Magnetic imaging of spin waves and magnetic phase transitions with nitrogen-vacancy centers in diamond

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CONCLUSION

This chapter summarizes the most important results obtained throughout this thesis, and indicates possible future research directions.

8.1. CONCLUSION

The majority of this thesis is devoted to the investigation of spin waves and their properties. In Chapter 4 we established a new technique to image coherent spin waves using nitrogen-vacancy centers in diamond. We showed that such technique can be used to extract quantitative information - such as the spin-wave amplitude - and to measure the spin-wave velocity in real space. Our results suggest that the sensitivity of the technique should allow the detection of spin waves in monolayer magnets, such as Van der Waals materials.

In Chapter 5 we used such technique to study the spin-wave damping caused by metallic electrodes. We modelled the damping as being induced by eddy currents in the metal, which dissipate energy, obtaining a good match with the experimental results. We showed that the capability of our technique for imaging spin waves underneath optically opaque material (such as metals) makes it possible to characterize the quality of a buried interface.

In Chapter 6 we characterized the magnetic noise caused by thermally excited spin waves using NV relaxometry. We found a good agreement with a model based on the chiral coupling between the spin-wave fields and the NV spin, but we detected discrepancies at the ferromagnetic resonance (FMR) frequency, ascribed to local variations of the static field.

In Chapter 7 we studied a metamagnetic phase transition, showing that the use of statistical methods can enable the characterization of the global properties of a system, even using a local technique such as NV magnetometry.

Unlike the most common spin-wave imaging techniques, NV magnetometry detects spin waves via their stray magnetic field. While this could introduce uncertainty (reconstructing a magnetization pattern from the magnetic field is an underdefined problem), it also opens up several research directions. Additionally, some constrains on our technique can be addressed and made less severe. In the next section we will describe both aspects.

8.2. OUTLOOK

This thesis focused on establishing a new technique to image spin waves and using it to characterize various aspects of spin-wave propagation, rather than maximizing the spatial resolution or the magnetic field sensitivity. Future research can therefore improve on our results by implementing NV-based imaging of spin waves in a scanning geometry, i.e. embedding a single NV center into a pillar at the apex of a diamond AFM cantilever. The achievable NV-magnet distance should be of a few tens of nanometers, resulting in a spatial resolution on a similar scale, and an enhancement in magnetic field sensitivity of several orders of magnitude, since the spin-wave stray magnetic fields typically decay exponentially with the ratio of the distance over the wavelength. Additionally, the sensitivity could be increased by using NV ensembles in a wide-field setup, in which an image can be recorded at once, such that measurement time can be devoted to reducing noise rather than scanning the laser spot on the diamond.

These advancements will enable several new research directions. The improved spatial resolution will allow to study spin waves with much shorter wavelength (i.e. tens of nanometers). These waves are more interesting for technological purposes, but also harder to excite inductively. New excitation strategies, effective at the nanoscale, could be designed and tested.

Investigating magnetic van der Waals materials (i.e. CrI_3 and $Cr_2Ge_2Te_6$) could provide information regarding spin waves in truly two-dimensional systems, which might be different (e.g. a different dispersion) from conventional ones. Even though it seems already possible to detect spin waves in such monolayer magnets (from the estimated sensitivity of our approach), an improved sensitivity would be beneficial to this end.

Additionally, detecting spin waves via their stray magnetic fields enables several research directions because it grants the possibility of imaging underneath non-magnetic material. Opportunities that appear within reach include studying the interactions of spin waves with electrical currents, with superconductors, and with van der Waals materials. In the first case, depositing a platinum electrode on YIG enables injecting spin waves via the spin-Hall effect. Imaging underneath the contacts could shed new light on the physical processes at play, including spin-wave damping via the inverse spin-Hall effect. Interesting phenomena stemming from the interactions of superconductors and spin waves could include the motion of superconducting vortices coupled to spin waves and the partial screening of the spin-wave fields by AC currents in the superconductor. Depositing a van der Waals material on another magnet (e.g. YIG) could lead to a coupling between the valley pseudo-spin and (coherent) spin waves propagating in YIG.

One constraint of our technique is the need for the resonance between the frequency of the NV electron spin resonance (ESR) and that of the spin waves. One possible future research direction involves trying to address this challenge, relaxing the constraint. One possibility is to rely on non-linear processes, such as four-magnon scattering, to reveal the presence of high-frequency modes (non resonant with the ESR): two spin waves of frequency above the ESR can simultaneously scatter to the ESR and to a higher frequency, if both modes are allowed in the magnet, and if the scattering event conserves frequency and momentum. When the high-frequency mode is populated to a higher degree, the scattering rate increases (similar to a stimulated emission process) and the contrast of the ESR increases as a consequence. A large population of the high-frequency mode could be the result of coupling the magnet with a different system - e.g. a magnet of unknown saturation magnetization where the ferromagnetic resonance (FMR) is driven - resulting in a signature at the ESR. This phenomenon could be used to detect any signals of frequency above the ESR, provided that it couples to existing modes in the magnet in which the non-linear scattering is taking place. Besides the extended capabilities of NV magnetometry, understanding non-linear scattering processes of spin waves is interesting *per se*. We could start by studying this process in YIG, i.e. characterizing the frequency range (and its power-dependence) and if higher-order processes are allowed as well.

While it is interesting to improve the technique we developed, trying to compete with other spin-wave imaging techniques is not necessary. For example, performing time-resolved measurement is best left to techniques such as Brilouin light scattering (BLS) and magneto-optical Kerr effect (MOKE) microscopy, which can work with pump-probe schemes and reach femtosecond time resolution. Rather, NV-based imaging of spin waves should focus on the tasks that are virtually impossible to achieve with other techniques, such as studying phenomena at buried interfaces, characterizing the interaction of spin waves with other excitations that generate a magnetic stray field (i.e. currents, superconducting vortices), and exploiting the high sensitivity to probe monolayer van der Waals magnets.