

Quantifying the amplitudes of ultrafast magnetization fluctuations in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ using femtosecond noise-correlation spectroscopy

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Spin fluctuations are an important issue for the design and operation of future spintronic devices. Femtosecond noise-correlation spectroscopy (FemNoC) was recently applied to detect ultrafast magnetization fluctuations. FemNoC gives direct access to the spontaneous fluctuations of magnetization in magnetically ordered materials. In FemNoC experiments, the magnetic fluctuations are imprinted on the polarization state of two independent femtosecond probe pulses upon transmission through a magnetic sample. Using a subharmonic demodulation scheme, the cross-correlation of the signals from both pulse trains is calculated. Here, we quantitatively link the FemNoC output signal to an optical polarization rotation, and then in turn to the magnitude of the inherent spin fluctuations. To this end, three different calibration protocols are presented and compared in accuracy. Ultimately, we quantitatively determine both the variance of optical polarization noise in rad^2 and that of the ultrafast magnetization fluctuations in $(\text{A/m})^2$.

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I. INTRODUCTION

Macroscopic noise in condensed-matter systems often originates from microscopic fluctuations [1]. For example, the transport of charge by quantized units produces large-scale electronic shot noise [2]. Also, fluctuations of elementary spins cause macroscopic magnetization noise, as seen, for example, in paramagnets [3–6]. Studying such phenomena provides valuable insights into the functionality of physical systems. In particular, the dynamical noise properties reveal the timescales of elementary excitations. Optical spin-noise spectroscopy (SNS) [3–13] enables such investigations. In SNS, spin fluctuations are transferred to the polarization state of a laser via the Faraday effect, which may be analyzed in the megahertz to gigahertz range [6,13]. Physical information, such as the paramagnetic Larmor frequency, spin-relaxation times T_1 and T_2 [3], homogeneous and inhomogeneous linewidths

in quantum dot ensembles [12], and spatially resolved doping concentrations in semiconductors [9], may be accessed by such measurements.

Recently, there has been growing interest in noise correlations at terahertz frequencies [14,15]. For example, spin excitations in antiferromagnets fall in this range. Due to their high-frequency magnons, antiferromagnets are promising materials for future ultrafast spintronic devices. To study spin fluctuations at such high frequencies, femtosecond noise-correlation spectroscopy (FemNoC) [16–18] based on a subharmonic detection scheme was recently developed. FemNoC uses two ultrashort probe pulses, which are transmitted through the magnetic sample with variable time delays. Upon transmission, transient magnetization noise is translated into polarization noise by the Faraday effect. This Faraday-rotation (FR) noise is then analyzed in two separate detection branches, subharmonically demodulated and finally cross-correlated in a lock-in amplifier.

However, directly linking the correlated lock-in output to quantifiable FR noise is challenging due to the stochastic nature of the measurement scheme. Thus far, FemNoC has only enabled qualitative noise evaluation. In this work, we present three calibration methods to quantify the lock-in output as effective FR noise. We compare their accuracy and extract a combined scaling factor to calibrate the lock-in output in units of rad^2 . Ultimately, this procedure allows us to quantify the magnitude of ultrafast magnetization

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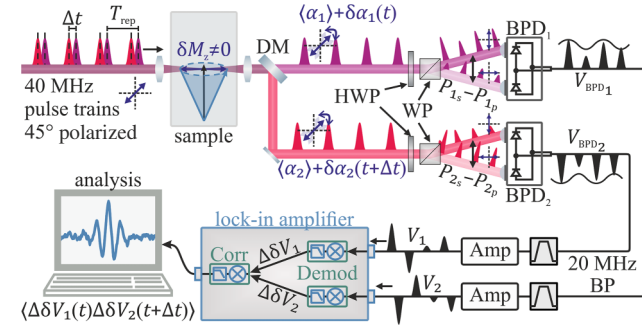


FIG. 1. Overview of the experimental setup and electronic data processing. Two femtosecond laser pulse trains with marginally different wavelengths [center wavelengths of 767 nm (purple) and 775 nm (red)] and variable time delay, Δt , experience a polarization rotation, $\delta\alpha_{1,2}$, proportional to out-of-plane spin fluctuations, δM_z , in addition to their initial polarization angle of $\langle\alpha_{1,2}\rangle = 45^\circ$ (with respect to the optical table). $\delta\alpha_{1,2}$ are measured in separate detection branches, each consisting of a half-wave plate (HWP), a Wollaston prism (WP), and a balanced photodetector (BPD). WP splits the light into *s*- and *p*-polarized components (blue arrows) with optical powers $P_{1,2s}$ and $P_{1,2p}$, respectively. BPD output voltages, $V_{\text{BPD},1,2}$, are proportional to $P_{1,2s} - P_{1,2p}$. After amplification and extraction of the pulse-to-pulse voltage fluctuations, $\Delta\delta V_{1,2}$, from each branch, the cross-correlation function, $\langle\Delta\delta V_1(t)\Delta\delta V_2(t+\Delta t)\rangle$, is calculated in real time. DM, dichroic mirror; BP, electronic bandpass filter; Amp, amplifier; Demod, demodulator; Corr, real-time correlation.

fluctuations in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ using its magneto-optic constant.

II. METHODS

The experimental scheme is depicted in Fig. 1. Two 40-MHz probe-pulse trains with variable time delay, Δt , are focused onto a magnetically ordered sample using a microscope objective lens (20 $\times$ magnification). They consist of femtosecond laser pulses with 300-fs duration and wavelengths centered around 767 and 775 nm, respectively. They are generated by spectrally and spatially separating the frequency-doubled output of a mode-locked Er-fiber laser (fundamental wavelength, 1.55 μm ; pulse energy, 5 nJ; repetition rate, 40 MHz), using a dichroic mirror. Furthermore, they are linearly polarized under an angle of 45° with respect to the optical table.

Upon transmission through the magnetic sample, the transient out-of-plane (OOP) magnetization noise, $\delta M_z(t)$, along the laser propagation direction induces polarization noise, $\delta\alpha_{1,2}(t)$, in probe beams 1 and 2 via the Faraday effect. This results in time-varying polarization:

$$\alpha_{1,2}(t) = \langle\alpha_{1,2}\rangle + \delta\alpha_{1,2}(t). \quad (1)$$

Here, $\langle\alpha_{1,2}\rangle$ is the mean polarization, which is periodic with the 40-MHz repetition rate, f_{rep} , of the femtosecond pulse train. The beams are guided into two separate polarimetric detection branches using a dichroic mirror. Each branch contains a HWP, a WP, and BPDs. The WP separates the probe beams into *s*- and *p*-polarized components, which are subsequently focused on the BPDs. Here, an output voltage proportional to the optical power difference, $P_{1,2s} - P_{1,2p}$, of *s*- and *p*-polarized components; the gain (G) of the photoamplifier; and the wavelength- (λ) dependent responsivity [$R(\lambda)$] is generated [19]. For high-frequency signals, the output voltage also needs to be scaled with the frequency- (f) and gain- (G) dependent spectral response, $s(G, f)$, of the photodetector. This yields the final output:

$$V_{\text{BPD},1,2} = R(\lambda)s(G, f) G \times (P_{1,2s} - P_{1,2p}). \quad (2)$$

The power difference depends on the polarization angle, $\alpha_{1,2}$, and mean power, P_0 , of the probe [20]:

$$\begin{aligned} (P_{1,2s} - P_{1,2p}) &= P_0(1 - 2\cos^2(\alpha_{1,2})) \\ &= P_0(1 - 2\cos^2(\langle\alpha_{1,2}\rangle + \delta\alpha_{1,2})). \end{aligned} \quad (3)$$

Combining Eqs. (2) and (3) gives

$$V_{\text{BPD},1,2} = R(\lambda)s(G, f)G \times P_0(1 - 2\cos^2(\langle\alpha_{1,2}\rangle + \delta\alpha_{1,2})). \quad (4)$$

It shows that the BPD output reflects both the mean polarization, $\langle\alpha\rangle$, and fluctuations, $\delta\alpha$. Note that $V_{\text{BPD},1,2}$ is dominated by $\langle\alpha_{1,2}\rangle$, which is periodic with repetition rate $f_{\text{rep}} = 40$ MHz, whereas the noise is mostly contained in the first subharmonic frequency, $f_{\text{rep}}/2 = 20$ MHz (pulse-to-pulse fluctuations) [18,21]. The HWPs compensate for any additional static polarization components, $\langle\alpha_{1,2}\rangle$, ensuring that $\langle\alpha_{1,2}\rangle \approx 45^\circ$. If this condition is fulfilled and fluctuations are small ($\delta\alpha_{1,2} \approx 0$), the optical power difference simplifies to [18]

$$(P_{1,2s} - P_{1,2p}) = 2P_0\delta\alpha_{1,2} \frac{1}{\text{rad}}. \quad (5)$$

Note that the dimensionality factor, $1/\text{rad}$, appears due to the small-angle approximation. This factor is omitted in the following. Inserting Eq. (5) into Eq. (4) then yields the detector output:

$$V_{\text{BPD},1,2} \approx 2P_0R(\lambda)s(G, f)G \times \delta\alpha_{1,2}. \quad (6)$$

Therefore, analyzing $V_{\text{BPD},1,2}$ grants direct access to polarization fluctuations. In practice, a dominant 40-MHz component persists. We utilize a 20-MHz BP and Amp to

enhance the subharmonic pulse-to-pulse fluctuation, and at the same time, suppress the fundamental frequency. This enables full use of the lock-in amplifier's dynamic range, which is defined by its digitization depth.

Next, filtered voltages V_1 and V_2 are fed into demodulation channels of the lock-in amplifier (UHFLI, Zurich Instruments [22]) for subharmonic demodulation [17,18]. Here, the 20-MHz pulse-to-pulse fluctuations, $\Delta\delta V_{1,2}$, are extracted from the low-frequency and fundamental laser components. Subsequently, $\Delta\delta V_1$ and $\Delta\delta V_2$ are multiplied and averaged in real time. This yields the correlated noise, $\langle\Delta\delta V_1(t) \times \Delta\delta V_2(t + \Delta t)\rangle$, as the final output of the lock-in amplifier (see inset in Fig. 1). $\langle\Delta\delta V_1(t) \times \Delta\delta V_2(t + \Delta t)\rangle$ is proportional to the correlated FR noise, $\langle\Delta\delta\alpha_1(t) \times \Delta\delta\alpha_2(t + \Delta t)\rangle$, and the ultrafast magnetization fluctuation autocorrelation, $\langle\delta M_z(t) \times \delta M_z(t + \Delta t)\rangle$, along the laser propagation direction:

$$\begin{aligned} \langle\Delta\delta V_1(t) \times \Delta\delta V_2(t + \Delta t)\rangle \\ = C_\alpha \times \langle\Delta\delta\alpha_1(t) \times \Delta\delta\alpha_2(t + \Delta t)\rangle, \\ = C_\alpha \times C_M \times \langle\delta M_z(t) \times \delta M_z(t + \Delta t)\rangle. \end{aligned} \quad (7)$$

Here, C_α and C_M are proportionality constants. Note that throughout this article, $\langle\Delta\delta V_1(t) \times \Delta\delta V_2(t + \Delta t)\rangle$ is given in units of V instead of V^2 due to an internal scaling factor of 1/V applied in the lock-in amplifier [22].

