

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

HELENA LA  
TU DELFT



Cover art by Brecht G. Simon.

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

Helena La

*Supervision:*

Dr. Toeno van der Sar  
Brecht G. Simon

*Exam committee:*

Prof. Dr. Yaroslav Blanter  
Prof. Dr. Sander Otte

Thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science

Department of Quantum Nanoscience  
Technische Universiteit Delft

July 2021



# 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 a yttrium-iron-garnet film with a thickness of  $235(10) \text{ nm}$ . Our model is available as an open-source Python module.



# Contents

<b>Abstract</b>	<b>V</b>
<b>Contents</b>	<b>VIII</b>
<b>List of Figures</b>	<b>X</b>
<b>1 Introduction</b>	<b>11</b>
<b>2 Magnons in thin magnetic films</b>	<b>13</b>
2.1 Spin waves in magnetic insulators . . . . .	14
2.2 Magnetization dynamics described by the LLG equation . . . . .	15
2.3 Free energy to describe magnetisation in thin films . . . . .	16
2.3.1 Exchange energy . . . . .	17
2.3.2 Zeeman energy . . . . .	17
2.3.3 The demagnetizing field . . . . .	18
2.4 Spin-wave susceptibility . . . . .	19
2.4.1 Magnetic field transverse to the equilibrium magnetization	19
2.4.2 Susceptibility matrix . . . . .	20
2.4.3 Magnon correlations . . . . .	21
2.5 Spin-wave dispersion and distance filter function . . . . .	22
2.5.1 Exchange energy and the shape of spin-wave dispersion .	23
2.5.2 Film thickness dependency . . . . .	25
<b>3 NV center: QM sensor for magnetic fields</b>	<b>26</b>
3.1 Electron spin resonance of an isolated spin . . . . .	27
3.2 Electron spin resonance of the NV center . . . . .	27
3.3 NV orientations and their ESR frequencies . . . . .	29
<b>4 Coupling between the NV and magnons</b>	<b>32</b>
4.1 Chiral coupling: stray fields reaching the NV center . . . . .	32
4.2 NV relaxation rate induced by magnon stray fields . . . . .	34

4.3	Magnon stray field outside the magnetic film . . . . .	35
<b>5</b>	<b>Relaxation rate for a well-aligned bias field</b>	<b>37</b>
5.1	Numerical approach to solve the rate . . . . .	38
5.2	Relaxation rate as function of external field . . . . .	40
5.2.1	Frequency-dependent magnon occupation . . . . .	40
5.2.2	Wavenumber filtering . . . . .	42
5.3	Nonzero relaxation rates below the FMR . . . . .	42
<b>6</b>	<b>Relaxation rates for arbitrary NV orientations</b>	<b>45</b>
6.1	Rate for different OOP angles of external field . . . . .	46
6.2	Relaxation for different NV families . . . . .	47
6.3	Magnon wavenumbers for each NV family . . . . .	49
<b>7</b>	<b>Determination of NV-to-film distance</b>	<b>52</b>
7.1	Method to extract the initial NV-to-film distance . . . . .	53
7.2	Fitting the offset distance . . . . .	54
<b>8</b>	<b>Conclusion</b>	<b>56</b>
	<b>Acknowledgement</b>	<b>58</b>
<b>A</b>	<b>Supplemental material</b>	<b>59</b>
A.1	Time-dependent fluctuations . . . . .	59
A.2	Limit of the film thickness . . . . .	59
A.3	Mass on a spring . . . . .	60
A.4	Cross-relaxation rates . . . . .	61
<b>B</b>	<b>Python code</b>	<b>63</b>
B.1	Code installation . . . . .	63
B.2	Examples . . . . .	64
	<b>Bibliography</b>	<b>71</b>

# List of Figures

2.1	Collectively precessing spins forming a spin wave. . . . .	14
2.2	Precessional motion of the magnetization due to a damping torque. . . . .	16
2.3	DE and BV spin-wave dispersion with filter function for a 235-nm-thick YIG film . . . . .	23
2.4	Exchange stiffness and its effect on the spin-wave dispersion. . . . .	24
2.5	The Damon-Eshbach (DE) and Backward-Volume (BV) spin-wave dispersion for 60 Gauss and film thickness between 20 and 200 nm . . . . .	25
3.1	Spin-level structure of the NV . . . . .	28
3.2	Illustration of the four possible NV orientations . . . . .	29
3.3	NV-ESR frequencies in the presence of an external magnetic field perfectly aligned with NV in 111 direction . . . . .	31
4.1	Chiral coupling between the NV center and thermally excited magnons in a magnetic thin film . . . . .	33
5.1	Wavenumber distribution of the rate integrand for a 235-nm-thick YIG film in an external field of 250 Gauss and NV-to-film distance of 109 nm . . . . .	39
5.2	Relaxation rates as function of external field for a 20-nm-thick YIG film, including maps of the wavenumber contributions to the rate integrand mapped out for external fields 50, 250 and 310 Gauss . . . . .	41
5.3	Relaxation rate for a 20-nm-thick YIG film with ESR frequency and filtered wavenumbers for external field of 100, 225 and 300 Gauss . . . . .	43
5.4	Nonzero relaxation below the FMR . . . . .	44
6.1	Relaxation rate as function of external field for a 20-nm-thick YIG film and different OOP angles for the external field . . . . .	46

