Microwave Frequency Stability and Spin Wave Mode Structure in Nano-Contact Spin Torque Oscillators

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For my family
Abstract

The nano-contact spin torque oscillator (NC-STO) is an emerging device for highly tunable microwave frequency generation in the range from 0.1 GHz to above 65 GHz with an on-chip footprint on the scale of a few µm. The frequency is inherent to the magnetic material of the NC-STO and is excited by an electrical DC current by means of the spin torque transfer effect. Although the general operation is well understood, more detailed aspects such as a generally nonlinear frequency versus current relationship, mode-jumping and high device-to-device variability represent open questions. Further application-oriented questions are related to increasing the electrical output power through synchronization of multiple NC-STOs and integration with CMOS integrated circuits.

This thesis consists of an experimental part and a simulation part. Experimentally, for the frequency stability it is found that the slow but strong 1/f-type frequency fluctuations are related to the degree of nonlinearity and the presence of perturbing, unexcited modes. It is also found that the NC-STO can exhibit up to three propagating spin wave oscillation modes with different frequencies and can randomly jump between them. These findings were made possible through the development of a specialized microwave time-domain measurement circuit. Another instrumental achievement was made with synchrotron X-rays, where we image dynamically the magnetic internals of an operating NC-STO device and reveal a spin wave mode structure with a complexity significantly higher than the one predicted by the present theory.

In the simulations, we are able to reproduce the nonlinear current dependence by including spin wave-reflecting barriers in the nm-thick metallic, magnetic free layer. A physical model for the barriers is introduced in the form of metal grain boundaries with reduced magnetic exchange coupling. Using the experimentally measured average grain size of 30 nm, the spin wave mode structure resulting from the grain model is able to reproduce the experimentally found device nonlinearity and high device-to-device variability.

In conclusion, the results point out microscopic material grains in the metallic free layer as the reason behind the nonlinear frequency versus current behavior and multiple propagating spin wave modes and thereby as a source of device-to-device variability and frequency instability.

Keywords: spintronics, microwave oscillators, magnetization dynamics, spin waves, phase noise, device modelling, electrical characterization, X-ray microscopy, STXM, XMCD
Sammanfattning

Dagens snabba utveckling inom informationsteknik drivs på av ständigt växande informationsmängder och deras samhällsanvändning inom allt från resursoptimering till underhållning. Utvecklingen möjliggörs till stor del hårdvarumässigt av miniatyrisering och integrering av elektroniska komponenter samt trådlös kommunikation med allt större bandbredd och högre överföringshastighet. Det senare uppnås främst genom utnyttjande av högre radiofrekvenser i teknologiskt tidigare oåtkomliga delar av spektrumet. Frekvensutnyttjandet har det senaste årtiondet ökat markant i mikrovågsområdet med typiska frekvenser runt 2.4 GHz och 5.2–5.8 GHz.

I den spintroniska oscillatorn (STO:n) möjliggörs frekvensgeneratorering i det breda området från 0.1 GHz upp till över 65 GHz av en komponent med mikrometerstorlek som kan integreras direkt i CMOS-mikrochip. Till skillnad från i konventionella radiokretsar med oscillatorer konstruerade av integrerade transistorer och spolar, genereras mikrovågsfrekvensen direkt i STO:ns magnetiska material och omvandlas därefter till en elektrisk signal genom komponentens magnetoresistans. Dess materialegenskaper möjliggör ett tillgängligt frekvensband med extrem bredd i en och samma STO, som därtill kan frekvensmoduleras direkt genom sin styström och på så sätt förenklar konstruktionen av sändarsystem. STO:ns icke-linjära egenskaper kan potentiellt också användas för att i en och samma komponent bland annat mottagna mikrovågssignaler och på så sätt förenkla konstruktionen även av mikrovågsmottagare.

STO:ns signalegenskaper bestäms av det magnetiska materialets fysik i form av magnetiseringsdynamik driven av elektriskt genererade spinnströmmar. I denna avhandling studeras denna dynamik experimentellt med särskilt fokus på frekvensstabiliteten i den hittills mest stabila STO-typen; nanokontakts-STO:n. Genom mätningar i tidsdomän av STO:ns elektriska signaler runt 25 GHz har frekvensstabiliteten funnits hänga samman med den typ av icke-linjärt beteende som också funnits vara utmärkande för tillverkningsvariationen i komponenterna. Mikroskopiska undersökningar av materialet visar att en trolig källa till denna variation är den magnetiska metallens uppsyggnad i form av korn i storleksordningen 30 nm, och datorsimuleringar av en sådan materialstruktur har visats kunna reproducerera de experimentella resultaten. Därtill har en metod utvecklats för att med röntgenstrålning direkt mätta de små, magnetiska mikrovågsrörelserna i materialet. Denna röntgenteknik möjliggör detaljerade experimenterliga studier av magnetiseringsdynamiken och kan användas för att verifiera och vidareutveckla den existerande teorin för mikrovågsspintronik.

Sammantaget förs STO-teknologin genom denna studie ett steg närmare sina tänkbara samhällsbreda tillämpningar inom snabb, trådlös kommunikation för massproducerade produkter med integrerad sensor- och datorfunktionalitet.
Acknowledgement

The work leading up to this thesis would not have been possible without the professional and friendly support from many people and organizations. I owe you all, in different ways, for making my PhD studies an interesting, developing, exciting and fun time in my life.

