the antisqueezed-light probing.

For BBOPM, both the enhancement in high-frequency sensitivity and the broader measurement bandwidth are evident and, in all scenarios, beneficial due to the evasion of MBA—meaning that low-frequency sensitivity is not sacrificed to achieve a wider bandwidth. In the case of hOPM, high-frequency sensitivity is also improved, along with the slightly increased measurement bandwidth. However, the benefit of the broader bandwidth is not always guaranteed, as it depends on the interplay of various noise contributions. Therefore, the specific frequency range of interest should always be considered to determine whether squeezing provides a net advantage.

VI. MBA IN QE-HOPM

In the hOPM, the collective spin $\mathbf{F}$ is governed by a Bloch equation for the precession velocity $d\mathbf{F}/dt$ (see the Appendix for details), to which MBA contributes a term $GS_3\hat{z} \times \mathbf{F}$. Here $GS_3\hat{z}$ can be interpreted as a fictitious

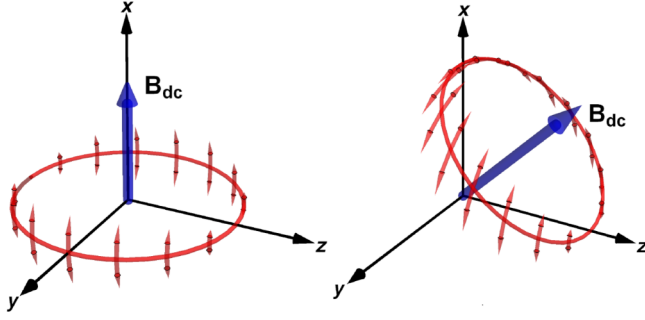


FIG. 3. Visualization of the effect of S_3 noise on spin precession. Left: BBOPM, as in Refs. [17,29]. Right: hOPM, as in Ref. [23]. The probing direction is along z . The thick blue arrow shows the magnetic-field direction. Red double-headed arrows represent perturbations to spin precession (direction and relative magnitude) due to the OZS, which produces a random rotation about the z axis proportional to the ellipticity, i.e., the Stokes component S_3 .

field produced by ac Stark shifts [35] induced by the probe light, i.e., optical Zeeman shifts (OZS). The OZS noise term $GS_3\hat{z}$ is weak compared with the bias field that drives the spin precession and is treated as a perturbation. Components of this noise near the Larmor frequency accumulate to perturb the spin by an amount comparable to the intrinsic spin variance. Visualization of this effect on spin precession is shown in Fig. 3 for the BBOPM and hOPM. In the BBOPM, the OZS perturbs in first order only the F_x component, and thus neither the amplitude nor the phase of the spin precession, which is in the y - z plane. This makes the BBOPM MBA-evading.

In the hOPM, the same $GS_3\hat{z}$ noise term due to OZS affects all of the F_x , F_y , and F_z components in first order, and thus can change both the amplitude and phase of the spin precession. As a result, hOPM is not measurement backaction evading. This also explains why when using squeezed light—which reduces noise in S_2 and increases noise in S_3 , as these two components are constrained by an uncertainty relation—we observe increased low-frequency MBA noise in the measured signal with respect to the MBA contribution observed for coherent light (Fig. 2). We note that despite this increase, the overall low-frequency noise (MBA + PSN + SPN) remains no worse for the squeezed probing than for the coherent probing.

VII. CONCLUSIONS

We have studied the interplay of photon shot noise, spin projection noise, and measurement backaction in a high-performance multiparameter quantum sensor. With the help of squeezed probe light, we separate the various noise contributions and observe experimentally that squeezing the S_2 Stokes component improves the sensitivity to both slow and rapid changes in measured dc and rf fields. We also find evidence that S_3 antisqueezing, which necessarily

accompanies S_2 squeezing, increases measurement backaction noise, such that excessive squeezing would worsen the sensitivity to slow changes. These observations imply not a single quantum sensitivity limit, but rather a trade-off between enhancement of different parts of the sensitivity spectrum. Similarly, we observe bandwidth enhancement due to S_2 squeezing. A simple model shows that these trade-offs are the result of the multiparameter operation of the sensor and are not present in its single-parameter version. These observations are expected to apply to other continuously operating sensors, including both atomic and opto-mechanical instruments. The present experiment is, to our knowledge, the first in which these effects can be simultaneously observed.

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DATA AVAILABILITY

The data that support the findings of this study are available in Ref. [36].