The mean value of polarization rotation, $\langle\alpha\rangle$, and with that the mean OOP magnetization, M_z , can easily be determined with simple polarimetric measurement schemes [4]. In contrast, the fluctuations, $\delta\alpha$, are orders of magnitude smaller and governed by different statistics. This fact significantly complicates their quantitative analysis. Nevertheless, we demonstrate three different protocols to calibrate the sample-induced FR noise by calculation of the proportionality factor, C_α . Subsequently, the magneto-optic constant of $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ at the probing wavelength is determined to obtain C_M . With this information, we determine the variance of the spontaneous spin fluctuations in absolute units (A/m)².

III. RESULTS AND DISCUSSION

A. Faraday-rotation noise calibration schemes

The first calibration method involves analyzing each signal processing step in the detection chain individually. The second method compares the correlated noise to the optical shot noise. In the third approach, an acousto-optic modulator (AOM) is used to introduce amplitude modulation of the pulses at the subharmonic frequency, which is compared to the FR noise.

1. Calibration via transfer functions

In this method, we analyze each step of the signal processing chain to determine the linear proportionality factors, C_i , that relate the input and output for each detection stage, i . Using the transfer functions of each device, the total calibration factor, $C_{\alpha, \text{TF}}$, is determined as

$$\langle\Delta\delta V_1 \times \Delta\delta V_2\rangle = \underbrace{C_1^2 C_2^2 C_3}_{C_{\alpha, \text{TF}}} \times \langle\Delta\delta\alpha_1 \times \Delta\delta\alpha_2\rangle. \quad (8)$$

We divide the setup into three key signal processing steps [see Fig. 2(a)]:

1. Step 1 (area I): Conversion of pulse-to-pulse polarization noise, $\delta\alpha_{1,2}$, into the fluctuation of power difference between s - and p -polarized components ($\delta P_{1,2s} - \delta P_{1,2p}$) using a WP. The first transfer function, C_1 , relating these

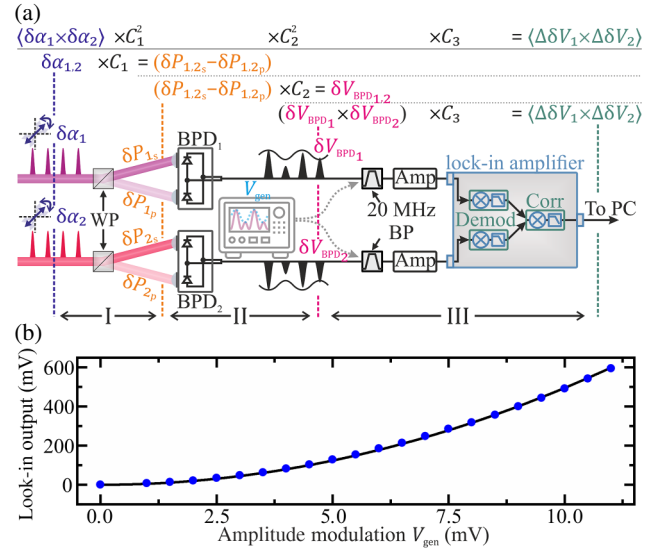


FIG. 2. Calibration of the detection chain using transfer functions. (a) Schematic of the calibration process. Area I, after transmission through the magnetic sample, femtosecond probe pulses exhibit polarization fluctuations, $\delta\alpha_{1,2}$, relative to their mean polarization angle, $\langle\alpha_{1,2}\rangle = 45^\circ$, with respect to the optical table. WP splits the beams into their s - and p -polarized components. Area II, fluctuations in the optical power are analyzed in BPDs, which output the corresponding voltage fluctuations, $\delta V_{\text{BPD}1,2}$. Area III, $\delta V_{\text{BPD}1,2}$ are first bandpass filtered and amplified before subharmonic demodulation (Demod) in a lock-in amplifier. Subsequent correlation analysis (Corr) yields the correlated voltage fluctuations $\langle\Delta\delta V_1 \times \Delta\delta V_2\rangle$. Proportionality factor, C_3 , arising in this signal processing step is determined using a function generator (gray box), which produces 40-MHz voltage, V_{gen} , with 20-MHz modulation. (b) Measured correlated lock-in output $\langle\Delta\delta V_1 \times \Delta\delta V_2\rangle$ as a function of the 20-MHz modulation amplitude, V_{gen} . Quadratic fit, $\langle\Delta\delta V_1 \times \Delta\delta V_2\rangle = C_3 \times V_{\text{gen}}^2$ reveals $C_3 = 4.95 \times 10^3$ 1/V.

two quantities is directly obtained from Eq. (5) and yields

$$C_1 = 2P_0. \quad (9)$$

2. Step 2 (area II): Optical detection, where the power fluctuations $(\delta P_{1,2s} - \delta P_{1,2p})$ are converted into voltage fluctuations, $\delta V_{\text{BPD}_{1,2}}$, by BPDs. This step is summarized in the second transfer function [see Eq. (4)]:

$$C_2 = R(\lambda)s(G,f)G, \quad (10)$$

where $R(\lambda)$, $s(G,f)$, and G are obtained from the BPD specifications [19], or alternatively, $R(\lambda) \times s(G,f)$ can be measured experimentally, e.g., by measuring the shot noise from a continuous-wave laser shone onto the detectors.

3. Step 3 (area III): Filtering and amplifying the detector outputs, $\delta V_{\text{BPD}_{1,2}}$, followed by subharmonic demodulation and correlation in a lock-in amplifier, yield the correlated pulse-to-pulse voltage fluctuations, $\langle \Delta \delta V_1 \times \Delta \delta V_2 \rangle$. The final calibration function, C_3 , describing this detection step is determined using a signal generator. This mimics the BPD outputs by producing a 40-MHz voltage with a 20-MHz modulation as an input for both lock-in channels. The correlated lock-in output is measured as a function of the modulation amplitude. Afterwards, C_3 is determined by applying the following fitting function to the data [Fig. 2(b)]:

$$\langle \Delta \delta V_1 \times \Delta \delta V_2 \rangle = C_3 \times V_{\text{gen}}^2. \quad (11)$$

Inserting experimental values (see Appendix E, Table I) and assuming both detection arms to have identical characteristics, we calculate the transfer-function calibration factor:

$$C_{\alpha, \text{TF}} = (4.8 \pm 1.6) \frac{\mu\text{V}}{(\mu\text{rad})^2}. \quad (12)$$

Details on the uncertainty analysis are provided in Appendix E.

2. Calibration via comparison to the optical shot noise

In this method, we calibrate the spin noise by comparing it to the level of optical shot noise. We determine the optical shot-noise contribution, $\langle (\Delta \delta V)^2 \rangle_{\text{SN}}$, to the total voltage noise in each detection branch. Afterwards, we relate it to the shot-noise-induced fluctuations in the optical power difference of *s*- and *p*-polarized components, $\langle (\delta P_{1,2s} - \delta P_{1,2p})^2 \rangle$. From Appendix A, Eq. (A9), this is found to be identical to the shot-noise level $\langle (\delta P)^2 \rangle_{\text{SN}}$ of a single beam with optical power P_0 :

$$\langle (\delta P_{1,2s} - \delta P_{1,2p})^2 \rangle = \langle (\delta P)^2 \rangle_{\text{SN}} = 2h\nu P_0 \Delta f. \quad (13)$$

Here, h is Planck's constant, ν is the photon frequency, and Δf is the noise bandwidth.

Now, we calculate $\langle (\delta \alpha)^2 \rangle_{\text{SN}}$. We define this as the effective polarization noise, which would produce equivalent power difference fluctuations as the optical shot noise. The calculation follows Malus' law [20] for the case of perfectly balanced photodetectors and small fluctuations [see Eq. (5)]:

$$\langle (\delta P_{1,2s} - \delta P_{1,2p})^2 \rangle = 4P_0^2 \langle (\delta \alpha)^2 \rangle_{\text{SN}}. \quad (14)$$

The voltage noise and polarization noise are linearly related:

$$\langle (\Delta \delta V)^2 \rangle_{\text{SN}} = C_{\alpha, \text{SN}} \times 2 \langle (\delta \alpha)^2 \rangle_{\text{SN}}, \quad (15)$$

with the proportionality factor $C_{\alpha, \text{SN}}$. Here, the factor of 2 arises because the pulse-to-pulse polarization fluctuation is twice the variance of $\langle (\delta \alpha)^2 \rangle$ [see Eq. (B2)]:

$$\langle (\Delta \delta \alpha)^2 \rangle = 2 \langle (\delta \alpha)^2 \rangle. \quad (16)$$

Inserting Eqs. (13) and (14) into Eq. (15) reveals the shot-noise proportionality constant:

$$C_{\alpha, \text{SN}} = \frac{\langle (\Delta \delta V)^2 \rangle_{\text{SN}}}{2 \langle (\delta \alpha)^2 \rangle_{\text{SN}}} = \frac{\langle (\Delta \delta V)^2 \rangle_{\text{SN}}}{h\nu \Delta f} \times P_0. \quad (17)$$

To determine $\langle (\Delta \delta V)^2 \rangle_{\text{SN}}$, we measure $\langle (\Delta \delta V_1 \pm \Delta \delta V_2)^2 \rangle$ as a function of the time delay, Δt , where

$$\begin{aligned} \langle (\Delta \delta V_1 \pm \Delta \delta V_2)^2 \rangle &= \langle (\Delta \delta V_1)^2 \rangle \\ &+ \langle (\Delta \delta V_2)^2 \rangle \pm 2 \langle \Delta \delta V_1 \times \Delta \delta V_2 \rangle. \end{aligned} \quad (18)$$

This expression includes both the correlated noise, $\langle \Delta \delta V_1 \times \Delta \delta V_2 \rangle$, between the detection branches and uncorrelated noise in each branch, $\langle (\Delta \delta V_1)^2 \rangle$ and $\langle (\Delta \delta V_2)^2 \rangle$. We assume the noise in each branch $\langle (\Delta \delta V_{1,2})^2 \rangle$ is dominated by three contributions: optical shot noise, $\langle (\Delta \delta V_{1,2})^2 \rangle_{\text{SN}} = 2C_{\alpha, \text{SN}} \langle (\delta \alpha_{1,2})^2 \rangle_{\text{SN}}$; dark noise of the electrical detection chain, $\langle (\Delta \delta V_{1,2})^2 \rangle_{\text{dark}}$; and FR-induced voltage noise, $\langle (\Delta \delta V_{1,2})^2 \rangle_{\text{FR}} \propto 2C_{\alpha, \text{SN}} \langle (\delta \alpha_{1,2})^2 \rangle_{\text{FR}}$. Substituting these into Eq. (18), we get

$$\begin{aligned} \langle (\Delta \delta V_1 \pm \Delta \delta V_2)^2 \rangle &= \langle (\Delta \delta V)^2 \rangle_{\text{SN}} + \langle (\Delta \delta V)^2 \rangle_{\text{dark}} \\ &+ \langle (\Delta \delta V)^2 \rangle_{\text{FR}} \pm 2 \langle \Delta \delta V_1 \times \Delta \delta V_2 \rangle_{\text{FR}}. \end{aligned} \quad (19)$$

Here, we defined $\langle (\Delta \delta V)^2 \rangle_{\text{SN}} \stackrel{\text{def}}{=} \langle (\Delta \delta V_1)^2 \rangle_{\text{SN}} + \langle (\Delta \delta V_2)^2 \rangle_{\text{SN}}$, $\langle (\Delta \delta V)^2 \rangle_{\text{dark}} \stackrel{\text{def}}{=} \langle (\Delta \delta V_1)^2 \rangle_{\text{dark}} + \langle (\Delta \delta V_2)^2 \rangle_{\text{dark}}$, and $\langle (\Delta \delta V)^2 \rangle_{\text{FR}} \stackrel{\text{def}}{=} \langle (\Delta \delta V_1)^2 \rangle_{\text{FR}} + \langle (\Delta \delta V_2)^2 \rangle_{\text{FR}}$. Furthermore, we assume that both the dark noise and shot noise, as well as their cross products, are uncorrelated. Note that the voltage noise correlation, $\langle \Delta \delta V_1 \times \Delta \delta V_2 \rangle_{\text{FR}} \propto$

TABLE I. Experimental values and uncertainties of calibration via transfer-function method.