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My office mate and closest co-worker, Dr. Tingsu Chen, I would like to thank for our always interesting and sometimes lively discussions about everything from magnetization dynamics to the noise properties of high-frequency integrated circuits. It has been a lot of fun spending this time with you, and I value your ability and willingness to give me a wide insight into the world of integrated circuit design.

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Anders Eklund

June 2016, Kista
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List of Acronyms

AFM  Atomic force microscope
BLS  Brillouin light scattering
CMOS Complementary metal-oxide-semiconductor
FFT  Fast Fourier transform
FMR  Ferromagnetic resonance
FWHM Full width at half maximum
GMR  Giant magnetoresistance
GPU  Graphics processing unit
GSG  Ground-signal-ground
IF   Intermediate frequency
LLGS Landau-Lifshitz-Gilbert-Slonczewski
LO   Local oscillator
MR   Magnetoresistance
MRAM Magnetoresistive random-access memory
MTJ  Magnetic tunnel junction
NA   Numerical aperture
NC   Nano-contact
<table>
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<th>Acronym</th>
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<tr>
<td>OSA</td>
<td>Order sorting aperture</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed circuit board</td>
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<tr>
<td>PLL</td>
<td>Phase locked loop</td>
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<tr>
<td>PSD</td>
<td>Power spectral density</td>
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<tr>
<td>Py</td>
<td>Permalloy (Ni$<em>{80}$Fe$</em>{20}$)</td>
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<tr>
<td>RF</td>
<td>Radio frequency</td>
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<tr>
<td>RMS</td>
<td>Root mean square</td>
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<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
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<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
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<td>SSRL</td>
<td>Stanford Synchrotron Radiation Lightsource</td>
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<tr>
<td>STFT</td>
<td>Short-time Fourier transform</td>
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<tr>
<td>STNO</td>
<td>Spin torque nano-oscillator</td>
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<td>STO</td>
<td>Spin torque oscillator</td>
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<tr>
<td>STT</td>
<td>Spin transfer torque</td>
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<tr>
<td>STXM</td>
<td>Scanning transmission X-ray microscope</td>
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<tr>
<td>TMR</td>
<td>Tunneling magnetoresistance</td>
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<tr>
<td>XMCD</td>
<td>X-ray magnetic circular dichroism</td>
</tr>
<tr>
<td>YIG</td>
<td>Yttrium iron garnet</td>
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List of Publications

List of appended papers


List of related papers not included in this thesis


Summary of Appended Papers


Summary: This paper discusses the propagating spin wave mode generated in a GMR nano-contact spin torque oscillator and presents electrical microwave measurements at 19 – 24 GHz in both the frequency and time domain. The time-domain measurement circuit is custom built and provides a measurement bandwidth of 2.5 GHz. The paper describes in detail a methodology for time-frequency analysis of the recorded waveform. In the frequency-domain measurements, it is for the first time revealed how two additional propagating submodes emerge at high drive currents. The time-domain measurements show that the STO precession is jumping between the frequencies of these modes on a wide time scale of 10 ns – 1 ms.

Author’s contribution: The author designed the time-domain measurement circuit and performed all measurements, developed the time-frequency analysis, analyzed the data and wrote the manuscript.


Summary: This paper presents electrical microwave measurements at 18 – 25 GHz of the frequency stability of GMR nano-contact STOs in both the frequency and time domains. By improving a technique for time-domain measurement of the frequency noise to obtain sufficient measurement bandwidth also at more unstable operating points, it is possible to present, for the first time, the detailed variation of both the white and the $1/f$-type frequency noise in the propagating spin wave mode. Previous work has established a correlation between the frequency-domain linewidth of the signal and the degree of nonlinearity of the device operation. In this paper, it is established
that not just the theoretically treated white frequency noise increases with the nonlinearity, but also the $1/f$ frequency noise. It is also shown how the $1/f$ frequency noise is further elevated in a sample that shows existence of additional modes (similar to the case of Paper I) – even though those modes are not excited. Two possible mechanisms for the $1/f$ frequency noise are proposed: toggling between various dominating free layer grains and $1/f$ resistive noise induced by microstructural inhomogeneity such as grains.

**Author’s contribution:** The author developed the time-domain measurement circuit and performed the electrical microwave measurements, identified and investigated the possible sources of measurement error, developed the time-domain data analysis, analyzed the results and wrote the manuscript.


**Summary:** This paper presents the first model of MTJ nano-pillar STOs accessible for straight-forward implementation in electrical hardware description languages. The model describes the DC operating point, the frequency, the electrical RF power and the oscillation stability in terms of the linewidth. The model is strongly based on the general nonlinear auto-oscillator theory for STOs given by Slavin and Tiberkevich, with the addition of additional types of magnetic field. The important device parameters are identified (along with guidelines for the phenomenological parameters) and the model is quantitatively verified against three sets of experimental data from different research groups with different device configurations.

**Author’s contribution:** The author contributed to the selection of device parameters and to the qualitative and quantitative validation of the model through analysis of the discrepancies between the predicted and experimental values in frequency, power and linewidth. The author co-wrote the manuscript.


**Summary:** This paper presents an implementation of the model in Paper III in the hardware description language Verilog-A. This is the first available MTJ STO model for Verilog-A that is self-contained and allows arbitrary biasing conditions including both the drive current and the orientation and magnitude of the applied magnetic field. It turns out that previous Verilog-A implementations of phase noise all introduce discontinuous jumps in the
phase, which results in a discontinuous signal and convergence issues for the Verilog-A simulator. Great care has therefore been taken in the implementation of the phase noise so that the generated time-domain waveform obtains the modelled frequency-domain linewidth and is at all times continuous, which is the experimentally observed behavior. The Verilog-A MTJ STO model is finally demonstrated at the circuit- and system-design levels including biasing and amplifying CMOS circuits, using Cadence SpectreRF.