APPENDIX: MEASUREMENT BACKACTION

We follow the model given in Ref. [17, supplement], in which the spin evolves as

$$\begin{aligned} \frac{d}{dt}\mathbf{F}(t) = & [-\gamma\mathbf{B}_{dc}(t) + GS_3(t)\hat{z}] \times \mathbf{F}(t) - \Gamma\mathbf{F}(t) \\ & + P(t)[\hat{z}F_{\max} - \mathbf{F}(t)] + \mathbf{N}_F(t), \end{aligned} \quad (\text{A1})$$

where $\mathbf{B}_{\text{dc}}$ is the dc magnetic field oriented along $\hat{\mathbf{B}}_{\text{dc}} \equiv \mathbf{B}_{\text{dc}}/|\mathbf{B}_{\text{dc}}|$, $GS_3\hat{z}$ is the OZS-induced effective field responsible for MBA, Γ is the relaxation rate, F_{max} is the maximum possible polarization, P is the optical pumping rate, and $\mathbf{N}_F$ is a stochastic term, which accounts for SPN.

The evolving spin $\mathbf{F}(t) = \mathbf{F}^{(0)}(t) + \alpha\mathbf{F}^{(1)}(t)$ includes a deterministic contribution $\mathbf{F}^{(0)}(t)$, which describes collective spin precession about $\mathbf{B}_{\text{dc}}$ when driven by optical pumping and subject to isotropic relaxation. We define the transverse component of $\mathbf{F}(t)$, i.e., the part in a plane orthogonal to $\mathbf{B}_{\text{dc}}$, as

$$\mathbf{F}_{\perp}(t) \equiv \mathbf{F}(t) - (\mathbf{F}(t) \cdot \hat{\mathbf{B}}_{\text{dc}})\hat{\mathbf{B}}_{\text{dc}}. \quad (\text{A2})$$

Analogously, the transverse part of the zeroth-order contribution is

$$\mathbf{F}_{\perp}^{(0)}(t) \equiv \mathbf{F}_{\perp}^{(0)}(t) - (\mathbf{F}^{(0)}(t) \cdot \hat{\mathbf{B}}_{\text{dc}})\hat{\mathbf{B}}_{\text{dc}}. \quad (\text{A3})$$

SPN, MBA, and fluctuations of B_{dc} contribute stochastic perturbations to $\mathbf{F}^{(1)}(t)$. In particular, MBA contributes an additive noise term proportional to $S_3(t)\hat{z} \times \mathbf{F}^{(0)}(t)$.

For the BBOPM, $\hat{\mathbf{B}}_{\text{dc}} = \hat{x}$ and $\mathbf{F}^{(0)}(t) = \mathbf{F}_{\perp}^{(0)}(t)$ is in the $y-z$ plane. Consequently, $S_3(t)\hat{z} \times \mathbf{F}^{(0)}(t)$ vanishes and there is zero MBA contribution to $\mathbf{F}_{\perp}^{(1)}(t)$. Rather, in first order the MBA is entirely in the F_x component, which, however, does not contribute to the signal S_2 . The BBOPM is thus backaction evading.

In the case of the hOPM, which for generality we consider with the B-field tipped by an angle ψ from the $\hat{x}$ axis, the spin precesses about the $\hat{\mathbf{B}}_{\text{dc}} = \hat{x} \cos \psi + \hat{z} \sin \psi$ direction. On resonance, $\omega_p = \omega_L$, with one brief pump pulse per cycle and with a high-quality-factor oscillation, i.e., with $\omega_L \gg \Gamma$, the unperturbed spin trajectory can be approximated as

$$\begin{aligned} \mathbf{F}^{(0)}(t) &\propto (-\hat{x} \sin \psi + \hat{z} \cos \psi) \cos \omega_L t + \hat{y} \sin \omega_L t \\ &\quad + (\hat{x} \cos \psi + \hat{z} \sin \psi) \tan \psi \end{aligned} \quad (\text{A4})$$

and thus

$$\hat{z} \times \mathbf{F}^{(0)}(t) \propto \hat{y}(1 - \cos \omega_L t) \sin \psi - \hat{x} \sin \omega_L t \quad (\text{A5})$$

$$\mathbf{F}_{\perp}^{(0)}(t) \propto (-\hat{x} \sin \psi + \hat{z} \cos \psi) \cos \omega_L t + \hat{y} \sin \omega_L t \quad (\text{A6})$$

$$\mathbf{F}^{(0)}(t) \times \hat{\mathbf{B}}_{\text{dc}} \propto (\hat{x} \sin \psi - \hat{z} \cos \psi) \sin \omega_L t + \hat{y} \cos \omega_L t \quad (\text{A7})$$

Because of the MBA contribution, the square magnitude $|\mathbf{F}_{\perp}(t)|^2$ and the angle $\theta_{\mathbf{F}_{\perp}}(t)$ of the precessing transverse spin are perturbed at rates

$$\begin{aligned} \frac{d}{dt} |\mathbf{F}_{\perp}(t)|^2 &\propto S_3(t) [\hat{z} \times \mathbf{F}^{(0)}(t)] \cdot \mathbf{F}_{\perp}^{(0)}(t) \\ &\propto S_3(t) \sin \omega_L t \sin \psi \end{aligned} \quad (\text{A8})$$

and

$$\begin{aligned} \frac{d}{dt} \theta_{\mathbf{F}_{\perp}}(t) &\propto S_3(t) [\hat{z} \times \mathbf{F}^{(0)}(t)] \cdot [\mathbf{F}^{(0)}(t) \times \hat{\mathbf{B}}_{\text{dc}}] \\ &\propto S_3(t) (1 - \cos \omega_L t) \sin \psi, \end{aligned} \quad (\text{A9})$$

respectively.