Name	Symbol	Value	Method of estimation	Uncertainty	Method of error determination
Optical probe power	P_0	1.09 mW	Optical power meter	0.05 mW	Estimated
Transfer function 1	C_1	2.2 mW	Calculated, $C_1 = 2P_0$	0.1 mW	Combined error
Responsivity	$R(\lambda = 771 \text{ nm})$	0.53 A/W	Specification sheet of Thorlabs BPD 450A-AC [19]	0.08 A/W	Estimated
Amplitude frequency response @ $G = 10^5 \text{ V/A}$; $f = 20 \text{ MHz}$	$s(G, f)$	$-11.37 \text{ dB} = 0.27 \text{ A/W}$	Specification sheet of Thorlabs BPD 450A-AC [19]	$1.5 \text{ dB} = 0.02 \text{ A/W}$	Estimated
Transimpedance gain	G	10^5 V/A	Specification sheet of Thorlabs BPD 450A-AC [19]	10^3 V/A	Estimated
Transfer function 2	C_2	$1.4 \times 10^4 \text{ V/W}$	Calculated, $C_2 = R(\lambda) \times s(G, f) \times G$	$0.3 \times 10^4 \text{ V/W}$	Combined error
Transfer function 3	C_3	$4.95 \times 10^3 \text{ 1/V}$	Fit	$0.05 \times 10^3 \text{ 1/V}$	95% error bounds of fit
Calibration factor – transfer function	$C_{\alpha, \text{TF}}$	$4.8 \text{ } \mu\text{V}/(\mu\text{rad})^2$	Calculated, $C_{\alpha, \text{TF}} = C_1^2 C_2^2 C_3$	$1.6 \text{ } \mu\text{V}/(\mu\text{rad})^2$	Combined error

$\langle \Delta\delta\alpha_1 \times \Delta\delta\alpha_2 \rangle_{\text{FR}}$, is the relevant signal measured in our FemNoC experiment.

To quantify the components given in Eq. (19), we first measure $\langle (\Delta\delta V_1 \pm \Delta\delta V_2)^2 \rangle$ with the laser beams blocked and obtain the dark noise level, $\langle (\Delta\delta V)^2 \rangle_{\text{dark}} = 5.1 \text{ mV}$ (Fig. 3). In a next step, we measure the same quantity without blocking the lasers as a function of Δt . Now, an extremum around $\Delta t = 0$ with an amplitude of approximately $11 \text{ } \mu\text{V}$ appears (top panel, Fig. 3). We attribute this to correlated FR noise due to its characteristic time dependence [17]. Employing the approximation $\langle (\Delta\delta V)^2 \rangle_{\text{FR}} = 2\langle (\Delta\delta V_{1,2})^2 \rangle_{\text{FR}} = 2\langle \Delta\delta V_1 \times \Delta\delta V_2(\Delta t = 0) \rangle_{\text{FR}}$, we now calculate the shot-noise level, $\langle (\Delta\delta V)^2 \rangle_{\text{SN}} = 4.57 \text{ mV}$, with the results obtained above.

Finally, inserting the experimental values (Appendix E, Table II), we find the shot-noise calibration factor:

$$C_{\alpha, \text{SN}} = (4.8 \pm 1.2) \frac{\mu\text{V}}{(\mu\text{rad})^2}. \quad (20)$$

3. Calibration via quantifiable amplitude noise introduced using an acousto-optic modulator

In this third calibration method, we replace the magnetic sample with a free-space AOM to artificially introduce a subharmonic ($f_{\text{rep}}/2 = 20 \text{ MHz}$) amplitude modulation on the probe beams [Fig. 4(a)]. This modulation is linked

to an equivalent FR noise that would induce equivalent optical power differences after the Wollaston prism. The probe beam consists of a fundamental frequency component, $f_{\text{rep}} = 40 \text{ MHz}$, with mean optical power P_0 and the 20-MHz amplitude modulation with optical power P_{20} . Both components induce voltages in the BPDs during polarimetric detection. According to Eq. (6), the voltage noise of the 20-MHz component relates to the optical power and voltage fluctuations at the same frequency. In this case, the voltage noise now depends on $\langle \alpha \rangle$ instead of the polarization fluctuations, $\delta\alpha$, due to amplitude modulation, which equally affects s - and p -polarized components:

$$\begin{aligned} \left\langle V_{\text{BPD}}^2 \left(\frac{f_{\text{rep}}}{2} \right) \right\rangle &= s^2(G, f) G^2 \times (P_{20s} - P_{20p})^2 \\ &\approx 4s^2(G, f) G^2 \times P_{20}^2 \langle \alpha \rangle^2. \end{aligned} \quad (21)$$

We now aim to link this to effective FR noise that produces equivalent subharmonic voltage noise as the amplitude modulation. Note that in this calibration method, the shot noise is much smaller than the AOM-induced amplitude modulation and is thus neglected. Again, using Eq. (6), the voltage noise from the effective FR noise is

$$\left\langle V_{\text{BPD}}^2 \left(\frac{f_{\text{rep}}}{2} \right) \right\rangle = 4s^2(G, f) G^2 \times P_0^2 \langle (\delta\alpha)^2 \rangle. \quad (22)$$

TABLE II. Experimental values and uncertainties of calibration via optical shot noise.

Name	Symbol	Value	Method of estimation	Uncertainty	Method of error determination
Optical probe power	P_0	1.09 mW	Optical power meter	0.05 mW	Estimated
Centre wavelength	λ	771 nm	Optical spectrum analyzer, mean of probe pulses	5 nm	Estimated
Photon energy	$h\nu$	2.58×10^{-19} J	Calculated, $h\nu = \frac{hc}{\lambda}$	0.02×10^{-19} J	Combined error
Effective bandwidth of el. bandpass filter	Δf	4 MHz	Specification sheet of Mini-Circuits BBP-21.4+ [31]	1 MHz	Estimated
Total noise level	$\langle(\Delta\delta V)^2\rangle_{\text{tot}}$	9.7×10^{-3} V	Calculated from slope-corrected curves [see Figs. 3(b) and 8]	0.1×10^{-3} V	Estimated
Dark noise level	$\langle(\Delta\delta V)^2\rangle_{\text{dark}}$	5.1×10^{-3} V		0.1×10^{-3} V	Estimated
FR noise correlation amplitude	$\langle\Delta\delta V_1 \times \Delta\delta V_2(\Delta t = 0)\rangle_{\text{FR}}$	1.10×10^{-5} V	Mean($\text{Max}(\langle(\Delta\delta V_1 \pm \Delta\delta V_2)^2\rangle_{\text{smooth}} - \langle\Delta\delta V^2\rangle_{\text{tot}})$)	0.06×10^{-5} V	Estimated
FR noise of detection channels 1 and 2	$\langle(\Delta\delta V_{1,2})^2\rangle_{\text{FR}}$	2.19×10^{-5} V	$\langle\Delta\delta V^2\rangle_{\text{FR}} = 2\langle\Delta\delta V_1 \times \Delta\delta V_2(\Delta t = 0)\rangle_{\text{FR}}$	0.11×10^{-5} V	Combined error
Shot-noise level	$\langle(\Delta\delta V)^2\rangle_{\text{SN}}$	4.57×10^{-3} V	$\langle\Delta\delta V^2\rangle_{\text{SN}} = \langle\Delta\delta V^2\rangle_{\text{tot}} - \langle\Delta\delta V^2\rangle_{\text{dark}} - \langle\Delta\delta V_{1,2}^2\rangle_{\text{FR}}$	0.14×10^{-3} V	Combined error
Calibration factor – shot noise	$C_{\alpha,\text{SN}}$	$4.8 \mu\text{V}/(\mu\text{rad})^2$	$C_{\alpha,\text{SN}} = \frac{\langle\Delta\delta V^2\rangle_{\text{SN}}}{h\nu\Delta f} \times \frac{P_0}{\text{rad}^2}$	$1.2 \mu\text{V}/(\mu\text{rad})^2$	Combined error

Inserting Eq. (21) into Eq. (22) gives

$$\langle(\delta\alpha)^2\rangle = \frac{P_{20}^2}{P_0^2} \langle\alpha\rangle^2. \quad (23)$$

Additionally, in this configuration, the correlation function is proportional to $\langle\alpha\rangle^2$ with proportionality factor D :

$$\langle\Delta\delta V_1 \Delta\delta V_2\rangle = D\langle\alpha\rangle^2 = \frac{D}{2} \frac{P_0^2}{P_{20}^2} \langle\Delta\delta\alpha_1 \Delta\delta\alpha_2\rangle. \quad (24)$$

Assuming the effective FR noise in each detection branch is approximately equal, and using Eq. (16), the calibration factor, $C_{\alpha,\text{AOM}}$, becomes

$$C_{\alpha,\text{AOM}} = \frac{D}{2} \frac{P_0^2}{P_{20}^2}. \quad (25)$$

To determine the power ratio P_0/P_{20} , we measure the BPD output at both the fundamental and subharmonic

frequencies using a spectrum analyzer [Fig. 4(b)]:

$$\frac{\langle V_{\text{BPD}}^2(f_{\text{rep}}) \rangle}{\langle V_{\text{BPD}}^2(f_{\text{rep}}/2) \rangle} = \frac{P_0^2}{P_{20}^2}, \quad (26)$$

and find $\langle V_{\text{BPD}}^2(40 \text{ MHz}) \rangle / \langle V_{\text{BPD}}^2(20 \text{ MHz}) \rangle = 0.012$ (Appendix D). Inserting Eq. (26) into Eq. (24) gives the final calibration relationship:

$$\langle\Delta\delta V_1 \Delta\delta V_2\rangle = \frac{D}{2} \underbrace{\frac{\langle V_{\text{BPD}}^2(f_{\text{rep}}) \rangle}{\langle V_{\text{BPD}}^2(f_{\text{rep}}/2) \rangle}}_{C_{\alpha,\text{AOM}}} \langle\Delta\delta\alpha_1 \Delta\delta\alpha_2\rangle. \quad (27)$$

Next, we measure $\langle\Delta\delta V_1 \Delta\delta V_2\rangle$ as a function of $\langle\alpha_1\rangle \langle\alpha_2\rangle$. Fitting the results with a polynomial function of the form $f(x) = cx + Dx^2$ reveals $D = (0.1024 \pm 0.003) \mu\text{V}/(\mu\text{rad})^2$ (Appendix D, Suppl. Fig. 4).