**Author’s contribution:** The author obtained and verified the expression for the random frequency fluctuations and, together with T. Chen, identified and explained the Verilog-A signal discontinuity problem induced by previously published methods for phase noise generation. The author developed the algorithm for continuous phase noise generation together with T. Chen and co-wrote the manuscript.


**Summary:** This paper presents the first time- and space-resolved measurement of the magnetization precession and spin wave pattern in a nano-contact GMR spin torque oscillator, utilizing X-ray microscopy. Apart from demonstrating the ability to perform such a measurement, the results of the measurements on the investigated, localized solitonic bullet mode show that the mode does not exhibit the expected radial symmetry but a more complicated pattern involving a nodal line separating regions of anti-phase oscillation. The experimental results are well reproduced by precisely configured micromagnetic simulations, including a number of contributions to the total magnetic field.

**Author’s contribution:** The author contributed in developing the experimental technique, including improvements in the extremely low signal-to-noise ratio and stability of the measurement, and performing the X-ray microscopy measurements. The author also took part in the analysis, including the consideration of the injected microwave signal strength and its locking efficiency, and performed simulations to determine the strength of the stray field from the patterned polarizing layer.


**Summary:** This paper investigates the GMR nano-contact STO and its propagating spin wave by means of micromagnetic computer simulations. It is found that by minimizing artificial spin wave reflections by using appropriate
boundary conditions, the frequency as a function of drive current displays a linear behavior. This is in stark contrast with all existing experimental measurements, which display a notable degree of nonlinearity and discontinuous frequency steps. It is shown how these effects emerge as a consequence of spin wave reflection back towards the current-driven active region. As a physical origin for the reflection, metal grain boundaries with reduced magnetic exchange coupling are considered. A typical grain size of 30 nm is obtained using atomic fore and scanning electron microscopy, and the micromagnetic simulations of such structures reproduce the nature of nonlinearities and frequency steps, the device-to-device variability and linewidth increase in the operating ranges where the grain-induced effects are strong.

Author’s contribution: The author designed the experiment, set up and performed the simulations, developed the analysis algorithms for the simulation output, performed the electrical microwave measurements, analyzed the data and wrote the manuscript. The basic starting-point simulation configuration was set up by M. Dvornik.
Chapter 1

Introduction

During the last decades, the utilization of the spin degree of freedom in electronics has invoked the field with the name spintronics. Today, all magnetic hard disk drives utilize spintronic components and it is currently finding its way into high-performance non-volatile random access memory. A research field which is currently active on the basic research level is that of microwave spintronics, which has the potential to revolutionize the design of high-frequency microwave systems. It also has a potential as a sensor of magnetic fields and, on a more hypothetical level, as an enabler for spin wave logic devices as an alternative to today’s transistor-based computer logic.

1.1 Spintronics

By taking advantage of the electron spin in electronic devices, it is possible to extend the functionality of electronics. While spin-based computing [1] is still on the research stage, the most eminent example of an application of spintronics is that of hard disk drives. Here, the evolution during the last decades has taken the capacity from a couple of GB to several TB – a 1000 times improvement. This development has been accomplished by shrinking the size of the individual data-storing magnetic domains in the magnetic thin films on the spinning disk. Shrinking the domain volume would not have been possible without sensors that are capable of detecting the weak magnetic field right above the domains. This requires the sensor to become smaller and increasingly sensitive, and spintronic sensors have proven to be an ideal solution to this scaling problem.

The primary advantages of hard disk drives are that they have large capacity and are non-volatile, i.e. the data is kept even when the electrical power is turned off. They are, however, slow compared to the volatile, random access memories (RAM) of various types that are used for more direct data-handling by the processor. By combining the magnetic non-volatile properties of a hard disk drive with the speed
CHAPTER 1. INTRODUCTION

of all-electronical devices, the magnetoresistive random-access memory (MRAM) [2, 3] was introduced commercially in 2006 by Freescale Semiconductor Inc. The memory cells were basically the same form of magnetic tunnel junctions (MTJs) that were in use as hard disk sensors, but with an overlaid array of write lines, acting to flip a cell’s magnetization by their current induced Oersted field.

A step further was taken by incorporating the switching mechanism in the MTJs themselves. By the utilization of spin transfer torque, a current passing through the MTJ cell could be used not just to read out the direction of the magnetization, but also to switch the direction — hence adding write capability directly through the device current instead of indirectly through the magnetic field from the write lines [4, 5]. The first commercial spin transfer torque MRAM (STT-MRAM or ST-MRAM) was introduced by Everspin Technologies, Inc. in 2012 [6].

Other research involving spin transfer torque is that of so called racetrack memories or domain-wall memories [7, 8]. These consist of a narrow line of magnetic material, patterned with domains pointing up or down in order to represent a one or a zero. On the line, there is one read and write device acting by means of the magnetic fields from the domains. The entire track of domains in the line can be shifted back and forth by running a current along the racetrack line, since spin transfer torque is generated at every domain wall and can be utilized to force the domain wall to move [9].

