# SPIN-WAVE-BASED COMPUTING

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Theses of the PhD Dissertation

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Budapest, 2017

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# CHAPTER 1

# INTRODUCTION

Magnetic computing has found special interest in the last decade and has been intensely researched as a candidate for beyond-CMOS technologies. Today's computing is mostly based on electrical signals and charges, and spin is almost always only used as an information storage element. However, it has been demonstrated that magnetization state [1], [2] as well as spin-wave amplitude and phase [3], [4], [5], [6], [7] may be used for information transfer and processing.

Spin-based devices offer relatively low power consumption, medium to high speed, intrinsic non-volatility, and small footprint, while typically they do not require exotic materials or new fabrication technologies. Spin waves are propagating excitations of the magnetic media, typically in ferromagnetic or ferrimagnetic materials. Spin waves are different from electromagnetic waves in a number of ways. They are non-linear (can be used in linear region with small amplitudes), require a magnetic medium to propagate, they have relatively short wavelength (potentially $\lambda < 100$ nm) in the frequency region of 1-100 GHz. These properties make spin waves attractive for on-chip applications. Most research recently has been conducted towards creating a new logical switch, which could replace today's CMOS based gates. However, spin waves may be used for analog information processing, wave computing, either used in the linear region or exploiting the nonlinearity of spin waves. Good summaries of the current directions in the field are [8] and [9].

We believe that an especially attractive application area for spin waves could be signal processing applications. There is a wide class of problems that require extensive use of linear transformations (such as spectral analysis), and these require extensive computational power. These problems are usually highly parallelizable and there are multiple dedicated device classes used as co-processors to accelerate these calculations, such as digital signal processors (DSP) or graphics processing units (GPU). These hardwares are usually based on CMOS technology and have a specialized limited instruction set that is optimized for certain problems. Typical applications include image processing, data mining, spectral decomposition, etc. These applications usually require high-speed processing of enormous amounts of data with a single instruction. A very good fit for these type of problems could be the use of wave-computing computational models instead of Boolean-logic-based arithmetics. These exploit the highly parallel nature of wave propagation and are able to process data by linear interference of waves. Information can be encoded in either the phase or the amplitude of waves, which can be in time domain or spatial. By designing appropriate interference patterns of the waves, it is possible to implement complex linear transformations. The underlying physical representation of the waves can be any linear or approximately linear interaction, e.g. spin waves or electromagnetic waves. Our choice of representation is the use of spin waves, and we will show that such wave-computing algorithms are indeed feasible using spin waves and argue about the benefits of using spin waves, keeping in mind their limitations as well.

# CHAPTER 2

# METHODS

We investigated the feasibility of spin-wave-based computing devices using micromagnetic simulations. For modeling the magnetic phenomena we used the micromagnetic model, which is a classical description of magnetism, and valid above a few nanometers. In order to demonstrate the validity of our results we also started experimental investigations, and we performed Brillouin Light Scattering measurements on spin waves in thin ferromagnetic films.

The magnetic properties of materials arise mainly from the spin of the elementary particles in the atom (most significantly the electron and nuclear spin) and the orbital angular momentum of the electrons. It is usually convenient to denote the spatial distribution of the magnetic moments using a vector field $\mathbf{M}(\mathbf{r}, t)$. A magnetic field applied on a magnetic moment creates a torque on it. This magnetic field can be an external field, e.g. created by a current, or the magnetic field of the elementary magnetic moments in the material. The latter is called demagnetizing field since the demagnetizing energy is minimal if the magnetic moments point in opposite directions, thus the net magnetic field of the sample diminishes.

Another important phenomenon is the exchange interaction, which is a purely quantum mechanical effect acting on the elementary particle level. In ferromagnets, the exchange energy is lowest if the electron spins are parallel to each other, and highest if they are antiparallel. The exchange interaction causes the spins to arrange in the same direction in the material, giving rise to magnetic domains. Although the exchange interaction is a quantum effect, it is convenient to represent it as a classical magnetic field in the micromagnetic model.

The effective magnetic field $\mathbf{H}_{eff}(\mathbf{r}, t) = \mathbf{H}_{ext} + \mathbf{H}_{demag} + \mathbf{H}_{exch} + \mathbf{H}_{aniso}$ is the sum of the fields above, which together act on the magnetic distribution $\mathbf{M}(\mathbf{r}, t)$.