Finally, inserting the experimental values (Appendix E, Table III), we calculate

$$C_{\alpha,\text{AOM}} = (4.2 \pm 1.3) \frac{\mu\text{V}}{(\mu\text{rad})^2}. \quad (28)$$

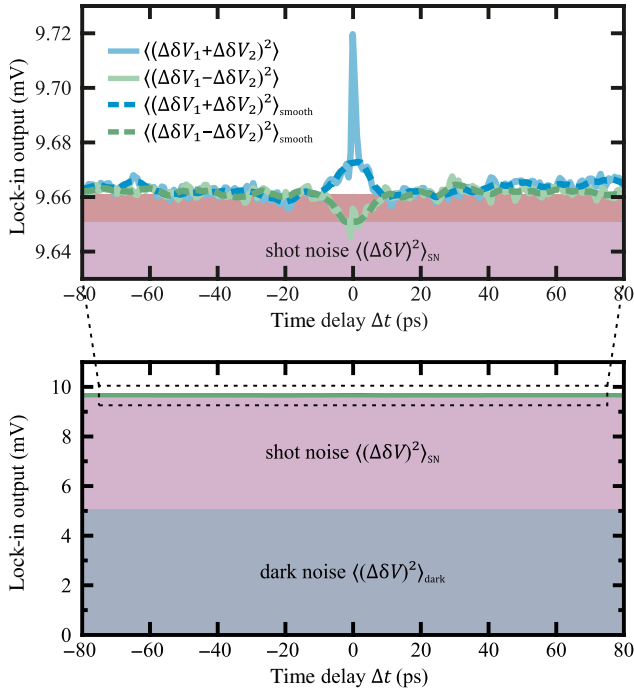


FIG. 3. Calibration based on optical shot-noise evaluation. Slope-corrected (solid lines) and smoothed (dotted lines) averages of the squared sum (blue) and difference (green) of pulse-to-pulse voltage fluctuations are plotted as a function of time delay, Δt . Sharp peak at $\Delta t = 0$ appears in the nonsmoothed curves, likely due to spectral leakage of the probes. To estimate the Faraday noise amplitude, $\Delta t = 0$ values from the smoothed curves are used. Lock-in output is primarily dominated by shot noise, $\langle(\Delta\delta V)^2\rangle_{\text{SN}}$ (purple area), and dark noise, $\langle(\Delta\delta V)^2\rangle_{\text{dark}}$ (dark-blue area), while the much smaller Faraday noise contributions, $\langle(\Delta\delta V_{1,2})^2\rangle_{\text{FR}}$ (red area) and $\langle\Delta\delta V_1 \times \Delta\delta V_2\rangle_{\text{FR}}$ appear on top (see top panel). Further details on data processing are provided in Appendix C.

B. Comparison of calibration methods and Faraday-rotation sensitivity

1. Comparison of calibration methods

The calibration factors determined for the three methods—transfer function (TF), shot noise (SN), and AOM—are specific to the optical probing power, $P_{0,\text{ref}} = 1.09$ mW, at which the present calibration is performed. However, these calibration factors can be generalized for any optical power P_0 using the following normalization:

$$C_{\alpha,\text{TF,SN,AOM}}(P_0) = \frac{P_0^2}{P_{0,\text{ref}}^2} C_{\alpha,\text{TF,SN,AOM}}(P_{0,\text{ref}}). \quad (29)$$

To account for uncertainties in the generalization, the error in the calibration factor for any power P_0 is extrapolated by incorporating the uncertainties of $C_{\alpha,\text{TF,SN,AOM}}(P_{0,\text{ref}})$ into

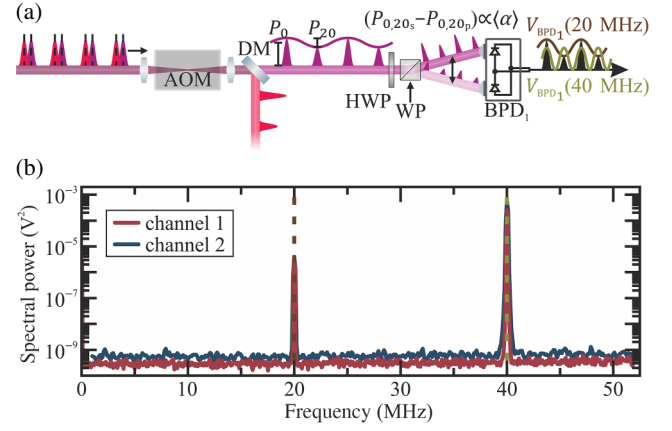


FIG. 4. Calibration using an AOM. (a) Sketch of the calibration setup. In this method, the magnetic sample is replaced by an AOM, which applies a subharmonic (20 MHz) amplitude modulation with optical power P_{20} on the probe beams (red and purple) with mean optical power P_0 . Pulse trains are directed into the two detection branches via a DM. WP separates them into their s - and p -polarized components. Their mean polarization angle, $\langle\alpha\rangle$, is adjusted using a HWP. (b) Power spectrum of detection channels 1 (red) and 2 (blue) measured using a spectrum analyzer. Details are discussed in Appendix D.

Eq. (29):

$$\begin{aligned} C_{\alpha,\text{TF,SN,AOM}}(P_0) &\pm u(C_{\alpha,\text{TF,SN,AOM}}(P_0)) \\ &= \frac{P_0^2}{P_{0,\text{ref}}^2} (C_{\alpha,\text{TF,SN,AOM}}(P_{0,\text{ref}}) \\ &\quad \pm u(C_{\alpha,\text{TF,SN,AOM}}(P_{0,\text{ref}}))). \end{aligned} \quad (30)$$

A comparison between Eqs. (29) and (30) shows that, although the absolute uncertainty of the calibration factor increases with higher probe powers, the relative uncertainty remains constant. Despite the increasing uncertainty with higher P_0 , the three methods show comparable calibration factors at $P_0 \approx P_{0,\text{ref}}$, with all falling within their respective error margins.

To improve the accuracy of the final calibration, we utilize the inverse-variance weighted mean [23], which gives more weight to calibration values with smaller uncertainties. This approach incorporates the experimental errors of the individual methods (see Appendix E) and yields a final calibration factor:

$$C_{\alpha,\text{ave}}(P_{0,\text{ref}}) = (4.6 \pm 0.8) \frac{\mu\text{V}}{(\mu\text{rad})^2}. \quad (31)$$

By using Eqs. (29) and (30), the calibration factor and corresponding uncertainty can be extrapolated for any power P_0 . It is important to note that the individual calibration factors $C_{\alpha,\text{TF}}$, $C_{\alpha,\text{SN}}$, and $C_{\alpha,\text{AOM}}$ carry uncertainties of approximately 25–33%. This reflects the inherent challenge of calibrating stochastic fluctuations, where standard

TABLE III. Experimental values and uncertainties of calibration via acousto-optic modulator.

Name	Symbol	Value	Method of estimation	Uncertainty	Method of error determination
Optical probe power	P_0	1.09 mW	Optical power meter	0.05 mW	Estimated
Mean spectral amplitude ratio of 40 and 20 MHz components	$\frac{\langle V_{\text{BPD}}^2(f_{\text{rep}}) \rangle}{\langle V_{\text{BPD}}^2(f_{\text{rep}}/2) \rangle}$	0.012	Mean of all calculated ratios in Fig. 9(b)	0.004	Standard deviation of all calculated ratios
Proportionality factor	D	$0.102 \text{ V}/(\mu\text{rad})^2$	Polynomial fit (see Fig. 10)	$0.003 \text{ V}/(\mu\text{rad})^2$	95% error bounds of fit
Calibration factor – AOM	$C_{\alpha, \text{AOM}}$	$4.2 \mu\text{V}/(\mu\text{rad})^2$	$C_{\alpha, \text{AOM}} = \frac{D}{2} \frac{\langle V_{\text{BPD}}^2(f_{\text{rep}}) \rangle}{\langle V_{\text{BPD}}^2(f_{\text{rep}}/2) \rangle}$	$1.3 \mu\text{V}/(\mu\text{rad})^2$	Combined error

calibration procedures do not apply. Within this context, we consider the reported accuracy to be a realistic and robust result.

2. Faraday-rotation sensitivity

We apply the combined calibration factor, $C_{\alpha, \text{ave}}$, to the measured correlated noise time traces. The data consist of the average of $n = 7$ correlated noise time traces recorded on a 10- μm -thick sample of the antiferromagnet $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ kept at room temperature ($T \approx 297 \text{ K}$). An external magnetic field, $B = (63 \pm 5) \text{ mT}$, is applied in the OOP direction to suppress stochastic picosecond random telegraph noise near the spin-reorientation transition [17]. Each time trace spans $\Delta t = -80 \text{ ps}$ to $\Delta t = +80 \text{ ps}$ in 1 - ps steps with probing power $P_{0, \text{ref}} = 1.09 \text{ mW}$ and averages taken from approximately 10^7 correlation samples per data point.

Figure 5 shows the calibrated time-trace average, which is obtained by dividing the raw data by calibration factor $C_{\alpha, \text{ave}}$. The correlated FR noise exhibits a peak at $\Delta t = 0$ with an amplitude of approximately $2(\mu\text{rad})^2$, followed by a symmetric damped oscillation with a characteristic frequency in the picosecond range. As discussed in Ref. [17], this oscillation directly reflects the temporal autocorrelation of thermal fluctuations in the quasiferromagnetic (qF) magnon mode of $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. The observed picosecond oscillation corresponds to the eigenfrequency of the qF mode, while the envelope decay arises from the finite correlation time of these fluctuations. Beyond $\pm 50 \text{ ps}$, the correlated FR noise amplitude drops below the background noise level, which limits the sensitivity of our experimental setup (see Appendix F):

$$S_{\text{rad}} = 0.52 \frac{(\mu\text{rad})^2}{\text{mW}\sqrt{n}}. \quad (32)$$

This sensitivity means that, with a probe power of 1 mW, we can resolve FR noise as small as $0.52(\mu\text{rad})^2$ per number of averaged time traces, n , where each data point is the average of approximately 10^7 correlation samples. This resolution can be improved by increasing the probe power or averaging more samples. Experimentally, however, care must be taken with large powers because optical excitation effects might eventually take place [24,25].

