SPIN-WAVE NOISE AND ITS DETECTION USING NITROGEN-VACANCY RELAXOMETRY

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Abstract

Magnons are quanta of spin waves, modes of collectively precessing spins. Thermally excited magnons in thin magnetic films generate stray fields at the film surface which can be detected using nitrogen-vacancy (NV) centers. NVs are lattice defects in diamond and are able to couple with magnon stray fields. Assuming a thermal occupancy of magnon modes, we study the magnetization dynamics of the magnons propagating through thin magnetic insulators using the Landau-Lifshitz-Gilbert equation. We implement a numerical model to predict and understand the response of the NV center to proximal magnons in thin films. We investigate how the NV relaxation rate changes for different NV orientations by extending and generalizing the existing theory on chiral magnetic noise, and simulate an experimental setup for an NV placed just above the surface of a thin magnetic insulator. The simulation includes a static bias field in an arbitrary orientation with respect to the quantization axis of the NV center using the diamond's tetrahedral symmetry. This extended model is in demand due to limitations in present-day measurement techniques to align the bias field with an NV center. We use it to detect magnons that contribute to the relaxation rate of the NV, and determine an NV-to-film distance of $0.28(3)\ \mu\text{m}$ from measured relaxation rates of an NV center placed above an yttrium-iron-garnet film with a thickness of 235(10) nm. Our model is available as an open-source Python module.

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Chapter 1

Introduction

Computers have become indispensible devices in our daily lives. They come in diverse shapes and sizes with different functionalities in the form of e.g. laptops, smartphones or a Raspberry Pi. These computing devices all make use of microchips to process data. The most common microchips are made of transistors that heavily rely on charges carrying information. Such microchips have drawbacks: moving charges dissipate heat due to resistance. To solve this issue, an alternative for information processing is a technology based on spintronics. This technique relies on information transfer via spins rather than moving charges, preventing computing devices from overheating and damage.

For future spintronic devices to work efficiently, information transfer over large distances is desirable. Magnetic insulators such as yttrium iron garnet ($Y_3Fe_5O_{12}$, 'YIG') have low damping [1] allowing spin waves to travel distances in the order of centimeters [2]. Spin waves (or their quanta: magnons) are modes of collectively precessing spins. Experiments have shown that thin magnetic films are a good candidate for the development of spin-wave based signal processing devices [3, 4]. Until recently, theoretical analysis [5–7] of experiments neglected the effect of chirality of the magnetic fields generated by spin waves in magnetic insulators. For this reason, a recently formulated theory on quantum-impurity (QI) relaxometry includes the role of chiral coupling between QIs and thermal magnons in thin films on QI relaxation [8], showing excellent agreement with experimental results [6].

Atomic defects in a diamond's crystal lattice such as nitrogen-vacancy (NV) centers can be used as magnetic field sensors. They have convenient optical properties and therefore enable imaging of spin waves propagating through magnetic insulators [5–7, 9]. However, detecting magnetic noise very close to a magnetic sample is experimentally challenging since difficulties lie within placing a diamond tip containing a single NV center in close proximity (nanometer range) to a thin-film sample, requiring localization of NVs inside the diamond lattice.

This work is an extension to the chiral theory proposed by Rustagi et al. [8]. The central goal of this thesis is to understand the role of chirality of spin-wave noise in predicting NV relaxation rates under different arbitrary experimental conditions. We find that it is in particular important to understand the relation between NV relaxation and arbitrary directions of an external magnetic field with respect to NV orientations. Assuming thermal occupancy of the spin-wave modes, we calculate stray fields produced by the spin waves in thin magnetic films. We first calculate the magnetic field fluctuations generated by thermal spin waves in a magnetic thin film and corresponding NV relaxation rates to reproduce the results from Ref. [8]. Next, we extend and generalise the existing chiral theory to include arbitrary angles of the NV relevant to explain the ensemble NV measurements. We build a numerical model for a simulated setup in which the static bias field is not well-aligned with the NV axis. Achieving this is relevant to present-day measurement setups [10] in which misalignment occurs due to limitations of experimental methods. Herewith, we investigate how the relaxation rate changes when choosing any arbitrary orientation for the NV axis. Finally, we use our predictive model to determine the NV-to-film distance from thermal magnon noise.

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