6.2	Four orientations of the NV quantization axis above a ferromagnetic (FM) thin film with the direction of magnon-wavevector components $k_x$ and $k_y$ . . . . .	47
6.3	Relaxation rates for a 20-nm-thick YIG film with $\vec{B}_{\text{ext}} \parallel \text{NV}_1$ with heatmaps of the rate integrand and external field of 250 G for all four NV families . . . . .	48
6.4	Enhanced peak heights of the rate integrand for a 20-nm-thick YIG film in an external field of 250 G and NV-to-film distance of 50, 200 and 500 nm . . . . .	50
6.5	NV-ESR isofrequency for $\text{NV}_2$ with filter circle $\mathcal{C}$ . . . . .	51
7.1	Curve fit method: shifting the modeled rate decay to determine NV-to-film distance . . . . .	53
7.2	Extracting the initial NV-to-film distance via thermal magnon noise	54
A.1	Cross-relaxation between two NVs with different spin polarizations	62

# Chapter 1

## Introduction

Computers have become indispensable 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 ( $\text{Y}_3\text{Fe}_5\text{O}_{12}$ , '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.

# Bibliography

1. Bertelli, I., Carmiggelt, J. J., Yu, T., Simon, B. G., Pothoven, C. C., Bauer, G. E. W., Blanter, Y. M., Aarts, J. & van der Sar, T. Magnetic resonance imaging of spin-wave transport and interference in a magnetic insulator. *Science Advances* **6**. <https://advances.sciencemag.org/content/6/46/eabd3556> (2020).
2. Chumak, A. V., Vasyuchka, V. I., Serga, A. A. & Hillebrands, B. Magnon spintronics. *Nature Physics* **11**, 453–461. <https://doi.org/10.1038/nphys3347> (2015).
3. Papp, A., Porod, W. & Csaba, G. Hybrid yttrium iron garnet-ferromagnet structures for spin-wave devices. *Journal of Applied Physics* **117**, 17E101. <https://doi.org/10.1063/1.4906209> (2015).
4. Lee-Wong, E., Xue, R., Ye, F., Kreisel, A., van der Sar, T., Yacoby, A. & Du, C. R. Nanoscale Detection of Magnon Excitations with Variable Wavevectors Through a Quantum Spin Sensor. *Nano Letters* **20**, 3284–3290 (2020).
5. Van der Sar, T., Casola, F., Walsworth, R. & Yacoby, A. Nanometre-scale probing of spin waves using single electron spins. *Nature Communications* **6**, 7886. <https://doi.org/10.1038/ncomms8886> (2015).
6. Du, C., van der Sar, T., Zhou, T. X., Upadhyaya, P., Casola, F., Zhang, H., Onbasli, M. C., Ross, C. A., Walsworth, R. L., Tserkovnyak, Y. & Yacoby, A. Control and local measurement of the spin chemical potential in a magnetic insulator. *Science* **357**, 195–198. <https://science.sciencemag.org/content/357/6347/195> (2017).
7. Purser, C. M., Bhallamudi, V. P., Guo, F., Page, M. R., Guo, Q., Fuchs, G. D. & Hammel, P. C. Spinwave detection by nitrogen-vacancy centers in diamond as a function of probe–sample separation. *Applied Physics Letters* **116**, 202401. <https://doi.org/10.1063/1.5141921> (2020).
8. Rustagi, A., Bertelli, I., van der Sar, T. & Upadhyaya, P. Sensing chiral magnetic noise via quantum impurity relaxometry. *Phys. Rev. B* **102**, 220403. <https://link.aps.org/doi/10.1103/PhysRevB.102.220403> (22 2020).