C. Magnetization calibration

The calibration methods presented in Sec. III A allow for the quantitative identification of Faraday-rotation values. It is further possible to connect this information to the absolute value of magnetization fluctuation in units of A^2/m^2 . To do this, we determine the proportionality factor, C_M , which relates correlated FR noise to inherent spin fluctuations [see Eq. (7)]. This calibration enables

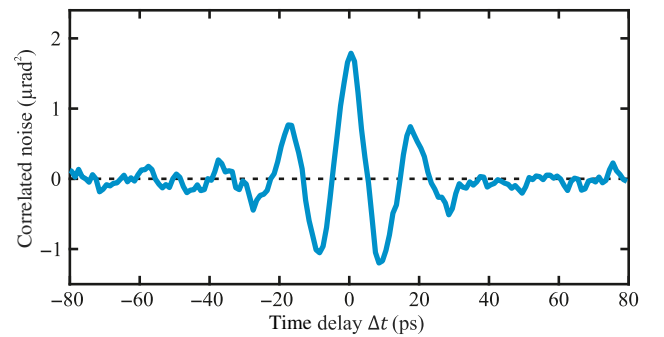


FIG. 5. Calibrated correlated Faraday noise in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ at $T = 297 \text{ K}$ and external out-of-plane field of $B = (63 \pm 5) \text{ mT}$ as a function of time delay Δt . Data represent the baseline-subtracted average of seven correlated noise time traces (see Appendix F for details), calibrated by dividing raw data by calibration factor $C_{\alpha, \text{ave}}$.

us to quantify the magnitude of magnetization noise and compare it to the saturation magnetization, M_S , of the $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ sample. We assume the proportionality of the Faraday-rotation angle, α , with magnetization along the laser propagation direction, M_z , predicted for magnetized solids [26], and find

$$\alpha(t) = \underbrace{\mu_0 \times V(\lambda) \times d}_{\sqrt{C_M}} \times M_z(t). \quad (33)$$

Here, the Verdet constant, $V(\lambda)$, at wavelength λ , sample thickness d , and vacuum permeability μ_0 , define the proportionality factor, C_M . Typically, in the literature, the magneto-optic constant is represented as $V' = V(\lambda)\mu_0 M_S$ (in deg/cm), which assumes saturated magnetization and does not allow direct conclusions about instantaneous magnetization in A/m.

To determine C_M and $V(\lambda)$, we require both the OOP magnetization component, M_z , along the laser propagation axis, z , and the corresponding polarization rotation, α . We measure M_z through magnetometry with a superconducting quantum interference device (SQUID) and compare it to Faraday-rotation data obtained at similar temperatures and external fields. Measurements span a range of temperatures through the spin-reorientation transition [27] (SRT) in orthoferrite $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. Here, the spin lattice continuously rotates by 90° with temperature. The SRT initiates at T_L (where $\mathbf{M} \parallel a$) and completes at T_U (where $\mathbf{M} \parallel c$) along the material's crystalline axes a and c [Fig. 6(a)].

SQUID magnetometry measurements were performed on a cylindrical bulk sample of $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ (radius $r = 3.1$ mm, thickness $d = 1.7$ mm) grown by the floating-zone technique. Details of the measurements are provided in Appendix G, and data are plotted in Fig. 6(b). For optical measurements, we use a 10- μm -thick single-crystal platelet from the same batch as the bulk sample. The laser is aligned along the c axis, with a ± 62 mT magnetic field applied in the same direction. The FR data are shifted by +7 K to correct for laser-induced heating [17] and symmetrization removes the linear background attributed to sample birefringence (see Appendix G). The resulting curves are presented in Fig. 6(b).

Above 313 K, both FR and SQUID magnetometry show a similar trend: the FR angle and measured OOP magnetization continuously increase with temperature, saturating at $T_U \approx 334$ K. This is consistent with spin reorientation from the a axis to the c axis [Fig. 6(a)]. We denote the saturation magnetization as $M_S := M(T_U) \approx 8.4$ kA/m. Below 313 K, the FR angle trends toward zero as expected from the SRT, although SQUID data show finite magnetization. This is likely due to sample misalignment. Furthermore, it needs to be noted that SQUID measures the spatially averaged magnetization of the whole sample, while FR probes the local environment around the focus

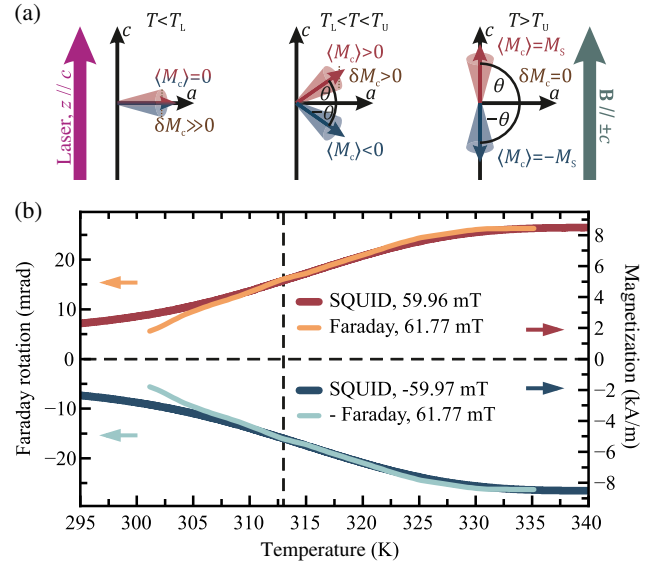


FIG. 6. Faraday rotation and magnetization in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. (a) Schematic of the spin-reorientation transition (SRT). Laser and external magnetic field are aligned with the c axis of the orthoferrite sample. Below the lower threshold temperature, T_L , the net magnetization (blue and red arrows) aligns with the a axis. As the SRT progresses ($T_L < T < T_U$), the magnetization rotates by an angle $\pm\theta$, which changes the c -axis projection of the mean magnetization, $\langle M_c \rangle$, and fluctuation component, δM_c . (b) Temperature-dependent FR in comparison with magnetization data from SQUID magnetometry. To obtain the magnetization values (dark-red and dark-blue curves), SQUID raw data are divided by the sample volume. FR data are background-subtracted (see Appendix G) and shifted by +7 K to account for laser-induced heating. Light-blue curve corresponds to the orange curve mirrored around the zero line.

spot. This may also lead to discrepancies between the two methods.

We determine C_M by computing the ratio between FR and SQUID data for all temperatures above 313 K. Following Eq. (33), the resulting ratios are averaged and squared to obtain

$$C_M = (9.9 \pm 3.2) \frac{(\mu\text{rad})^2}{(\text{A/m})^2}. \quad (34)$$

Using C_M , the Verdet constant at 771 nm is

$$V(771 \text{ nm}) = \frac{\sqrt{C_M}}{\mu_0 d} = (2.5 \pm 0.8) \times 10^5 \frac{\text{rad}}{\text{Tm}}, \quad (35)$$

with $M_S \approx 8.4$ kA/m; the normalized Verdet constant, V' , in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ is approximately 1510 deg/cm, comparable to values for SmFeO_3 ($V' \approx 800$ deg/cm) and ErFeO_3 ($V' \approx 2300$ deg/cm) in Ref. [28].

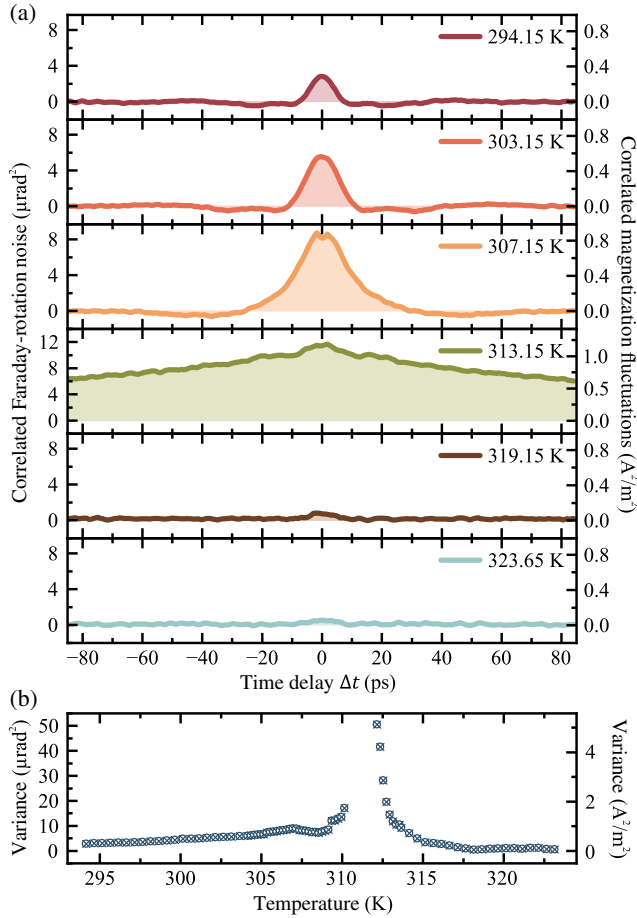


FIG. 7. Ultrafast spin noise near the spin reorientation in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ calibrated in absolute units of $(\mu\text{rad})^2$ and A^2/m^2 . Data presented here are taken from Ref. [17] and calibrated using the protocols provided in the main text. (a) Correlated noise dynamics as a function of the probe-probe time delay, Δt , for multiple temperatures near the spin reorientation in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$. (b) Time-zero amplitude (variance) as a function of temperature.

D. Quantitative magnetization noise

Finally, we apply our calibration to experimental data presented in our previous work [17]. Here, correlated spin fluctuations in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ were investigated near the SRT. The calibrated correlation waveforms, depicted in Fig. 7(a), were measured using a probing power of 1.13 mW. These measurements span from -85 to $+85$ ps in 0.6-ps increments and represent the average of 5–30 repetitions each. The variance, defined as the correlation amplitude at $\Delta t = 0$, and the temporal dynamics of the noise correlation exhibit significant temperature dependence around the SRT. Figure 7(b) illustrates the variance as a function of temperature. As the temperature approaches 307 K, a steady increase in variance is observed. This increase is linked to anisotropy softening around the SRT, which results in enhanced magnetic

susceptibility. Beyond this temperature, a sharp increase in variance around 312 K is found, resulting from ultrafast spontaneous spin switching [17]. This phenomenon manifests as an additional exponentially decaying feature, which is superimposed on the damped oscillation resulting from the correlated fluctuations of the quasiferromagnetic magnon mode [green curve, Fig. 7(a)]. For a detailed discussion of the temporal dynamics, see Ref. [17]. At higher temperatures, the noise amplitude continuously decreases, nearly vanishing around 320 K. This behavior is consistent with the reduction of the OOP fluctuation component due to the equilibrium rotation of the spin system within the SRT [see Fig. 6(a)].