Spin transfer torque can also be utilized for compact generation of electrical signals in the microwave frequency band. This is facilitated by the ferromagnetic resonance (FMR) frequency inherent to ferromagnetic materials. Here, spin transfer torque can be used to fully compensate the damping of the motion of the resonance and thereby excite and sustain an oscillation. The oscillation results in a time-varying device resistance, which together with the constant drive current provides an oscillating voltage signal. These devices are referred to as spin torque oscillators (STOs) or spin torque nano-oscillators (STNOs) [4, 10, 11, 12] and are the topic of this thesis. STOs are CMOS-integrable [13] and apart from their potential use in microwave radio applications [14], the strong dependence of the frequency on the magnetic field makes them a candidate for upcoming generations of magnetic field sensors [15]. The oscillating external magnetic field produced by the oscillating magnetization may also be used in microwave assisted magnetic recording [16] for improved switching control of hard disk bits and thereby increased areal density.

1.2 Microwave technology

The electromagnetic spectrum covers all the way from extremely low frequencies via radio waves, microwaves and infrared radiation to the visible spectrum, ultraviolet, X-ray and gamma rays. Due to the frequency-determined photon energy and wavelength, photons in different parts of the spectrum interact in highly different ways with various substances, materials and geometrical structures. Coupling pho-
tons to electronic systems, such as in a radio receiver, puts technological constraints on the photon frequency that can be used, with higher frequencies requiring faster electronic components. Another constraint is the wavelength; by going to lower frequencies the wavelength becomes larger, and requires larger antenna structures for coupling the electrical signal to the photons. Another aspect to consider for transmission in the electromagnetic spectrum is the frequency-dependent attenuation caused by the Earth’s atmosphere. The radio and microwave window covers from to 30 MHz up to 3 GHz before gradually (but non-monotonically) falling off and closes around 300 GHz.

The development trend of utilizing higher and higher microwave frequencies is motivated by several factors, including non-occupied spectral bandwidth with less interference, higher modulation rates for faster data transmission and decreased system size due to the shorter wavelength and decreased antenna size. For sensing applications, such as radar which is typically operated in the microwave regime, the shorter wavelength also allows reflection against and thereby detection of smaller objects.

Wireless communication is today in many cases performed in the microwave band. For example, wireless networks typically operate at 2.4 GHz and 5.2–5.8 GHz. Mobile phones in the 4G generation also utilize frequencies in the mid-2 GHz band, and 5G is currently under design with frequencies up to 86 GHz and beyond [17]. Most radar systems lie within 1–12 GHz, with the notable exception of automotive radar which operates at 75 GHz.

1.3 Thesis organization

This thesis is organized into three parts: I) Background, II) Experimental work and III) Conclusions and future outlook. In Part I, a brief background on the physics of the nano-contact spin torque oscillator will be given. This background includes the main physical, spintronic phenomena that give rise to the oscillation of the magnetization of a material and to the generation of a corresponding electrical signal. This will be followed by a description of the main modelling approaches as well as some device operational characteristics that are built upon throughout the rest of the thesis. In this general modelling part, we will describe the contribution of Paper III. Part I also includes a chapter on frequency stability. Within the context of its general properties and characterization, the contribution of Paper IV is presented. This is followed by an overview of the research field of frequency stability in spin torque oscillators.

Part II contains a description of the experimental work of this thesis, conducted with the aim of increasing the understanding of the nano-contact spin torque oscillator with a particular focus on its frequency stability. A large part of this work has been concentrated on developing the measurement methods necessary to characterize the operating devices. Experimental characterization of the devices is
complicated due to their small size and comparatively weak and quickly fluctuating electrical signals. The experimental part has three chapters on the developed methods and the results from Electrical DC and microwave measurements (Papers I and II), Micromagnetic simulations (Paper VI) and X-ray microscopy (Paper V).

In Part III we will conclude the main findings of this thesis and provide an outlook on future work where the methods developed in this thesis can be used to further improve the understanding of nano-contact spin torque oscillators in general and their frequency stability in particular.
Part I

Background
Chapter 2

Nano-contact spin torque oscillators

Ferromagnetic materials such as nickel, cobalt and iron all have a built-in resonance mechanism, called ferromagnetic resonance (FMR) [18]. The actual FMR frequency depends on the material and can be controlled by applying an enclosing magnetic field, but typically lies in the microwave regime from a few GHz and up to many tens of GHz. This thesis deals with the physics of exciting and driving the FMR by means of sending an electrical current through the material. The effect that is driving the oscillation is the spin transfer torque and the devices are hence called spin torque oscillators (STOs). STOs operate within a widely tunable frequency range with a maximum frequency predicted to exceed 65 GHz [19].

Once excited, the oscillation can be output electrically owing to the mechanism awarded with the Nobel Prize in Physics for 2007: the giant magnetoresistance effect (GMR) [20, 21]. This effect and the following improvements in its successor, the tunneling magnetoresistance (TMR) effect [22, 23] have been driving the hard disk development since the late 1990’s and all hard disks ever since have GMR- or TMR-based sensor heads for detecting the weak magnetic fields from small data-storing magnetic domains pointing either up or down representing either a one or a zero.

2.1 Spin currents and giant magnetoresistance

That a particle has a spin means that it has a certain spin angular momentum, from a perspective of classical mechanics resembling the massive particle rotating about its own axis. The origin of spin angular momentum is however purely quantum mechanical [24].