9. Bertelli, I., Simon, B. G., Yu, T., Aarts, J., Bauer, G. E. W., Blanter, Y. M. & van der Sar, T. *Imaging spin-wave damping underneath metals using electron spins in diamond* 2021.
10. Simon, B. G., Kurdi, S., La, H., Bertelli, I., Carmiggelt, J. J., Ruf, M., de Jong, N., van den Berg, H., Katan, A. & van der Sar, T. *Directional excitation of a high-density magnon gas using coherently driven spin waves* 2021.
11. Kittel, C. *Introduction to Solid State Physics* 8th ed. [http://www.amazon.com/Introduction-Solid-Physics-Charles-Kittel/dp/047141526X/ref=dp\\_ob\\_title\\_bk](http://www.amazon.com/Introduction-Solid-Physics-Charles-Kittel/dp/047141526X/ref=dp_ob_title_bk) (Wiley, 2004).
12. Carmiggelt, J. J., Simon, B. G., Bertelli, I. & van der Sar, T. Spinsensoren in diamant onthullen golvende spinzee. <https://www.ntvn.nl/2021/6/spinsensoren-diamant-onthullen-golvende-spinzee/> (2021).
13. Gilbert, T. A phenomenological theory of damping in ferromagnetic materials. *IEEE Transactions on Magnetics* **40**, 3443–3449 (2004).
14. Zhao, Y., Song, Q., Yang, S.-H., Su, T., Yuan, W., Parkin, S. S. P., Shi, J. & Han, W. Experimental Investigation of Temperature-Dependent Gilbert Damping in Permalloy Thin Films. *Scientific Reports* **6**. <http://dx.doi.org/10.1038/srep22890> (2016).
15. Kupriyanova, G. & Orlova, A. Simulation of the FMR Line Shape. *Physics Procedia* **82**, 32–37. <https://www.sciencedirect.com/science/article/pii/S1875389216300906> (2016).
16. Qin, H., Hämäläinen, S. J., Arjas, K., Witteveen, J. & van Dijken, S. Propagating spin waves in nanometer-thick yttrium iron garnet films: Dependence on wave vector, magnetic field strength, and angle. *Physical Review B* **98**. <http://dx.doi.org/10.1103/PhysRevB.98.224422> (2018).
17. Polder, D. On the theory of ferromagnetic resonance. *Physica* **15**, 253–255. <https://www.sciencedirect.com/science/article/pii/0031891449900518> (1949).
18. Adachi, H. & Maekawa, S. in *Handbook of Spintronics* (eds Xu, Y., Awschalom, D. D. & Nitta, J.) 1553–1576 (Springer Netherlands, Dordrecht, 2016). [https://doi.org/10.1007/978-94-007-6892-5\\_54](https://doi.org/10.1007/978-94-007-6892-5_54).
19. Bhaskar, U. K., Talmelli, G., Ciubotaru, F., Adelman, C. & Devolder, T. Backward volume vs Damon–Eshbach: A traveling spin wave spectroscopy comparison. *Journal of Applied Physics* **127**, 033902. <http://dx.doi.org/10.1063/1.5125751> (2020).

20. Klingler, S., Chumak, A. V., Mewes, T., Khodadadi, B., Mewes, C., Dubs, C., Surzhenko, O., Hillebrands, B. & Conca, A. Measurements of the exchange stiffness of YIG films using broadband ferromagnetic resonance techniques. *Journal of Physics D: Applied Physics* **48**, 015001. <http://dx.doi.org/10.1088/0022-3727/48/1/015001> (2014).
21. Fujiwara, M., Shikano, Y., Tsukahara, R., Shikata, S. & Hashimoto, H. Observation of the linewidth broadening of single spins in diamond nanoparticles in aqueous fluid and its relation to the rotational Brownian motion. *Scientific Reports* **8**, 14773. <https://doi.org/10.1038/s41598-018-33041-6> (2018).
22. Weggler, T., Ganslmayer, C., Frank, F., Eilert, T., Jelezko, F. & Michaelis, J. Determination of the Three-Dimensional Magnetic Field Vector Orientation with Nitrogen Vacancy Centers in Diamond. *Nano Letters* **20**, 2980–2985. <http://dx.doi.org/10.1021/acs.nanolett.9b04725> (2020).
23. Tiesinga, E., Mohr P. J. Newell, D. B. & Taylor, B. N. *The 2018 CODATA Recommended Values of the Fundamental Physical Constants (Web Version 8.1). Database developed by J. Baker, M. Douma, and S. Kotochigova.* 2020. <http://physics.nist.gov/constants>.
24. Simons, B. *Lecture notes: Advanced Quantum Mechanics* 2009. <http://www.tcm.phy.cam.ac.uk/~bds10/aqp.html>.
25. La, H., Simon, B. G., Kurdi, S. & van der Sar, T. *QI relaxometry: sensing spin-wave noise* 2021. <http://github.com/helenala/qi-relaxometry>.
26. Demokritov, S. O., Demidov, V. E., Dzyapko, O., Melkov, G. A., Serga, A. A., Hillebrands, B. & Slavin, A. N. Bose–Einstein condensation of quasi-equilibrium magnons at room temperature under pumping. *Nature* **443**, 430–433. <https://doi.org/10.1038/nature05117> (2006).
27. Demidov, V. E., Urazhdin, S., Divinskiy, B., Bessonov, V. D., Rinkevich, A. B., Ustinov, V. V. & Demokritov, S. O. Chemical potential of quasi-equilibrium magnon gas driven by pure spin current. *Nature Communications* **8**, 1579. <https://doi.org/10.1038/s41467-017-01937-y> (2017).
28. Flebus, B. & Tserkovnyak, Y. Quantum-Impurity Relaxometry of Magnetization Dynamics. *Physical Review Letters* **121**. <http://dx.doi.org/10.1103/PhysRevLett.121.187204> (2018).
29. Mrozek, M., Rudnicki, D., Kehayias, P., Jarmola, A., Budker, D. & Gawlik, W. *Longitudinal spin relaxation in nitrogen-vacancy ensembles in diamond* 2015.