At the lowest investigated temperature of 294.15 K, we find that the magnitude of the correlated magnon noise reaches approximately $0.3 \text{ A}^2/\text{m}^2$. Here, contributions from picosecond random telegraph switching are assumed to be negligible. From approximately 310 K, picosecond switching contributes significantly to the correlated spin noise, reaching variances as large as $5.1 \text{ A}^2/\text{m}^2$. These values show that the magnitude of OOP magnon fluctuations and picosecond switching constitute less than 0.01 % and 0.03 % of the saturation magnetization amplitude, M_S , respectively. Here, we referenced the standard deviation (square-root of variance) of the magnetization noise to M_S . It is important to note that the spin noise represents spatially averaged magnetization fluctuations within the probing volume. This fact leads to significant variance differences when altering the laser focusing, as reported in Ref. [17]. At more microscopic spatial scales, the amplitude of local spin fluctuations is expected to exceed the calibrated values presented above.

IV. CONCLUSION

We present three calibration methods to quantitatively link a femtosecond noise correlation signal to correlated polarization noise in femtosecond probe-pulse trains. All methods yield consistent results, thereby validating our calibration approaches. By combining these methods, we determine a combined calibration factor, $C_{\alpha,\text{ave}}(P_{0,\text{ref}}) = (4.6 \pm 0.8) \mu\text{V}/\mu\text{rad}^2$, for our current setup. Additionally, we estimate the sensitivity of the setup as $S_{\text{rad}} = 0.52 \mu\text{rad}^2/\text{mW}\sqrt{n}$ per measurement repetition n , facilitating tailored measurements for specific samples. Furthermore, by comparing Faraday-rotation experiments with SQUID magnetometry, we calibrate the magnetization fluctuations in absolute units of A^2/m^2 . Applying these calibration techniques to FemNoC data captured in $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ within the SRT regime, we find that the magnon fluctuations are on the order of 0.01 % and ultrafast spontaneous switching reaches 0.03 % of the saturation magnetization. This quantitative evaluation of the spin-noise magnitude in an antiferromagnet provides

important information for the development of future spintronic devices.

ACKNOWLEDGMENTS

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The authors declare no competing interests.

DATA AVAILABILITY

The data that support the findings of this article are openly available [33], embargo periods may apply.

APPENDIX A: SHOT NOISE IN A BALANCED PHOTODETECTION SYSTEM

We investigate the fluctuations in the optical power difference, $\Delta P = P_s - P_p$, between s - and p -polarized components, as measured in a balanced photodetector. The variance of ΔP is given by

$$\begin{aligned} \langle (\Delta P)^2 \rangle &= \langle (P_s - P_p)^2 \rangle = \langle P_s^2 + P_p^2 - 2P_s P_p \rangle, \\ &= \langle P_s^2 \rangle + \langle P_p^2 \rangle - 2\langle P_s P_p \rangle, \end{aligned} \quad (\text{A1})$$

where $\langle P_{s,p}^2 \rangle$ represents the variance of s - and p -polarization components, and $\langle P_s P_p \rangle$ is their cross-correlation. First, we analyze the individual variances:

$$\begin{aligned} \langle P_{s,p}^2 \rangle &= \langle (P_{s,p} + \delta P_{s,p})^2 \rangle \\ &= \langle P_{s,p}^2 + \delta P_{s,p}^2 + 2P_{s,p} \delta P_{s,p} \rangle, \\ &= \langle P_{s,p}^2 \rangle + \langle \delta P_{s,p}^2 \rangle + 2\langle P_{s,p} \delta P_{s,p} \rangle = \langle P_{s,p}^2 \rangle \\ &\quad + \langle \delta P_{s,p}^2 \rangle. \end{aligned} \quad (\text{A2})$$

Here, $\langle P_{s,p} \rangle$ is their mean power, and $\delta P_{s,p}$ represents their fluctuations, where $\langle \delta P_{s,p} \rangle = 0$. Assuming Poissonian statistics (with $\langle n^2 \rangle = \langle n \rangle$ [29]), and using the definition for the mean optical power, $\langle P \rangle = h\nu/\tau$, averaged in the time window τ , the fluctuations in power are

$$\langle \delta P_{s,p}^2 \rangle := \langle (\delta P_{s,p})^2 \rangle_{\text{SN}} = 2h\nu \langle P_{s,p} \rangle \Delta f, \quad (\text{A3})$$

where h is Planck's constant, ν is the photon frequency, and $\Delta f = 1/\tau$ is the noise bandwidth. The cross-correlation term, $\langle P_s P_p \rangle$, simplifies as

$$\begin{aligned} \langle P_s P_p \rangle &= \langle (P_s + \delta P_s) \times (P_p + \delta P_p) \rangle, \\ &= \langle P_s \rangle \langle P_p \rangle + \langle P_s \rangle \delta P_p + \delta P_s \langle P_p \rangle + \delta P_s \delta P_p, \\ &= \langle P_s \rangle \langle P_p \rangle + \langle P_s \rangle \langle \delta P_p \rangle + \langle \delta P_s \rangle \langle P_p \rangle + \langle \delta P_s \delta P_p \rangle. \end{aligned} \quad (\text{A4})$$

Again, we use a value for the mean of the fluctuation components of zero, $\langle \delta P_{s,p} \rangle = 0$. Furthermore, we assume that the fluctuation components in the s - and p -polarization components are uncorrelated ($\langle \delta P_s \delta P_p \rangle = 0$), which simplifies Eq. (A4) to

$$\langle P_s P_p \rangle = \langle P_s \rangle \langle P_p \rangle = \langle P_s \rangle \langle P_p \rangle. \quad (\text{A5})$$

By combining Eqs. (A2), (A3), and (A5) into (A1), we obtain

$$\begin{aligned} \langle (\Delta P)^2 \rangle &= (\langle P_s^2 \rangle + \langle \delta P_s^2 \rangle) + (\langle P_p^2 \rangle + \langle \delta P_p^2 \rangle) \\ &\quad - 2\langle P_s \rangle \langle P_p \rangle, \\ &= \langle P_s \rangle^2 + \langle P_p \rangle^2 + 2h\nu \Delta f (\langle P_s \rangle + \langle P_p \rangle) \\ &\quad - 2\langle P_s \rangle \langle P_p \rangle. \end{aligned} \quad (\text{A6})$$

Using Malus' law [20], $\Delta P = P_s - P_p = [P_0 \sin^2(\alpha)] - [P_0 \cos^2(\alpha)] = P_0(1 - 2\cos^2(\alpha))$, where α is the input beam's polarization angle, we simplify the terms of Eq. (A6):

$$\begin{aligned} \langle P_s \rangle^2 + \langle P_p \rangle^2 - 2\langle P_s \rangle \langle P_p \rangle &= \langle P_0 \sin^2(\alpha) \rangle^2 + \langle P_0 \cos^2(\alpha) \rangle^2 \\ &\quad - 2\langle P_0 \sin^2(\alpha) \rangle \langle P_0 \cos^2(\alpha) \rangle, \\ &= P_0^2 [\sin^4(\alpha) + \cos^4(\alpha) - 2\sin^2(\alpha)\cos^2(\alpha)] \\ &= P_0^2 \cos^2(2\alpha) = \langle \Delta P \rangle^2. \end{aligned} \quad (\text{A7})$$

Inserting (A7) into (A6) then yields

$$\langle (\Delta P)^2 \rangle = \langle \Delta P \rangle^2 + \underbrace{2h\nu P_0 \Delta f}_{\langle \delta \Delta P^2 \rangle}. \quad (\text{A8})$$

This shows that the shot-noise fluctuations, $\langle \delta \Delta P \rangle^2 = \langle \delta P_s - \delta P_p \rangle^2$, in the power difference are equivalent to the shot-noise level of a single beam with optical power P_0 :

$$\langle (\Delta P)^2 \rangle_{\text{SN}} = 2h\nu P_0 \Delta f = \langle \delta P_s - \delta P_p \rangle^2. \quad (\text{A9})$$

APPENDIX B: VARIANCE OF PULSE-TO-PULSE FLUCTUATION

A key aspect of femtosecond noise-correlation spectroscopy is the extraction of pulse-to-pulse polarization fluctuations, $\Delta\delta\alpha$, using subharmonic lock-in detection. This method not only removes stationary background signals [18] but also doubles the noise variance compared

to $\delta\alpha$. Below is mathematical proof for this variance doubling:

Consider two independent random variables X and X' , independently drawn from the same probability distribution, $p(X)$, with expectation value $\mu[X]$ and variance $V(X) = \mu(X^2) - \mu(X)^2$. We calculate the variance of their difference, $X - X'$:

$$\begin{aligned} V(X - X') &= \mu[(X - X')^2] - \mu[X - X']^2 = \mu[X^2 + X'^2 - 2XX'] - (\mu[X] - \mu[X'])^2, \\ &= \mu[X^2] + \mu[X'^2] - 2\mu[XX'] - (\mu[X]^2 + \mu[X']^2 - 2\mu[X]\mu[X']), \\ &= \underbrace{\mu[X^2] - \mu[X]^2}_{V(X)} + \underbrace{\mu[X'^2] - \mu[X']^2}_{V(X')} - 2 \underbrace{(\mu[XX'] - \mu[X]\mu[X'])}_{\text{COV}(X, X')}. \end{aligned} \quad (\text{B1})$$

Here, $\text{COV}(X, X')$ is the covariance between X and X' . Since X and X' are independent, their covariance is zero, and because X and X' follow identical distributions, $V(X) = V(X')$. Thus, we have

$$V(X - X') = 2V(X). \quad (\text{B2})$$

This shows that the variance of the difference between two uncorrelated random variables is twice the variance of each individual variable. This applies to femtosecond noise-correlation spectroscopy, where subharmonic lock-in detection doubles the noise variance and must be accounted for in calibration. Notably, this is only valid when the polarization noise in consecutive pulses is uncorrelated. In our case, the 50 - ns interpulse distance from our 40-MHz laser system is much larger than the subnanosecond noise correlation time reported in Ref. [17].

APPENDIX C: POSTPROCESSING OF CORRELATION DATA

The data presented in Figs. 3, 5, and 11 undergo several postprocessing steps, as described below. The data in Fig. 7 are reproduced from Ref. [17]. Corresponding data processing procedures can be found in that reference.

1. Processing of data in Fig. 3

The raw correlation data (solid lines in Fig. 8) for the $\langle(\Delta\delta V_1 \pm \Delta\delta V_2)^2\rangle$ curves in Fig. 3 exhibit a strong linear background drift and a sharp peak at $\Delta t = 0$. The drift likely results from slight misalignment of the optical delay line, while the peak arises from spectral leakage, i.e., a small fraction of one probe beam entering the other detection path due to imperfect separation by the dichroic mirror. This leads to pulse interference within the same detection branch.

Each raw dataset is averaged over 10 measurement repetitions, with time delays ranging from -80 to $+80$ ps in 600 - fs steps.