In an electrical current flowing in a general non-magnetic material, the spins of
the electrons are randomly oriented. But similarly to photons acquiring a polariza-

tion by passing through a polarizing glass, a current of electrons can become spin polarized when entering and passing through a ferromagnetic material. Every electron spin acquires either a parallel or anti-parallel orientation with relation to the magnetization axis. Due to spin-dependent scattering [25], the two different spin directions experience different electrical resistivities. This results in a two-channel parallel resistance model ($R^{-1} = R_{\uparrow}^{-1} + R_{\downarrow}^{-1}$) for the spin-up and spin-down electron channels [26, 27]. In a structure where the current flows from one ferromagnet into another and the two magnetizations are parallel (such that the spin-up electrons coming out from the first magnet will be spin-up also in the second), the resulting resistance is $R_\text{P}^{-1} = (R_{\uparrow} + R_{\downarrow})^{-1} + (R_{\uparrow} + R_{\downarrow})^{-1}$, while in the case of anti-parallel magnetizations (where spin-up electrons will become spin-down and vice versa) $R_\text{AP}^{-1} = (R_{\uparrow} + R_{\downarrow})^{-1} + (R_{\downarrow} + R_{\uparrow})^{-1}$. This leads to a relation between the total resistances in the two states:

$$\frac{R_\text{AP}}{R_\text{P}} = \frac{(R_{\uparrow} + R_{\downarrow})^2}{4R_{\uparrow}R_{\downarrow}}$$ (2.1)

with the properties that $R_\text{AP}/R_\text{P} > 1$ whenever the two channels have different resistance and $R_\text{AP}/R_\text{P} = 1$ only if $R_{\uparrow} = R_{\downarrow}$. This is the basic phenomenology describing giant magnetoresistance (GMR). It can be refined by allowing an arbitrary angle $\beta$ between the magnetization axes of the ferromagnets (not just parallel or anti-parallel) and the resulting resistance can then be found to obey a $\sin^2(\beta/2)$ dependence.

The resistance in a GMR thin film is hence directly determined by the angle between the magnetization directions in the two ferromagnetic layers, with the highest resistance in the anti-parallel state and the lowest in the parallel state.

### 2.2 Spin transfer torque

When a spin-polarized current with a certain spin polarization axis flows through a normal, non-magnetic metal it carries a flow of spin angular momentum. As the spin current enters into a ferromagnet with a polarization axis different from that of the spin current, the spins will realign to this new polarization axis. This means that during a short transition distance just inside the ferromagnet, the spin current is being twisted. In other words, there is a change of the spin angular momentum. As can be recalled from classical mechanics, the rate of change of angular momentum of a rigid body can be described as a torque acting on the body in question.

In the case of the twisting of the spin current, the rotation is accomplished by a torque acting on the spins. Through the law of conservation of angular momentum, the change of the angular momentum of the spin current has to be accompanied by an opposite change of the angular momentum of the ferromagnet. This can
be viewed also in terms of Newton’s third law about action and reaction in the sense that if there is a torque caused by the ferromagnet acting on the spin current, there is an opposite reaction torque acting on the ferromagnet itself. This torque is referred to as spin transfer torque [28] and was first predicted in 1996 by Slonczewski [29] and Berger [30], independent of each other. By means of the spin transfer torque, a spin current entering a ferromagnet can change the angular momentum and hence the magnetization direction of the ferromagnet. This spin transfer torque, or in short spin torque, can be used to completely reorient the direction of the magnetization of the ferromagnet as already utilized in industry in spin transfer torque magnetoresistive random access memory (STT-MRAM). It can also be used to continuously move the magnetization in a precessional manner – the foundation for the spin torque oscillator (STO) device.

In an STO, the oscillating magnetization direction in the so called free layer results in an oscillating relative angle between the free and the fixed layer. This, in turn, results in an oscillating device resistance through either the giant or the tunnel magnetoresistance effect (depending on the material of the spacer layer between the ferromagnetic films). The direct current used to excite and sustain the oscillation hence at the same time results in an oscillating voltage signal by virtue of Ohm’s law. The first experimental realization of a GMR-based STO was demonstrated in 1998 by Tsoi et al. [31] and the first TMR STO in 2008 by Deac et al. [32].

2.3 Magnetization precession

The magnetic state of a ferromagnetic material is described in terms of its magnetization, $\mathbf{M}$ and can vary in time ($t$) such that $\mathbf{M} = \mathbf{M}(t)$. Mathematically, the time evolution of a spin torque driven magnetization can be described by the vectorial differential equation given by Landau, Lifshitz and Gilbert with the addition of the Slonczewski spin torque term (the LLGS equation):

$$
\frac{d\mathbf{M}}{dt} = -\gamma [\mathbf{M} \times \mathbf{H}_{\text{eff}}] 
+ \frac{\alpha}{M_0} \left[\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right] 
+ \gamma (a_J \mathbf{M} \times [\mathbf{M} \times \mathbf{M}_p] + b_J \mathbf{M} \times \mathbf{M}_p) 
$$

(2.2a) (2.2b) (2.2c)

where $\gamma$ is the gyromagnetic ratio, $\mathbf{H}_{\text{eff}}$ is the effective magnetic field, $\alpha$ is the dimensionless Gilbert damping, $M_0$ is the saturation magnetization of the free layer, $a_J$ and $b_J$ are the coefficients of the in-plane and perpendicular spin torque and $\mathbf{M}_p$ is the magnetization vector of the fixed (polarizing) layer. In-plane here refers to spin torque directed within the plane spanned by $\mathbf{M}$ and $\mathbf{M}_p$. The effective magnetic field $\mathbf{H}_{\text{eff}}$ is the sum of all fields acting on the magnetization, including the externally applied field, the dipolar demagnetizing (shape anisotropy) field, the magneto-crystalline anisotropy field, the exchange field and the thermal field.
CHAPTER 2. NANO-CONTACT SPIN TORQUE OSCILLATORS