A magnetic field creates a torque on a magnetic moment, which causes it to precess about the magnetic field direction at the Larmor frequency. This precession occurs as long as the field acts, however in real world there is always some damping which causes the magnetic momentum to eventually spiral in to the direction of the magnetic field as can be seen in Figure 2.1. This process is described by the Landau-Lifshitz-Gilbert equation:

$$\frac{d\mathbf{M}}{dt} = -\left|\gamma\right| \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_S}\left(\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right) \tag{2.1}$$

where $\gamma$ is the Gilbert gyromagnetic ratio, $\alpha$ is the damping constant and $M_S = |\mathbf{M}(\mathbf{r}, t)|$ is the saturation magnetization. The first term on the right side is the precessional term, the second is the damping term.

Solving the Landau-Lifshitz-Gilbert equation analytically is only feasible for simple cases, and for complex designs one has

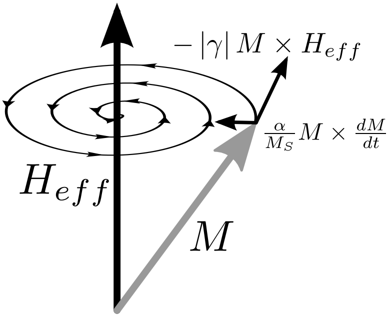


Figure 2.1: Precession of the magnetic moment around the effective field.

to use a numerical approach. We used OOMMF [10] for most of the simulations, which is a well established and widely known micromagnetic solver. For larger designs, GPU accelerated calculators can be used, and we also used MuMax3 [11] in some cases.

Through the coupling between the individual spins, excitations can travel in a magnetic material in the form of spin waves. There are basically two coupling mechanisms that play a role in the formation of spin waves: the demagnetizing field and the exchange interaction. It is customary to talk about two types of spin waves, dipole dominated and exchange dominated spin waves, based on the dominant coupling interaction. There are actually always both types of coupling present, but for short wavelengths exchange interaction dominates, while dipole interaction dominates in case of long wavelengths. In this work we concentrated on spin waves in thin magnetic films, as these are more compatible with planar fabrication technologies.

Unlike optical waves, spin waves do not have a linear dispersion relation, and they do not allow wave propagation below a cutoff frequency. This cutoff frequency is typically a few gigahertz, thus spin-wave devices would operate in the several gigahertz range, up to approximately one terahertz, although such high frequencies would require very high magnetic fields.

# CHAPTER 3

# NEW SCIENTIFIC RESULTS

In this dissertation, we proposed a new way of computing and signal processing with spin waves. We showed that optical computing principles work well with spin waves as well, and many of the already established concepts can be used to construct spin-wave-based computing devices. This approach is different from previous works in that it uses spin-wave interference patterns to realize complex computing tasks, such as linear transformations, filtering, and signal decomposition. Most of the devices presented in the literature so far applied spin waves as a new signal carrier to realize binary operations. Our approach minimizes the magnetic-electric conversion overhead by performing the function of several gates in a single operation.

Spin waves has many advantages compared to electromagnetic waves in computing applications. Most of today's communication channels and the operation frequency of computing devices fall in the several GHz frequency range. Spin waves have wavelengths in the nanometer–micrometer range at these frequencies, which enables very compact designs, without the need of transferring signals to higher frequency regimes. This means that at microwave frequencies spin waves enable creation of interference patterns at the scale of optical wavelengths. We believe, that this is a very good match for many applications.

Future challenges of spin-wave computing devices include efficient electric-magnetic conversion methods, the integration of low-damping magnetic material in the CMOS fabrication process, and development of efficient high frequency support circuitry for spin-wave circuits. We believe that current technologies are sufficient for the demonstration of some of the devices presented in this work, but still there are several issues to be solved for this technology to be competitive.

Here we summarize the original contributions of the author of this dissertation, in a list of theses.

*Thesis I. – I have shown that in principle, basic optical building blocks can be constructed for spin waves. I performed micromagnetic simulations to verify the concepts and demonstrate the operation of these devices.*

I presented a case study on how to re-invent optical computing primitives in a spin-wave medium. I investigated several methods for the construction of coherent spin-wave sources and phase shifters. These are the key components of a wave-based processing system. Lenses and mirrors are the most omnipresent components of an optical processing system. I used micromagnetic simulations to demonstrate that spin-wave lenses and mirrors can be constructed.