To correct for the linear drift and obtain slope-corrected data, $\langle(\Delta\delta V_1 \pm \Delta\delta V_2)^2\rangle_{\text{SC}}$, we apply the following transformation:

$$\begin{aligned} \langle(\Delta\delta V_1 \pm \Delta\delta V_2)^2\rangle_{\text{SC}} &= \langle(\Delta\delta V_1 \pm \Delta\delta V_2)^2\rangle \\ &\quad - f_{\text{slope}}(\Delta t) + f_{\text{slope}}(\Delta t = 0). \end{aligned} \quad (\text{C1})$$

Here, $f_{\text{slope}}(\Delta t)$ is defined as the average of the slope functions computed for both the sum and difference signals:

$$\begin{aligned} f_{\text{slope}}(\Delta t) &= \frac{1}{2} \sum_{\pm} (\Delta t - \Delta t_{i=1}) S_{\pm} \\ &\quad + \langle(\Delta\delta V_1 \pm \Delta\delta V_2)^2\rangle_{i \in [1,5]}. \end{aligned} \quad (\text{C2})$$

The slope, $S_{\pm}$, is calculated by dividing the difference between the average of the last and first five data points

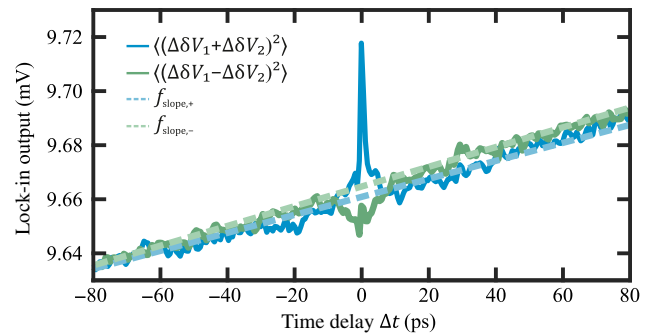


FIG. 8. Slope correction of raw correlation data according to the procedure described in the text. Solid lines represent raw data, $\langle(\Delta\delta V_1 \pm \Delta\delta V_2)^2\rangle$, and dashed lines their corresponding slope functions, $f_{\text{slope},\pm}$.

by the total time window:

$$S_{\pm} = \frac{\langle (\Delta \delta V_1 \pm \Delta \delta V_2)^2 \rangle_{i \in [N-5, N]} - \langle (\Delta \delta V_1 \pm \Delta \delta V_2)^2 \rangle_{i \in [1, 5]}}{|\Delta t_N - \Delta t_1|}, \quad (\text{C3})$$

where $i \in \mathbb{Z}\{0\}$ indexes the data points and N is the total number of points. The slope functions, $f_{\text{slope}, \pm}(\Delta t)$, are shown as dashed lines in Fig. 8, and the corrected data appear as solid lines in Fig. 3.

After slope correction, we remove the interference artifact at $\Delta t = 0$ by omitting a 1.2 - ps window centered at this point. Finally, a third-order Savitzky-Golay filter is applied to smooth the data, resulting in the dotted curves shown in Fig. 3.

2. Processing of data in Figs. 5 and 11

The raw correlated noise waveforms shown in Figs. 5 and 11 are first slope-corrected using Eq. (C1), then offset-subtracted to remove the linear offset arising in the lock-in detector. The slope-corrected waveforms are fitted with the function

$$f(\Delta t) = c + A \times \text{sech}\left(\frac{\Delta t}{\tau}\right) \cos(2\pi \Delta t f), \quad (\text{C4})$$

where τ is the damping timescale; f is the oscillation frequency; and A and c are the amplitude and offset, respectively. The final curves shown in Figs. 5 and 11 are obtained by subtracting the fitted offset c . No data points were omitted, and no Savitzky-Golay filtering was applied in this case.

APPENDIX D: CALIBRATION VIA ACOUSTO-OPTIC MODULATOR

In this calibration method, we introduce a controllable subharmonic (20 MHz) amplitude modulation with optical power P_{20} on the probe beams (total power P_0) using an AOM. Since this modulation affects both the s - and p -polarized components equally, the subharmonic power difference, ΔP_{20} , depends on the mean polarization angles, $\langle \alpha_{1,2} \rangle$ [see Eq. (21)].

Directly determining P_{20} and ΔP_{20} is challenging, so instead, we calculate the ratio of the BPD output voltage variances, $\langle V_{\text{BPD}}^2(f_{\text{rep}}) \rangle / \langle V_{\text{BPD}}^2(f_{\text{rep}}/2) \rangle = P_0^2 / P_{20}^2$ [see Eq. (26)], at both the laser's fundamental frequency, f_{rep} , and its subharmonic, $f_{\text{rep}}/2$, using the spectrum-analyzer function of our lock-in amplifier. Figure 4(b) shows an example power spectrum recorded at power $P_0 = 1.09$ mW and polarization angles $\langle \alpha_1 \rangle = 205^\circ$ and $\langle \alpha_2 \rangle = 195^\circ$ for detection channels 1 and 2. The 40- and 20-MHz peak amplitudes are extracted from the spectra

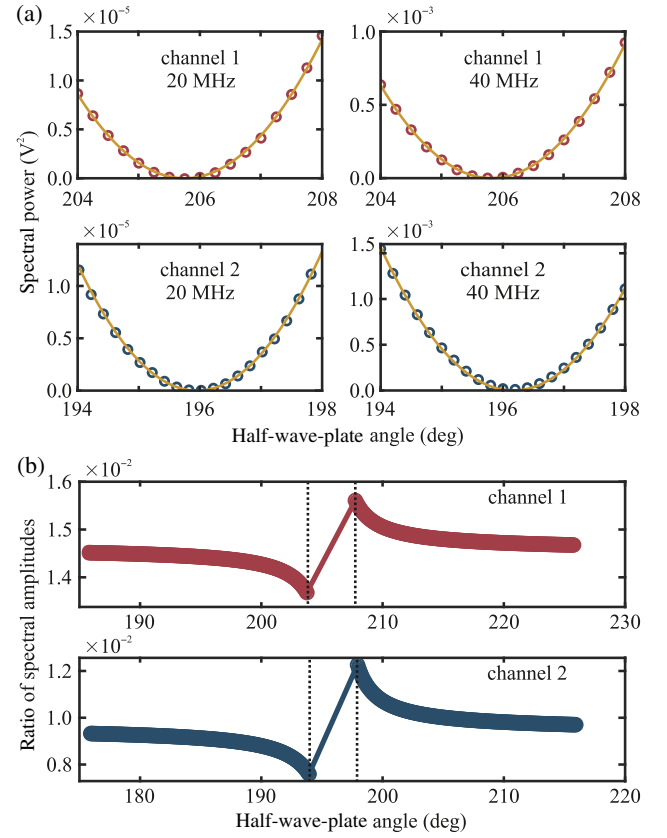


FIG. 9. Estimation of the spectral amplitude ratio of 20 and 40 MHz components. (a) Spectral power of 20-MHz (left) and 40-MHz peaks (right) as a function of the absolute half-wave-plate angles of detection channels 1 (red circles) and 2 (blue circles). Square fit (yellow) is used to interpolate the measured values. (b) Ratio between spectral amplitudes of the 20- and 40-MHz components for detection channels 1 (red circles) and 2 (blue circles) calculated from the fits in (a). Due to an angle mismatch of the minimal spectral amplitudes of 20- and 40-MHz components, the ratio is not constant as a function of the half-wave-plate angle. To avoid artifacts arising from this mismatch, we neglect data points between the dashed lines in the following discussion.

recorded for different angles $\langle \alpha \rangle$, with the results shown in Fig. 9(a).

Note that we plot the absolute angles of the HWPs, which may have an offset from the polarization angle. The 40- and 20-MHz components show minima at different polarization angles, which we attribute to the BPD's spectral response. To enhance statistics, we interpolate the data in Fig. 9(a) using the fitting function:

$$\begin{aligned} & \langle (\Delta V_{20,40})^2 \rangle (\langle \alpha \rangle) \\ &= \left(c \left(1 - 2 \cos^2 \left(2\pi \times \frac{\langle \alpha \rangle - \langle \alpha_0 \rangle}{360^\circ} - \frac{\pi}{4} \right) \right) \right)^2, \\ &\approx 4c^2 \left(\frac{2\pi (\langle \alpha \rangle - \langle \alpha_0 \rangle)}{360^\circ} - \frac{\pi}{4} \right)^2. \end{aligned} \quad (\text{D1})$$

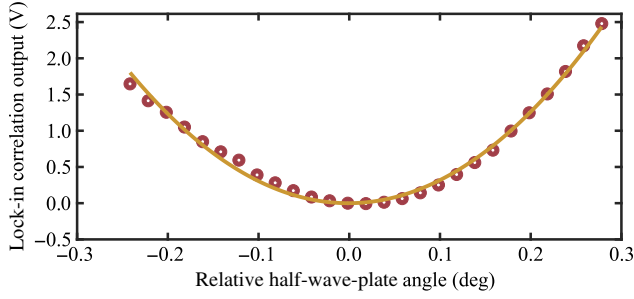


FIG. 10. Estimation of the proportionality factor, D , relating the lock-in correlation output to the mean polarization angles, $\langle\alpha_{1,2}\rangle$, of the 20-MHz amplitude-modulated probe beams. Polynomial fit (yellow) with fitting function $f(x) = cx + Dx^2$ yields $c = (0.072 \pm 0.102) \text{ V}/\mu\text{rad}$ and $D = (0.102 \pm 0.003) \text{ V}/(\mu\text{rad})^2$.

Here, $\langle\alpha_0\rangle$ is the offset between HWP angle and the 45° polarization reference. Note that the small-angle approximation used in Eq. (21) is justified in this case, because $\langle\alpha\rangle$ varies by less than 5° .

From the fits in Fig. 9(a), we infer the ratio of spectral amplitudes as a function of the HWP angles [Fig. 9(b)]. While the ratio $\langle V_{\text{BPD}}^2(f_{\text{rep}}) \rangle / \langle V_{\text{BPD}}^2(f_{\text{rep}}/2) \rangle$ is expected to remain constant, a slight angle dependency is observed due to minima occurring at different angles. To address this, we discard ratio data within 2° of the subharmonic minimum [dashed lines, Fig. 9(b)] and average the remaining angles, yielding a mean ratio of

$$\frac{\langle V_{\text{BPD}}^2(f_{\text{rep}}) \rangle}{\langle V_{\text{BPD}}^2(f_{\text{rep}}/2) \rangle} = 0.012 \pm 0.004.$$

To extract the proportionality factor, D , for calibration, we examine the lock-in response to the mean polarization angles, $\langle\alpha_{1,2}\rangle$, of the 20-MHz amplitude-modulated beam. We simultaneously vary the HWP angles of detection channels 1 and 2 relative to the fitted minima in Fig. 9(a) from -0.25° to $+0.29^\circ$ in 0.02° steps and measure the lock-in correlation output. The data, shown in Fig. 10, follow quadratic behavior with a quadratic coefficient of $D = (0.102 \pm 0.003) \text{ V}/(\mu\text{rad})^2$ obtained from the polynomial fit. A small linear background persists, likely due to imperfections in the detection branches, such as finite extinction ratios of the HWPs or nonlinearities in the photodetectors.

