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Frequency fluctuations of ferromagnetic resonances at milliKelvin temperatures

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Unwanted fluctuations over time, in short, noise, are usually detrimental to device performance, especially for quantum coherent circuits. Recent efforts have demonstrated routes to utilizing magnon systems for quantum technologies by interfacing single magnons with superconducting qubits. However, the coupling of several components often introduces additional noise to the system, hence degrading its coherence. Researching the system's temporal behavior can help to identify the underlying noise sources, which is a vital step for improving coherence times and hybrid device performance. Yet, the frequency noise of the ferromagnetic resonance (FMR) has so far been unexplored at mK-temperatures. Here, we investigate such FMR frequency fluctuations of a YIG sphere and find that these fluctuations are independent of temperature and drive power. This suggests that the measured frequency noise in YIG is dominated by undetermined noise sources, whose properties are not consistent with the conventional model of two-level systems, despite their effect on the sample linewidth. Moreover, the functional form of the FMR frequency noise power spectral density (PSD) cannot be described by a simple power law. By employing time-series analysis, we find a closed function for the PSD that fits to the observations. Our results underline the necessity of coherence improvements to magnon systems for useful applications in quantum magnonics.

Fluctuations of the resonance frequency and other forms of noise can drastically hamper the performance of sensors, amplifiers, and information processing circuits. This is accurate at room temperature but particularly crucial for quantum devices, where environmental noise leads to decoherence. The recent coupling of single magnons to superconducting qubits¹⁻³ and resonators⁴⁻⁶ has led to research on hybrid quantum magnonics⁷⁻⁹. There, the goal is a combination of quantum computing's exponential speed-up with magnonics^{10,11} versatile low-loss devices. A radio frequency-to-light conversion based on magnons¹²⁻¹⁴ presents a possible direction towards a quantum internet, but it also requires a coupling of several quantum systems. Such a coupling often results in additional loss channels and increased noise, which presents a major obstacle in quantum magnonics¹⁵. Yet, the influence and origin of magnonic noise is still largely an open question. So far, the phase noise of magnetic tunnel junction oscillators^{16,17}, the amplitude and phase noise of a magnonic waveguide^{18,19} at room temperature, and the magnetization noise of spins²⁰⁻²² from a theoretic viewpoint have been explored. At room temperature, YIG oscillators are known to exhibit extremely low phase noise²³⁻²⁵. At mK temperatures however, frequency fluctuations of the ferromagnetic resonance (FMR) have eluded attention, despite the recent reports of an increased linewidth due to two-level systems (TLS)²⁶⁻²⁸.

Here, we experimentally observe such FMR frequency fluctuations with a focus on an yttrium-iron-garnet (YIG). After an introduction to the measurement setup and the spec-

troscopic characterization of the YIG sample, we present the results of the fluctuation measurements and analyze them in the frequency- as well as time domain.

Our experimental setup (Fig. 1 (a)) consists of a vector network analyzer (VNA) connected to the magnetic medium via a strip-line in a notch-type configuration. The sample, a YIG sphere with diameter $d = 0.2\text{mm}$, is mounted in a solenoid coil inside a dilution refrigerator. The VNA offers a straightforward procedure for frequency noise measurements. Sweeping the probe frequency allows for a characterization of the sample via its $S_{ij}(\omega)$ -matrix element, from which we extract the FMR linewidth. Then, to measure frequency fluctuations, we employ the continuous wave mode of the VNA with probe frequency ω_p . Here, we record a time trace of the sample's frequency response at one single point close to resonance ($\omega_p \approx \omega_r$). Fluctuations in the phase $\arg S_{21}$ can then be converted to resonance frequency fluctuations via the slope in the linear region of $\arg S_{21}(\omega)$, see Fig. 1 (b) for a schematic overview and supplementary material I for more details. All measurements are performed and evaluated with the open-source measurement suite qkit³⁰.

We start with the spectroscopic characterization of our sample. The FMR is tuned to $\omega_r/2\pi = 6.11\text{GHz}$, corresponding to an external field $\mu_0 H \approx 0.21\text{T}$, where the sample is fully magnetized. Figures 1 (c,d) show the amplitude and phase of the background-corrected complex S_{21} frequency response. A circle fit²⁹ returns the internal linewidth (HWHM) $\kappa_i = \omega_r/(2Q_i)$, with Q_i as internal Q-factor. Varying power, P , and temperature, T , we find a linewidth dependence that

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FIG. 2. Frequency fluctuations of a ferromagnetic resonance (FMR) at mK temperatures. (a) A segment of the measured time trace of the frequency fluctuations ($P = -60$ dBm, $T = 50$ mK) compared to generated data, a realization of a third order autoregressive process AR(3). For better visibility the data are offset by ± 200 kHz and the measured time trace is post averaged to 8 Hz, so that periodic signals are removed. (b) Power spectral density (PSD) of FMR frequency fluctuations for different input powers and temperature (without post averaging). Below 3 Hz, the sample noise PSD exceeds the amplitude of parasitic noise sources, such as the HEMT amplifier and the current source. No dependence on these external parameters can be observed in the low frequency range of the PSD. The functional form of the PSDs is close to a Lorentzian but shows a steeper decay at around 1 Hz. (c,d) Autocorrelation (ACF) and partial autocorrelation (PACF) of the time trace data displayed in (a). PACF only shows values significantly different from zero up to lag $n = 3$, indicating an AR(3) process. Note the different scales of the x-axes. (e) A comparison of measured FMR noise data with an AR(3) process shows excellent agreement. Shaded area is due to the resampling to 8 Hz for the time series analysis. For the generated data, the PSD is calculated via Welch's method and via Eq. (4) with estimated coefficients.