From Eqs. (A8) and (A9), we see that the amplitude and angle are both perturbed by $S_3(t)$, except at particular phases $\omega_L t$ of the precession cycle. Since $S_3(t)$ is delta-correlated, MBA noise imparted by $S_3(t)$ at one instant will not be canceled by noise imparted by $S_3(t)$ at other instants. Thus the hOPM accumulates measurement backaction in both components of $\mathbf{F}_{\perp}$. This MBA noise then manifests in both quadratures of the measured Stokes parameter $S_2(t)$, and thus in the low-frequency parts of both the dc and rf field measurements. The noise powers in both cases are proportional to $\sin^2 \psi$, offering a convenient “knob” by which to adjust the MBA effects. Only if $\psi = 0$ does the measurement become fully MBA-evading—at which point the OPM is only measuring the dc field; the response to rf fields vanishes. It is precisely the multi-parameter estimation capability that makes the sensor vulnerable to MBA.

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- [1] C. W. Helstrom, Quantum detection and estimation theory, *J. Stat. Phys.* **1**, 231 (1969).
 - [2] C. L. Degen, F. Reinhard, and P. Cappellaro, Quantum sensing, *Rev. Mod. Phys.* **89**, 035002 (2017).
 - [3] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Quantum metrology with nonclassical states of atomic ensembles, *Rev. Mod. Phys.* **90**, 035005 (2018).
 - [4] M. Szczykulska, T. Baumgratz, and A. Datta, Multi-parameter quantum metrology, *Adv. Phys.: X* **1**, 621 (2016).
 - [5] R. Demkowicz-Dobrzański, W. Górecki, and M. Guţă, Multi-parameter estimation beyond quantum Fisher information, *J. Phys. A Math. Theor.* **53**, 363001 (2020).
 - [6] J. Řehaček, Z. Hradil, B. Stoklasa, M. Paúr, J. Grover, A. Krzic, and L. L. Sánchez-Soto, Multiparameter quantum metrology of incoherent point sources: Towards realistic superresolution, *Phys. Rev. A* **96**, 062107 (2017).
 - [7] T. J. Proctor, P. A. Knott, and J. A. Dunningham, Multi-parameter estimation in networked quantum sensors, *Phys. Rev. Lett.* **120**, 080501 (2018).
 - [8] A. Carollo, B. Spagnolo, A. A. Dubkov, and D. Valenti, On quantumness in multi-parameter quantum estimation, *J. Stat. Mech. Theory Exp.* **2019**, 094010 (2019).
 - [9] J. Liu, H. Yuan, X.-M. Lu, and X. Wang, Quantum Fisher information matrix and multiparameter estimation, *J. Phys. A Math. Theor.* **53**, 023001 (2019).

