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

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Citation

Bertelli, I. (2021, November 24). *Magnetic imaging of spin waves and magnetic phase transitions with nitrogen-vacancy centers in diamond*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/3245183

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INTRODUCTION

1.1. BEYOND CONVENTIONAL ELECTRONICS: MAGNONICS

In the last decades, the ever-increasing technological needs have been pushing electronic devices towards their speed and size limits [1]. Therefore, researchers have tried to establish new technologies beyond conventional electronics - which relies on the diffusive motion of electric charges to process and transport information. One field that emerged is that of *spintronics* (spin-electronics), established with the discovery of the giant magneto-resistance (GMR) [2, 3]. The central idea of spintronics is that information can be encoded in the spin of an electron [4–6]. Spintronics has already delivered a number of devices that find commercial applications, including GMR-based spin valves [4], magnetic tunnel junctions based on the giant tunnel magneto-resistance [7, 8] (TMR) as read heads in storage devices [9]. Recently, the magnetic random-access memory (MRAM) based on spin-transfer [10–14] or spin-orbit torques [15–19] (STT and SOT, respectively), started replacing conventional static and dynamic random-access memories (SRAM and DRAM, respectively), in certain applications [20–22].

Compared to the spin-polarized electric currents used in most of these applications, an advantage of pure spin currents is that the motion of spins is decoupled from the motion of charges. Such diffusive charge transport is characterized by electron scattering, which leads to dissipative effects known as Joule (or Ohmic) heating [23]. The transport of pure spin information can be achieved in magnetic insulators such as yttrium-iron garnet (YIG), where coherent spin excitations (spin waves, Fig. 1.1) can propagate with ultralow dissipation [24] (i.e. with propagation distance up to several millimeters and long spin-wave coherence times [25]). The branch of spintronics that deals with information transport and processing based on spin waves is called *magnonics*, from the name of the quanta of spin waves, the magnons [23, 26].

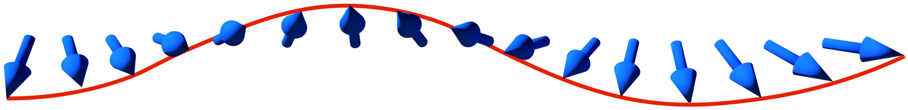

Figure 1.1: Spin wave. In a magnetic insulator, the spins (localized at lattice sites) precess around the static magnetization. The precession of neighbouring spins with a phase difference corresponds to a travelling signal, the *spin* wave.

1.1.1. SPIN WAVES

Spin waves were first predicted by Bloch almost 100 years ago as collective excitations of the spins in a ferromagnet [27]. Information transport and processing based on spin waves hold great promises [28–32], because of the several key properties of spin waves:

- Spin-wave frequencies range from the GHz to the THz regime [24], thus being well matched to the frequency of current electronic devices, but leaving plenty of room for further speed up.
- Spin-wavelengths can be as small as few nanometers, limited only by the lattice constant of the magnetic material [33], thus allowing device miniaturization.
- Unlike spin-polarized electrons, that retain information only up to the spin diffusion length (typically few tens of nanometers in metallic magnets), spin waves can propagate coherently over distances up to several millimeters [25].
- Because of their wavelike nature, information can be encoded in the phase of spin waves [34], enabling non-Boolean logic [35–39]. Parallel operation at different frequencies (i.e. multiplexing) is also possible [40–43].

Additionally, spin waves are interesting from a fundamental point of view because they show a wealth of non-linear [44–46] and non-reciprocal [47–53] effects, and they can show peculiar phenomena such as magnon condensation [54–57] and magnon supercurrents [56, 58–60].

1.1.2. SPIN-WAVE DETECTION

Because of the large interest in the physics of spin waves and their applications in information technology, many techniques have been develop to study spin waves. Among the non-local (i.e. without imaging capabilities) techniques, the most common are broadband-FMR [61], inelastic neutron scattering [62–65], the inverse spin-Hall effect [66–72] and, recently, superconducting qubits [73–76]. The leading techniques to image spin waves include Brillouin light scattering [77], scattering of x-rays [78, 79], thermal imaging [80, 81], and imaging based on the magneto-optical Kerr effect [82–84].

Because studying spin waves in magnonic devices is so important, in this thesis we develop a new technique to image spin waves relying on the detection of the spin-wave stray field with a quantum sensor [85]. Besides the high sensitivity that can be achieved by such a sensor [86], our method can image spin waves propagating underneath metallic electrodes [87], such as those routinely used to excite spin waves inductively. The sensor we use is the electron spin localized at lattice defects in diamond, known as nitrogen-vacancy (NV) centers.

1.2. THE NITROGEN-VACANCY CENTER IN DIAMOND

Nitrogen-vacancy centers are color centers in diamond with spin-dependent optical properties [88–90]. The absence of photobleaching and the long spin lifetime at room temperature, together with the optical addressability of its spin state, have made this defect one of the most studied in the 25 years after the first report of optically detected magnetic resonance (ODMR) of individual NV centers at room temperature [91]. The applications of NV centers in quantum science and technology [92] include quantum communication [93–100], quantum computation and simulation [101–108], and quantum sensing [109]. As a quantum sensor, the NV spin has been employed to study a wide variety of living [110–115] and condensed matter systems [116–120], thanks to the combination of small size, wide operating temperature and frequency range [121], and high sensitivity to stress [122–124], temperature [110, 125, 126], electric [127, 128] and magnetic fields [129–137].

In this thesis, we use NV centers as magnetometers to characterize magnetic stray fields. A significant part of this thesis is focused on probing spin waves. To do so, we study how the NV spin dynamics is driven by the GHz spin-wave stray fields. In addition, we explore magnetic phase transitions by characterizing the stray field-dependent energy structure of the NV centers.

1.3. THESIS OUTLINE

Chapter 2 provides an introduction to magnetometry with NV centers in diamond. We start with a short description of the NV's electronic structure and spin-dependent optical properties. Then, we focus on the detection of magnetic fields, showing how to characterize static and oscillating magnetic fields, both coherent and incoherent, using NV centers.

In Chapter 3 we discuss spin waves theoretically, and derive several useful equations, including the spin-wave dispersion and the coupling between the spin-wave stray fields and the NV spin, that are necessary to understand the following chapters.

Being able to quantitatively detect coherent spin waves via their microwave stray field is an alternative and complementary way of studying spin waves compared to existing techniques. In Chapter 4 we establish a new method to image coherent spin waves using ensembles of NV spins, that allows to extract the amplitude of the spin-wave precession, and we show that imaging spin waves in monolayer magnets is within reach of our sensitivity.

Using this newly introduced technique and its ability to image spin waves underneath metals, in Chapter 5 we characterize the excess damping caused by metallic electrodes on spin-wave propagation. We find a damping increase by roughly two orders of magnitude, which is well explained by a theoretical model we introduce.

The magnetic noise generated by a system is related to its excitations via the fluctuation-dissipation theorem, thus providing valuable insights into the spin-spin correlations, which characterize a particular magnetic phase. In Chapter 6 we detect magnetic field fluctuations generated by thermal spin waves, finding a good agreement with the model introduced in chapter 3.

One of the key strengths of NV magnetometry, i.e. its locality, can also be a drawback when addressing global properties of a system, such as the temperature of a phase transition. In Chapter 7 we apply statistical tools to overcome this challenge, focusing on the temperature-driven metamagnetic phase transition of FeRh, between the antiferro- and ferromagnetic states.

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