Mirrors can be created for spin waves by designing abrupt changes in the magnetic medium, such as a cut. Phase shifter may be created by changing the dispersion properties in the medium. This can be achieved by changing the material, the thickness of the film, or by applying an external magnetic field on the magnetic film. From the dispersion relation we can define a relative index of refraction between two regions, and build devices similarly as in optics. An important example is a lens, Fig. 3.1 shows the micromagnetic simulation that demonstrates the focusing of spin waves. In this example, a magnetic field was applied to change the dispersion relation in the lens shaped region. Similarly, phase plates (or phase gratings) can also be created. I also designed and simulated an alternative type of lens, the gradient index lens.

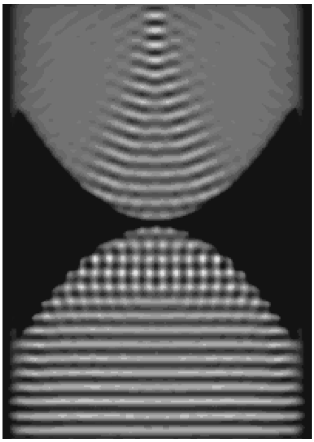

Figure 3.1: A micromagnetic simulation showing the focusing of a magnetic lens in a $1 \times 1.5\ \mu$m Py film. The plane wave entering at the bottom is focused to one point at the top focal plane. The black concave lens shaped area is where the $B = 1.6$ T magnetic field is applied.

*Thesis II. – I proposed the use of a spin-wave lens (or mirror) to perform Fourier transform via spin-wave interference. I used micromagnetic simulations to verify the operation principle of the device for multiple lens designs.*

The Fourier transform property of a lens is well known in optics. I used this concept to design a Fourier-transform device based on spin waves. I investigated the different lens (and concave mirror) designs and explored various ways to implement a spin-wave Fourier transform. In these designs, the input data is encoded spatially in a grating (or equivalent Huygens sources), in either the amplitude or the phase of the spin waves. By successive application of these lens structures, I showed that Fourier-domain filtering is also possible using spin waves. Micromagnetic simulation snapshots are shown in Fig. 3.2, where I used mirrors to achieve this. Filters are applied by spin currents through the magnetic material locally, in a configuration that I designed to increase the magnetic damping locally via spin torque.

*Thesis III. – I proposed a new microwave spectrometer based on spin-wave interference. The design is similar to the Rowland spectrograph used in x-ray spectrography, but designed for spin waves. I used micromagnetic simulations to verify the operation of the device.*

The Rowland circle spectrograph is a well known configuration in x-ray optics, I used a similar idea to design a microwave spectrometer using spin waves. This device is somewhat similar in principle to the lens-based Fourier transform, but there are important differences. In this case the input signal is repre-

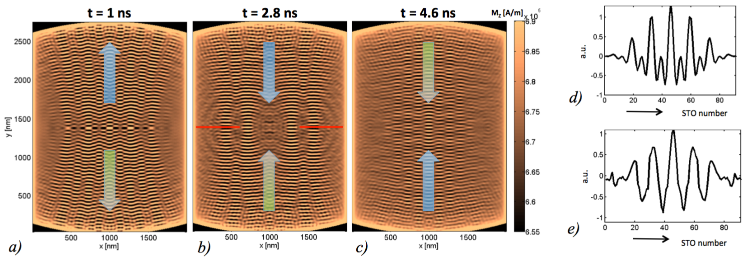


Figure 3.2: Fourier domain filtering using the double-mirror setup. a) Generation and propagation of spin waves. b) Absorbing filter applied when reflected waves reach focal plane. c) Filtered wave arrives focal plane – readout. d) Input pattern. e) Output (filtered) pattern.

sented in time-domain, in the microwave frequency regime, and a fix grating is used to create the diffraction pattern. Also, an important simplification is that in the Rowland circle arrangement focusing is achieved by the curvature of the grating, thus eliminating the lens from the system. In my design, the grating also acts as the source of spin waves. The input microwave signal is fed into a stripline antenna, and the magnetic field of this antenna generates spin waves on the edge of the magnetic film nearby. This edge is patterned to an arc shape with cogs on it. The cogs act as spin-wave sources with varying phase shifts. The frequency components of the input signal will be focused along the so called Rowland circle. I performed micromagnetic simulations to verify the operation of the device, the results can be seen in Fig. 3.3.