- [10] W. Górecki and R. Demkowicz-Dobrzański, Multiparameter quantum metrology in the Heisenberg limit regime: Many-repetition scenario versus full optimization, *Phys. Rev. A* **106**, 012424 (2022).
- [11] G. Colangelo, F. M. Ciurana, L. C. Bianchet, R. J. Sewell, and M. W. Mitchell, Simultaneous tracking of spin angle and amplitude beyond classical limits, *Nature (London)* **543**, 525 (2017).
- [12] C. B. Møller, R. A. Thomas, G. Vasilakis, E. Zeuthen, Y. Tsaturyan, M. Balabas, K. Jensen, A. Schliesser, K. Hammerer, and E. S. Polzik, Quantum back-action-evading measurement of motion in a negative mass reference frame, *Nature (London)* **547**, 191 (2017).
- [13] E. Polino, M. Riva, M. Valeri, R. Silvestri, G. Corielli, A. Crespi, N. Spagnolo, R. Osellame, and F. Sciarrino, Experimental multiphase estimation on a chip, *Optica* **6**, 288 (2019).
- [14] J. Aasi *et al.*, Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light, *Nat. Photonics* **7**, 613 (2013).
- [15] D. Sheng, S. Li, N. Dural, and M. V. Romalis, Subfemtotesla scalar atomic magnetometry using multipass cells, *Phys. Rev. Lett.* **110**, 160802 (2013).
- [16] V. Braginsky, F. Khalili, and K. Thorne, *Quantum Measurement* (Cambridge University Press, Cambridge, England, 1995).
- [17] C. Troullinou, R. Jiménez-Martínez, J. Kong, V. G. Lucivero, and M. W. Mitchell, Squeezed-light enhancement and back-action evasion in a high sensitivity optically pumped magnetometer, *Phys. Rev. Lett.* **127**, 193601 (2021).
- [18] D. Ganapathy *et al.*, Broadband quantum enhancement of the LIGO detectors with frequency-dependent squeezing, *Phys. Rev. X* **13**, 041021 (2023).
- [19] L. Bai, X. Wen, Y. Yang, L. Zhang, J. He, Y. Wang, and J. Wang, Quantum-enhanced rubidium atomic magnetometer based on faraday rotation via 795 nm stokes operator squeezed light, *J. Opt.* **23**, 085202 (2021).
- [20] R. J. Sewell, M. Koschorreck, M. Napolitano, B. Dubost, N. Behbood, and M. W. Mitchell, Magnetic sensitivity beyond the projection noise limit by spin squeezing, *Phys. Rev. Lett.* **109**, 253605 (2012).
- [21] V. Shah, G. Vasilakis, and M. V. Romalis, High bandwidth atomic magnetometry with continuous quantum non-demolition measurements, *Phys. Rev. Lett.* **104**, 013601 (2010).
- [22] F. Martin Ciurana, G. Colangelo, L. Slodička, R. J. Sewell, and M. W. Mitchell, Entanglement-enhanced radio-frequency field detection and waveform sensing, *Phys. Rev. Lett.* **119**, 043603 (2017).
- [23] M. Lipka, A. Sierant, C. Troullinou, and M. W. Mitchell, Multiparameter quantum sensing and magnetic communication with a hybrid dc and rf optically pumped magnetometer, *Phys. Rev. Appl.* **21**, 034054 (2024).
- [24] J. Kitching, Chip-scale atomic devices, *Appl. Phys. Rev.* **5**, 031302 (2018).
- [25] M. Stefszky, F. vom Bruch, M. Santandrea, R. Ricken, V. Quiring, C. Eigner, H. Herrmann, and C. Silberhorn, Lithium niobate waveguide squeezer with integrated cavity length stabilisation for network applications, *Opt. Express* **31**, 34903 (2023).
- [26] T. Park, H. Stokowski, V. Ansari, S. Gyger, K. K. S. Multani, O. T. Celik, A. Y. Hwang, D. J. Dean, F. Mayor, T. P. McKenna, M. M. Fejer, and A. Safavi-Naeini, Single-mode squeezed-light generation and tomography with an integrated optical parametric oscillator, *Sci. Adv.* **10**, ead11814 (2024).
- [27] W. E. Bell and A. L. Bloom, Optically driven spin precession, *Phys. Rev. Lett.* **6**, 280 (1961).
- [28] A. Predojević, Z. Zhai, J. M. Caballero, and M. W. Mitchell, Rubidium resonant squeezed light from a diode-pumped optical-parametric oscillator, *Phys. Rev. A* **78**, 063820 (2008).
- [29] C. Troullinou, V. G. Lucivero, and M. W. Mitchell, Quantum-enhanced magnetometry at optimal number density, *Phys. Rev. Lett.* **131**, 133602 (2023).
- [30] J. Kong, V. G. Lucivero, R. Jiménez-Martínez, and M. W. Mitchell, Long-term laser frequency stabilization using fiber interferometers, *Rev. Sci. Instrum.* **86**, 073104 (2015).
- [31] J. Kong, R. Jimenez-Martinez, C. Troullinou, V. G. Lucivero, G. Toth, and M. W. Mitchell, Measurement-induced, spatially-extended entanglement in a hot, strongly-interacting atomic system, *Nat. Commun.* **11**, 2415 (2020).
- [32] E. Aleksandrov and V. Zapasskii, Magnetic resonance in the faraday-rotation noise spectrum, *Zh. Eksp. Teor. Fiz.* **81**, 132 (1981).
- [33] G. M. Müller, M. Oestreich, M. Römer, and J. Hübner, Semiconductor spin noise spectroscopy: Fundamentals, accomplishments, and challenges, *Phys. E* **43**, 569 (2010).
- [34] V. G. Lucivero, A. Dimic, J. Kong, R. Jiménez-Martínez, and M. W. Mitchell, Sensitivity, quantum limits, and quantum enhancement of noise spectroscopies, *Phys. Rev. A* **95**, 041803(R) (2017).
- [35] W. Happer and B. S. Mathur, Effective operator formalism in optical pumping, *Phys. Rev.* **163**, 12 (1967).
- [36] A. Sierant, D. M. Avalos, S. Tabares, and M. Mitchell, Replication data for: Quantum noise in a squeezed-light-enhanced multiparameter quantum sensor (2025).