APPENDIX E: DETAILED QUANTIFICATION OF MEASUREMENT VALUES AND UNCERTAINTY EVALUATION

In this section, we summarize all experimental parameters, their uncertainties [denoted as $u(A)$, where A is the experimental parameter], and their sources (whether estimated, calculated, or fitted). Unless stated otherwise, uncertainties are calculated using Gaussian error

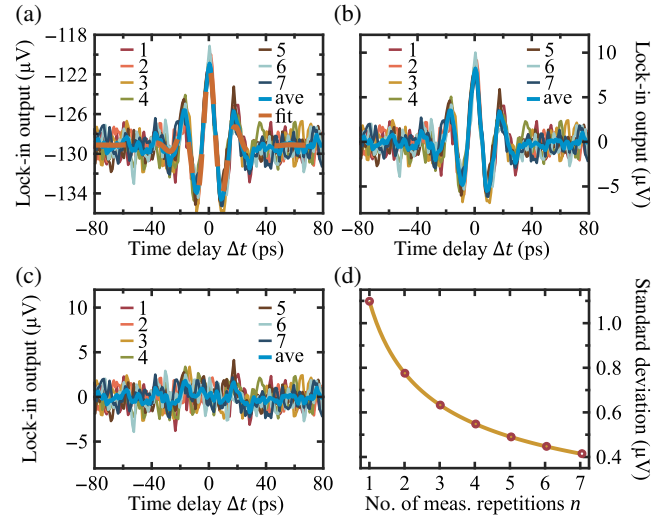


FIG. 11. (a) Slope-corrected data. (b) Slope-corrected and background-subtracted data. (c) Background noise extracted via subtraction of fit from waveforms in (a). (d) Average standard deviation of determined background noise as a function of waveform averages (red circles) and inverse square root fit (yellow line).

propagation [30]:

$$u(f(x_i)) = \sqrt{\sum_i \left(\frac{\partial f}{\partial x_i} \times u(x_i) \right)^2}. \quad (\text{E1})$$

Here, $u(f(x_i))$ is the combined uncertainty of the function $f(x_i)$, which depends on various parameters x_i , each with its own uncertainties $u(x_i)$.

The values and their uncertainties used in the individual calibration schemes (transfer-function method, Sec. III a 1; optical shot-noise comparison, Sec. III a 2; and acousto-optic modulator, Sec. III a 2) are summarized in Tables I–III, respectively.

Following these calibration schemes, we determine the individual calibration factors, $C_{\alpha, \text{TF}}$, $C_{\alpha, \text{SN}}$, and $C_{\alpha, \text{AOM}}$, along with their uncertainties, $u(C_{\alpha, \text{TF}})$, $u(C_{\alpha, \text{SN}})$, and $u(C_{\alpha, \text{AOM}})$. From these values, a combined calibration factor, $C_{\alpha, \text{ave}}$, is calculated with corresponding uncertainty $u(C_{\alpha, \text{ave}})$. This is done using the inverse-variance weighted-mean method [23], which assigns greater weight to values with smaller uncertainties, effectively accounting for experimental errors of each calibration method:

$$\begin{aligned} C_{\alpha, \text{ave}} &= \frac{\sum_{i \in \{\text{TF, SN, AOM}\}} (C_i / u(C_i)^2)}{\sum_{i \in \{\text{TF, SN, AOM}\}} (1 / u(C_i)^2)}, \\ &= 4.60 \frac{\mu\text{V}}{(\mu\text{rad})^2} \quad \text{and} \quad u(C_{\alpha, \text{ave}}), \\ &= \sqrt{\frac{1}{\sum_{i \in \{\text{TF, SN, AOM}\}} (1 / u(C_i)^2)}} = 0.77 \frac{\mu\text{V}}{(\mu\text{rad})^2}. \end{aligned} \quad (\text{E2})$$

TABLE IV. Experimental values and uncertainties of magnetization calibration.

Name	Symbol	Value	Method of estimation	Uncertainty	Method of error determination
FR sample thickness	d	10 μm	Estimated	1 μm	Estimated
Mean FR/SQUID ratio	$\left\langle \frac{\alpha(T)}{M_c(T)} \right\rangle$	3.2 $\mu\text{rad}/(\text{A/m})$	See Appendix G	1.0 $\mu\text{rad}/(\text{A/m})$	Estimated
Calibration factor – Magnetization	C_M	9.9 $(\mu\text{rad})^2/(\text{A/m})^2$	$C_M = \left\langle \frac{\alpha(T)}{M_c(T)} \right\rangle^2$	3.2 $(\mu\text{rad})^2/(\text{A/m})^2$	Combined Error
Verdet constant	$V(771 \text{ nm})$	$2.5 \times 10^5 \text{ rad/Tm}$	$V(771 \text{ nm}) = \frac{\sqrt{C_M}}{\mu_0 d}$	$0.8 \times 10^5 \text{ rad/Tm}$	Combined Error

Finally, the setup is calibrated in terms of magnetization in units of A^2/m^2 . The experimental values used in this calibration scheme, as well as their uncertainties, are summarized in Table IV.

APPENDIX F: SENSITIVITY OF THE FEMNOC SYSTEM

We estimate the Faraday noise sensitivity of the FemNOC system as a function of probing power P_0 and the number of measurement repetitions, n . This is based on the standard deviation (σ) of background noise in the measured correlation noise time traces. Seven waveforms of correlated magnetization noise were recorded for $\text{Sm}_{0.7}\text{Er}_{0.3}\text{FeO}_3$ at 297 K under an out-of-plane magnetic field of $(63 \pm 5) \text{ mT}$, using probe power $P_{0,\text{ref}} = 1.09 \text{ mW}$, with data points from $\Delta t = -80 \text{ ps}$ to $\Delta t = +80 \text{ ps}$ in 1-ps steps. Each data point represents an average of approximately 10^7 correlation samples. Figure 11(a) shows the slope-corrected waveforms, their average, and a fit using function (C4).

The offset-subtracted time traces are shown in Fig. 11(b), and the remaining background noise (obtained by subtraction of the fit from slope-corrected waveforms) is plotted in Fig. 11(c). The standard deviations of the first and last 20 ps of the time traces were calculated to avoid artifacts stemming from deviations of fit and measured data. We repeated this calculation for all possible combinations of the seven recorded waveforms, averaging them n at a time, and plotted the results in Fig. 11(d). As expected, the data follow an inverse square-root trend with averaging.

To generalize the results for different optical powers, we use the scaling $\sigma \propto P_0$ [18] and $\sigma \propto (1/\sqrt{n})$ [Fig. 11(d)], giving the generalized STD:

$$\sigma(P_0, n) = \sigma(P_{0,\text{ref}}, n_{\text{ref}}) \times \frac{P_0}{P_{0,\text{ref}}} \times \sqrt{\frac{n_{\text{ref}}}{n}}. \quad (\text{F1})$$

The sensitivity of our setup, $S(P_0, n)$, is defined as twice the standard deviation of the background noise:

$S(P_0, n) \stackrel{\text{def}}{=} 2 \times \sigma(P_0, n)$. To convert this into the Faraday-rotation noise sensitivity, $S_{\text{rad}}(P_0, n)$, units of $(\mu\text{rad})^2$, we divide by the average calibration factor, $C_{\text{ave}}(P_0)$ [Eq. (29)]:

$$S_{\text{rad}}(P_0, n) = \frac{S(P_0, n)}{C_{\text{ave}}(P_0)} = \frac{2\sigma(P_{0,\text{ref}}, n_{\text{ref}})}{C_{\text{ave}}(P_{0,\text{ref}})} \times \frac{P_{0,\text{ref}}}{P_0} \times \sqrt{\frac{n_{\text{ref}}}{n}} \stackrel{\text{def}}{=} \frac{S_{\text{rad,ref}}(P_{0,\text{ref}}, n_{\text{ref}})}{P_{0,\text{ref}} \sqrt{n}}. \quad (\text{F2})$$

Using $P_0 = P_{0,\text{ref}} = 1.09 \text{ mW}$, $n = n_{\text{ref}} = 1$, and $\sigma(P_{0,\text{ref}}, 1) = 1.1 \mu\text{V}$ [Fig. 11(d)], we calculated the sensitivity normalized to 1 mW of probe power:

$$S_{\text{rad}}(P_0, n) = \frac{S_{\text{rad}}(1.09 \text{ mW}, 1)}{P_{0,\text{ref}} \sqrt{n}} = 0.52 \frac{\mu\text{rad}^2}{\text{mW} \sqrt{n}}. \quad (\text{F3})$$

This provides the sensitivity per measurement repetition with the current setup, although it can be generalized for any number of correlation samples per time-delay data point.

APPENDIX G: POSTPROCESSING OF FARADAY-ROTATION DATA

The FR data in Fig. 7 undergo several postprocessing steps. Raw data were recorded under external out-of-plane fields of -63 and $+61 \text{ mT}$, similar to the fields used in SQUID magnetometry. Furthermore, we measure FR curves at small external fields of -5 and $+4 \text{ mT}$. The average of values recorded below 297 K from the small-field data serve as the zero reference level, with all FR curves shown in Fig. 12(a).

The absolute FR angles differ slightly between positive and negative field pairs of similar magnitude. This effect may be explained by birefringence of the sample, which also changes with temperature [32]. To separate the background, we calculate the sum and difference of the -63 and $+61 \text{ mT}$ curves. The results are depicted in Fig. 12(b). The sum (green curve) isolates the background, while the difference (yellow curve) provides the background-free magneto-optic response.

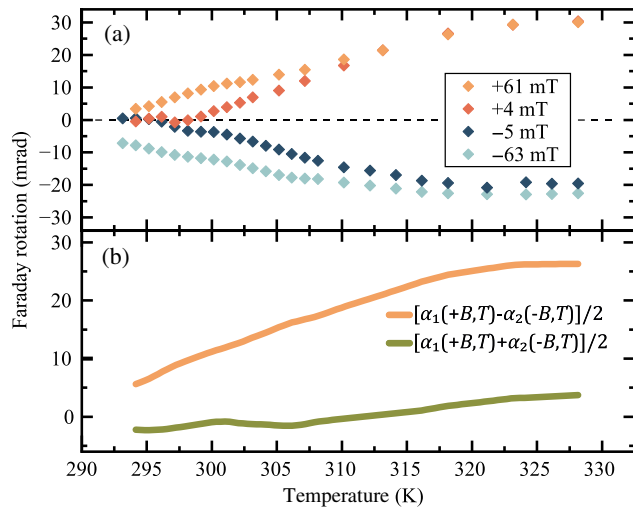


FIG. 12. (a) Raw Faraday rotation as a function of temperature. All rotation angles are referenced to average values recorded below 297 K from small-field data (-5 mT, $+4$ mT). (b) Difference (yellow) and sum (green) of the $+61$ - and -63 -mT FR curves. Sum reveals a linear background with temperature, which we assign to birefringence in the orthoferrite sample [32].

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