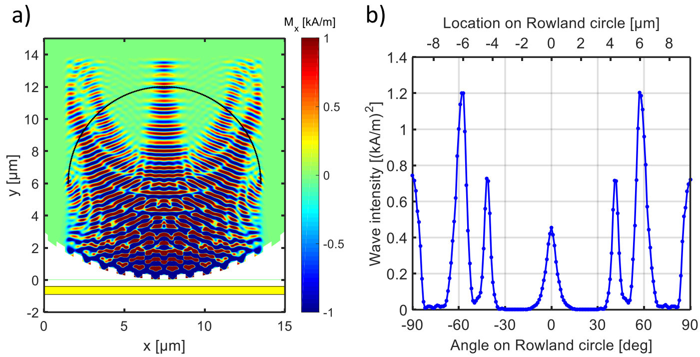


Figure 3.3: Micromagnetic simulation of the spin-wave-based Rowland circle spectrometer. a) The colormap shows a magnetization snapshot of a YIG film, the peaks on the Rowland circle correspond to frequencies $f_1$ = 10 GHz and $f_2$ = 10.25 GHz. The yellow stripe at the bottom is a sketch of the microstrip that is used as a source. b) Spin-wave amplitude along the Rowland circle indicated by black arc in a).

*Thesis IV. – I used micromagnetic simulations to investigate the interaction between YIG (yttrium-iron garnet) and Permalloy films. Based on our findings, we proposed a new way of spin-wave excitation in insulating films and using spin-torque oscillators.*

I performed micromagnetic simulations to investigate the interactions of insulating and metallic magnetic materials. This is important because spin polarized currents can be used in metallic magnets to generate spin waves, however the lowest magnetic damping can be found in insulating magnetic materials, such as YIG. From the simulations I found, that two modes will appear in the YIG layer, one corresponds to the Permalloy dispersion curve, and the other is the YIG mode, however the latter is strongly influenced by the coupling strength between the layers. In the simulations I assumed multiple interlayer exchange coupling values, the effect can be seen in Fig. 3.4. This parameter depends strongly on the quality of the interfaces, so it will probably depend on the fabrication method. I also designed and simulated the injection of spin waves from a Permalloy structure to a YIG film.

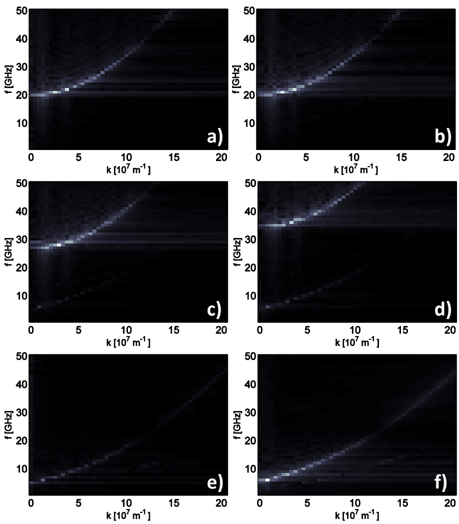


Figure 3.4: Numerically calculated dispersion plots for a YIG-Py bilayer. a) Stand-alone YIG film. b) $A_{\text{interface}} = 0$ J/m c) $A_{\text{interface}} = 0.5 \cdot 10^{-12}$ J/m d) $A_{\text{interface}} = 1 \cdot 10^{-12}$ J/m e) $A_{\text{interface}} = 6 \cdot 10^{-12}$ J/m f) Single Permalloy film. The YIG mode shifts due to the interaction and an additional Permalloy mode appears for stronger couplings.

*Thesis V. – I designed and constructed a ferromagnetic resonance measurement setup based on a time domain reflectometer. I performed measurements of saturation magnetization and damping coefficient of YIG films.*

Ferromagnetic resonance (FMR) is a very important characterization tool for the extraction saturation magnetization and damping parameters from magnetic materials. The two most popular setups for FMR measurements are the conventional FMR and the VNA-FMR. The conventional FMR uses a single frequency cavity resonator, while the VNA-FMR uses a vector network analyzer to excite and measure FMR in magnetic materials. In both setups, a magnetic field is applied on the sample by electromagnets, and multiple measurements are performed to plot the resonance curve in function of the applied field. The drawback of the conventional FMR setup is that it is limited to a single frequency. The VNA-FMR offers a large frequency resolution and bandwidth, but VNAs are expensive tools with high calibration requirements.