of the noise measurements, which are presented in Fig. 2. Panel (a) shows a recorded time trace of the FMR frequency fluctuations, which is used to evaluate the PSD, as displayed in Fig. 2 (b). We note that the observed frequency noise PSD is indeed higher than the noise floor of the setup, given by the HEMT amplifier. It is also higher than the noise produced by the current source and higher than measured FMR frequency noise at room temperature (see supplementary material IC). We also observe a functional form of the PSD that does not fit a simple power law. Up to 1 Hz, it can be described by a Lorentzian function but then a steep decrease follows. To test the influence of external parameters, we vary the temperature from 50 mK to 800 mK and sweep the input power around the critical power from -60 dBm down to -100 dBm. Three curves are shown as examples, see supplementary material II for more data. The frequency noise PSDs all show an independence of temperature and power. The increased white noise part for the low power PSD arises from amplifier noise. Taking all these points together, we conclude that TLS as described by the standard or generalized tunneling model are not the most dominant noise source for frequency fluctuations in our magnetic system. The lack of a power dependence is the strongest argument. A comparison to superconducting resonators³⁷ supports this statement. There, the TLS

noise PSD at 0.1 Hz is three magnitudes lower than the observed FMR fluctuation PSD. Hence, despite showing a power or temperature dependent resonance linewidth, undetermined noise sources most likely mask the influence of TLS noise in the magnon system.

As the measured PSD does not follow a simple power law, a quantitative analysis is difficult. As a starting point for future works, we present a method to find a closed function for FMR frequency noise. This method is closely related to maximum entropy spectral analysis⁴¹, and based on time series analysis. There, a basic model describing random data is the autoregressive (AR) process, defined as

$$y_t = \varepsilon_t + \sum_{i=1}^p a_i y_{t-i}. \quad (3)$$

A random data point y_t at time t is calculated via a weighted sum of the last p data points with free parameters a_i plus a white noise term with a Gaussian probability density function $\mathcal{N}(\sigma, \mu = 0)$. σ and μ denote the standard deviation and mean value, respectively. See supplementary material III A for further information about AR processes. Importantly, these processes can be described by the following

closed function⁴²:

$$S(f) = \frac{2\sigma^2\delta t}{|1 - \sum_{k=1}^p a_k e^{-i2\pi k\delta t f}|}. \quad (4)$$

Hence, our goal is to estimate the order p and the a_i . For this purpose, we make use of the autocorrelation function (see Fig. 2(c)), showing an exponential-like decay and hence pointing towards an AR process, as expected from Eq. (3). The partial autocorrelation function (PACF), displayed in Fig. 2(d), gives only the direct correlation between data points, i.e., the indirect propagation of a perturbation over other data points is switched off. We can therefore estimate the order $p = 3$ from the number of values significantly different from zero. The a_i coefficients can then be calculated by employing the Yule-Walker equations^{43,44}, which relate the ACF to the a_i (supplementary material III B). The estimated coefficients are $a_1 = 1.764$, $a_2 = -1.079$, $a_3 = 0.309$, $\sigma = 5.284$ kHz. Note that the order and subsequently the coefficients depend on the chosen sampling rate. For the time series analysis, a digital post averaging to a sampling frequency of 8 Hz was performed, removing periodic signals and the $1/f$ amplifier part. These noise forms are not captured by an AR process. See supplementary material IV for different sampling rates. With the estimated values, we can generate a model time trace for comparison (Fig. 2(a)) and calculate its PSD. Figure 2(e) shows an excellent agreement of the measured PSD with both the numerical simulation and the closed form, confirming the validity of the AR model. Furthermore, from the estimated parameters and the ACF, we can conclude that FMR frequency fluctuations show a Brownian motion like behavior. Yet these fluctuations are exponentially damped out over time and require a weighted sum of data points in the past. The weighted sum indicates several noise mechanisms that occur on different timescales²¹. Regarding the PSD, a damped Brownian motion would be one process that leads to the dominating Lorentzian part below 1 Hz. Since also other mechanisms exist that manifest in a Lorentzian PSD, such as random telegraphic noise or a modulation of the measured data, more work is necessary to completely understand the shape of the PSD and to identify the underlying noise mechanisms. Exploring FMR noise in a variety of magnetic materials, different sample geometries and fabrication procedures would be advantageous.

In conclusion, we studied FMR frequency fluctuations at mK temperatures. The recorded PSDs do not show a simple power law. They are independent of temperature and input power, which indicates undetermined noise mechanisms stronger than the influence of TLS described by the the generalized / standard tunneling model. We also presented a method to analyze noise data in the time domain. This is especially useful if a simple power law is not sufficient to describe the noise PSD. With this method and after post averaging of the data down to 8 Hz, we find an excellent agreement of the measured data with an AR(3) process, suggesting that several noise processes on different time scales are at play. A comparison to room temperature measurements has shown increased noise at low temperatures, underpinning the importance of improving magnon coherence for useful applications

in the quantum limit. With this work, we hope to spark a broader interest into magnon decoherence research.

SUPPLEMENTARY MATERIAL

See supplementary material for more information about the experimental details, including measurements of parasitic noise sources, room temperature noise measurements with YIG and lithium ferrite, and additional explanations about the time series analysis.

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DATA AVAILABILITY STATEMENT

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

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