The first right-hand term of the LLGS equation, (2.2a), describes the Larmor precession of the magnetization. This process is non-dissipative and describes the ferromagnetic resonance (FMR) of the film. The second right-hand term, (2.2b), is the dissipative Gilbert damping term, acting to decrease the amplitude of the FMR precession until a final, steady state of $M \parallel H_{\text{eff}}$ is obtained. The third term, (2.2c), is the spin-current induced spin torque. Its first term is the in-plane spin torque which, depending on the sign of the current, can either counteract or reinforce the damping term. Its second term is the perpendicular or field-like spin torque, which acts similar to the Larmor (field-induced) term.

For using a spin current and spin torque to excite and sustain an oscillation, the direction of the electrical current is important. If the electrical current is directed such that the net flow of electrons is going from the fixed layer to the free layer, the free layer magnetization will align with the direction of the spin angular momentum of the electrons, i.e. parallel to the fixed layer. The in-plane spin torque is thus acting in the same direction as the Gilbert damping and pulls the magnetization towards the steady state of parallel magnetizations. In order to counteract the Gilbert damping, the net flow of electrons needs to be from the free layer to the fixed layer. This will, as a first consequence, try to align the fixed layer with the free layer but since the fixed layer is difficult to reorientate this effect is small. The second consequence is that the electrons that are back-scattered against the interface between the spacer and the fixed layer will have their spin angular momentum direction anti-parallel against the fixed layer magnetization. Since the fixed and free layers to a good approximation are parallel, this means that the back-scattered electrons will impinge onto the free layer with a spin angular momentum direction anti-parallel to the free layer magnetization and hence act to turn it anti-parallel to the equilibrium direction – hence counteracting the Gilbert damping. By counteracting the Gilbert damping, the ferromagnetic resonance can be sustained indefinitely. Due to the generally small misalignment between the free and the fixed layers, the steady-state precession does not represent the case where the in-plane spin torque exactly cancels the damping everywhere on the trajectory; instead, the spin torque only on average cancels the damping during the course of a complete orbit.

2.4 Modelling of spin torque oscillators

There exist two conceptual ways of modelling the magnetization behavior in spin torque oscillators (or any other magnetization in general). In general, the magnetization is a vector field and possibly a function of time $t$ such that $M = M(\mathbf{r}, t)$ where $\mathbf{r}$ is the spatial coordinate vector. In the macrospin modelling approach, the magnetization is considered spatially uniform such that $M(\mathbf{r}, t) = M(t)$. This is also analogous to modelling the behavior of a localized magnetic moment in the material. The advantages of macrospin models are that they are possible to treat analytically and are not particularly computationally intense. The alternative to
2.4. MODELLING OF SPIN TORQUE OSCILLATORS

Macrospin modelling is micromagnetic modelling, where all the local magnetization vectors $\mathbf{M}(\mathbf{r}, t)$ are subject to the forces acting upon it from the magnetization at all other points $\mathbf{M}(\mathbf{r} \neq \mathbf{r}_i, t)$ through the exchange and dipolar contributions to the total and collective magnetic field $\mathbf{H}_{\text{eff}}(\mathbf{r}_i, t)$. This allows for a far more realistic description of the system, but the computation is also far more complex than in the macrospin case.

2.4.1 Macrospin modelling

Modelling the spin torque oscillator as a macrospin makes tractable both analytical investigation and comparatively quick numerical simulation of the dynamics. The validity of a strict macrospin representation of an entire system is however limited to systems where the modelled size of the nano-element does not exceed $\approx 30 \text{ nm}$ [33]. By assuming a quasi-uniform precession and utilizing classical Hamiltonian formalism for spin waves in magnetic films, models predicting the threshold current and frequency have been developed [34, 35]. A later, more common approach is to map the LLGS equation onto the general nonlinear auto-oscillator equation as originally done by Slavin and Tiberkevich [36, 37]. This approach facilitates predictions not only for the generated frequency and oscillation amplitude but also for the frequency stability in terms of the linewidth (level of white frequency noise) as well as phase-locking and modulation.

Utilizing the framework given in [37], we implemented a more tractable model in [38, 39] (Papers III and IV) for the case of TMR nano-pillar STOs. Our implementation is evaluated fast enough for use in hardware description languages and thereby self-contained simulations in electrical circuit- and system-level design using industry-standard design tools such as Cadence SpectreRF. The model accepts physically measurable parameters except for two phenomenological parameters: $q_1$, the linear coefficient of the expansion of the damping as a function of the oscillation amplitude (referred to as $\alpha(\xi) = \alpha_G(1 + q_1\xi)$, where $\alpha_G$ is the linear Gilbert damping parameter and $\xi$ is the dimensionless measure of the oscillation power [36]) and the noise power $\eta$. By adjusting these two parameters for the modelled device, it is possible to reproduce the device behavior to a reasonable degree of accuracy. The model in Paper III was verified to be compatible with three different device types from different research groups.