I designed and built an FMR setup similar to a VNA-FMR, but using a time domain reflectometer (TDR) instead of the VNA. TDR and VNA are equivalent in principle, with the Fourier transform connecting the two. However, in practice there are very significant differences in the dynamic range of the measurements. With TDRs being typically much cheaper, I investigated the feasibility of a TDR based FMR setup. I used an old Tektronix CSA803 oscilloscope with a TDR sampling head, which can perform measurements up to 20 GHz. The schematic of the setup can be seen in Fig. 3.5. I wrote a script that controls all the instruments in the setup and performs the measurement automatically. The magnetic field is controlled by a feedback control loop, which keeps the magnetic field at the desired value, within the precision of the Hall probe (0.5 G).

With the setup I successfully measured FMR curves of YIG samples that were fabricated via sputtering by Hadrian Aquino. The results are clear and reasonable, but I was able to identify the most important limitations of the setup. Due to the finite length of TDR signals, the frequency resolution of the setup is limited, although this still allows us to extract the material parameters we need. The other, more important limitation is the relatively small signal to noise ratio of the TDR oscilloscope. This can be problematic in case of small and very thin magnetic fields, as the signal strength is proportional to the volume of the magnetic material.

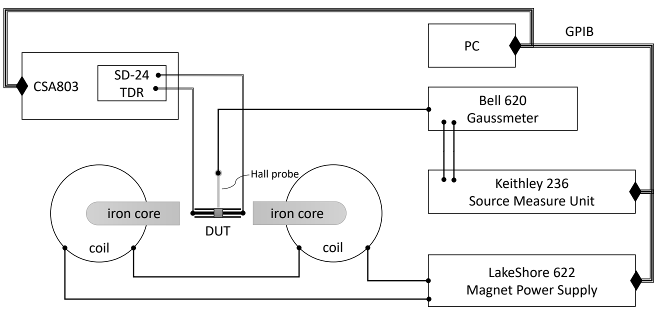


Figure 3.5: Schematic diagram of the FMR measurement setup.

*Thesis VI. – I proposed a threshold gate design for nanomagnetic logic. Novel features of the design include the use of domain-wall conductors for signal propagation, and the use of threshold gates instead of the traditional majority-gate-based designs. I performed micromagnetic simulations to verify the operation of the device.*

These results are not based on spin waves, but also belong to the topic of magnetic computing devices. Nanomagnetic logic is a novel concept that uses the magnetic coupling between magnetic dots that are close to each other. Information is represented by the magnetic field direction of these two-state nanomagnets. A complete logic can be built on these dots using majority gates as basic building blocks. In this work, I proposed the use of domain-wall propagation as the signal carrier instead of coupling between nanomagnets, and I proposed a more general layout to create threshold gates. Fig. 3.6 shows snapshots of the micromagnetic simulation of a full adder based on the proposed threshold gates. As in case of the nanomagnetic logics, an external alternating magnetic field is used as clock signal, but in this design much less cycle is required for the same operation, and the layout is also significantly reduced.

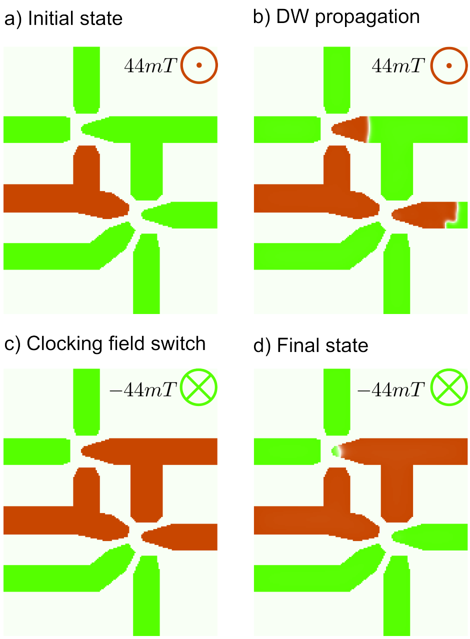


Figure 3.6: Snapshots of a micromagnetic simulation of the threshold gate. The green color represents the $-1$ state $(A, B, -S)$, red is the $+1$ state $(C_{in}, -C_{out})$.

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