2.4.2 Micromagnetic modelling

Despite the success of analytical modelling utilizing spin wave theory, as described in Section 2.4.1, the macrospin approach is not able to take into account any spatial variations of the parameters of the device. In this case, micromagnetic modelling has to be utilized in order to describe the dynamics of the system as well as possible [40]. One type of such variation is any physical boundaries of the magnetic film, as is the case of nano-pillar devices [41]. The boundaries produce local demagnetizing
fields, hence resulting in a spatially inhomogeneous magnetic field. Another source of inhomogeneous magnetic field is the current-induced Oersted field [41] and, from a more practical perspective, material inhomogeneity in the thin film stack. These types of phenomena require microscopic modelling of the spatially inhomogeneous magnetization dynamics and is the topic of Chapter 5 of this thesis.

2.5 Localized and propagating spin wave modes

In nano-contact spin torque oscillators with the most common configuration of the magnetic film stack, both the free layer and the fixed layer have their magnetizations directed into the plane of the film. In other words, there is no out-of-plane anisotropy designed into the materials. In this type of in-plane nano-contact spin torque oscillators, the injection of an electrical current perpendicularly into the magnetic film stack through an e-beam defined nano-contact [42] (Figure 2.1) can excite two fundamentally different spin wave modes [43, 44]; the localized solitonic “bullet” spin wave mode [45] and the propagating spin wave mode [46]. The fact that the excitation takes place in the form of spin waves is related to the fact that the driven oscillating region just below the current injection point (the nano-contact) is continuously linked to the surrounding and much larger remaining part of the thin film mesa. This means that the oscillation dynamics in the nano-contact region is connected via the magnetic exchange interaction to the magnetization in the rest of the mesa, and the dynamics that can be excited is the collective dynamics. In other words, the magnetization and its oscillation in the nano-contact region is not independent of the magnetization in the rest of the mesa and the dynamic solution has to take into account the transition from the driven oscillation region to the non-driven, largely static parts of the rest of the mesa.

The localized spin wave “bullet” mode can only be excited for magnetic fields with an out-of-plane angle below a certain critical value, i.e. it is primarily excited for fields oriented more in the plane. This critical value $\theta_c$ is around $60^\circ$ [47]. The propagating spin wave mode, however, can be excited in the same region as the “bullet” mode as well as all the way up to perpendicular, i.e. $\theta = 90^\circ$. It has been observed that for $\theta < \theta_c$, where both modes are excited, the spectral linewidths of both modes are in the region 100 – 1000 MHz [47]. For the propagating mode exclusively excited within the range $\theta > \theta_c$, the lowest linewidth values of around 10 MHz are obtained closest to $\theta_c$ and then again increases towards 100 MHz at $\theta = 90^\circ$. The propagating mode hence constitutes the most stable oscillation, at field angles where the localized “bullet” mode does not exist. Since the dual excitation of both the “bullet” and propagating modes has a negative effect on the frequency stability of both the modes, we will in this thesis focus on the propagating spin wave mode. Apart from having the higher stability, its propagating nature is also of great interest for the field of magnonics. In order to maximize the stability of the propagating mode, while at the same time minimizing any instability influence of the localized “bullet” mode, we have in the work of this thesis focused on an
angle of the applied field of $\theta = 70^\circ$, i.e. $10^\circ$ away from the critical angle.

2.6 Phase-locking

One interesting property of the STO is its ability to phase lock to other signals carrying the same frequency. Phase-locking of an STO has been demonstrated both to an additional RF component superposed onto the electrical drive current [48] and to an external RF magnetic field [49]. This phase-locking occurs on a timescale of only a few ns or a few tens of precessional cycles [50], as measured on the propagating spin wave mode. Phase-locking between multiple STOs has also been achieved between nano-contact STOs patterned on the same mesa [51, 52, 53, 54], operated in the propagating spin wave mode.
Chapter 3

Frequency stability

There are two types of stability related to oscillators: stability in the amplitude and stability in the frequency. Instability in the amplitude of an electrical oscillating signal can comparatively easy be controlled by the use of limiting amplifiers. Frequency instability, however, cannot be compensated once the signal has been generated. This is why frequency stability, next after the actual frequency, is usually considered as the key parameter for an oscillator. The spin torque oscillator is particular in the sense that it has a comparatively strong relationship between its amplitude and frequency, which leads to noise properties that are different from common types of non-coupled oscillators. In this chapter, a general overview of frequency noise will be given, followed by a review of the known properties of frequency noise for the case of spin torque oscillators.

3.1 Frequency noise theory

3.1.1 Introduction to frequency noise

In an ideal oscillator, the oscillator keeps the assigned frequency $f_0$ exactly. In reality all oscillators do however show momentary deviations in the frequency so that it occasionally oscillates slower or faster. These unintended frequency deviations are referred to as frequency noise. The instantaneous frequency of the oscillator can be written as $f(t) = f_0 + \nu(t)$ where $\nu(t)$ is the instantaneous frequency deviation (i.e. the frequency noise).

Equivalent to representing the frequency instability by the frequency deviation $\nu(t)$, it is possible to represent the instability in terms of the phase deviation $\phi(t)$ such that the phase of the oscillator is described by $\Phi(t) = 2\pi f_0 t + \phi(t)$ and

$$\nu(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt}. \tag{3.1}$$
In this representation, the frequency instability is referred to as phase noise \( \phi(t) \). It should be noted that phase noise \( \phi(t) \) and frequency noise \( \nu(t) \) are two representations of the same phenomenon (of instability in the timing of the oscillation).

Frequency noise has several implications for the achievable data-rate in communication systems [55]. It inevitably leads to broadening of the signal in the frequency domain [56], which constitutes a general problem for radio communication, where the available frequency spectrum is limited and it is desirable to stack as many communication channels as possible next to each other without leakage between them. Any leakage can be considered as interference noise and will hence degrade the signal-to-noise ratio and thereby the performance of the disturbed channel. Likewise, as the instantaneous frequency of the leaking channel falls outside the receiver bandwidth, the communication is interrupted.

Many applications of oscillators rely on information transfer obtained by modulating and measuring the phase of the signal. Such a measurement can only be defined as long as there exists a frequency of the carrier \( f_0 \), which can be regarded as constant during the measurement. Equivalently, the phase noise \( \phi(t) \) must be low in relation to the intended phase modulation of the signal.

### 3.1.2 Quantification of frequency noise

Since the frequency noise \( \nu(t) \) is a stochastic property, the most detailed way of characterizing it is in terms of its (single sideband) power spectral density \( S_\nu(f) \), where \( f \) is the Fourier frequency of the fluctuations in \( \nu(t) \). Since the instantaneous frequency deviation \( \nu(t) \) is in the units of Hz, the frequency noise (power) spectral density \( S_\nu(f) \) obtains the unit Hz\(^2\)/Hz. Likewise, the (single sideband) phase noise (power) spectral density \( S_\phi(f) \) obtains the unit rad\(^2\)/Hz. The two power spectral densities are related by the square of the Fourier identity of the derivative as

\[
S_\nu(f) = f^2 S_\phi(f).
\]  
(3.2)

Another way to represent the frequency noise is in terms of the Allan variance \( \sigma_\nu^2(\tau) \) [57], which is the variance of the normalized frequency \( y(t) = \nu(t)/f_0 \) as a function of the observation time \( \tau \).

A common measurement technique that is referred to as a phase noise measurement, is the measurement of the power spectral density of the signal as a function of the frequency offset \( f_{\text{offs}} \) from the center frequency \( f_0 \). This quantity is referred to as \( L(f_{\text{offs}}) \) ("script-L") and generally given in units of dBC/Hz where dBc is dB related to the carrier power. Although both the quantities \( S_\phi(f) \) and \( L(f_{\text{offs}}) \) are commonly referred to as the phase noise spectrum, they are in principle measures of two different quantities (i.e. the power spectral density of the phase noise and the power spectral density of the resulting oscillation waveform, respectively).
3.1. FREQUENCY NOISE THEORY

However, for signals with low levels of phase fluctuations,

\[ \langle \phi^2(t) \rangle = \int_{1/\tau}^{\infty} S_\phi(f) df < 0.1 \text{ rad}^2, \]  

it is possible to approximate the relation between the two as

\[ \mathcal{L}(f_{\text{offs}}) \approx \frac{S_\phi(f = f_{\text{offs}})}{2}. \]  

For practical purposes, it has been decided [58] that the above equality shall be considered absolute (by re-definition of \( \mathcal{L}(f_{\text{offs}}) \)), including the cases also where \( \langle \phi^2(t) \rangle > 0.1 \text{ rad}^2 \).

The simplest measure of the frequency stability, which has also been extensively employed in the characterization of STOs, is the full width at half maximum (FWHM) of the peak in the power spectral density denoted \( \Delta f \). Using the relation \( \Delta f = \pi S_\nu,\text{white} \), valid for white frequency noise of the level \( S_\nu(f) = S_\nu,\text{white} \) [59], we obtain the following relation between \( \Delta f \) and \( \mathcal{L}(f_{\text{offs}}) \) (expressed in dBc/Hz):

\[ \mathcal{L}(f_{\text{offs}}) = 10 \log_{10} \frac{\Delta f}{2\pi f_{\text{offs}}^2}. \]  

This means that for an oscillator with \( \Delta f = 1 \text{ MHz} \) (the order of magnitude of the best performing STOs at microwave frequencies), \( \mathcal{L}(f_{\text{offs}} = 1 \text{ MHz}) \approx -68 \text{ dBc/Hz} \).

3.1.3 Noise classification

Frequency noise, as other noise types in general, can be classified according to its statistics through the Fourier frequency dependence in its spectral density. This frequency is very often a power function \( S(f) = C_\alpha f^\alpha \) where the exponent \( \alpha \) usually takes on integer values although fractional values also occur. \( C_\alpha \) is here a constant associated with the noise process. The appearance in a noise spectrum \( S(f) \) of frequency ranges with different exponent \( \alpha \) is an indication of different governing noise processes on the different, corresponding time scales. Thereby, a noise spectrum can often be used as a tool for determining the relevant noise sources.

For processes generating noise spectra with a \( 1/f \)-type (\( \alpha = -1 \)) low-frequency noise, there seems to exist no general underlying noise phenomenon [60]. Instead, various sources need to be investigated – differing from system to system. In many cases, the low-frequency \( 1/f \) noise can be modelled as originating from a large number of fluctuating elements where each element can have two or more discrete states [61, 62].
3.1.4 Generation of time-domain signals with specified frequency noise

In order to simulate the performance of an electrical system such as a radio transmitter or receiver with an STO as its local oscillator, it is necessary to obtain a representative waveform for the STO. Since the frequency stability is such an important parameter, it is important that the frequency of the STO waveform in the simulations has the same fluctuating or random behavior as the fabricated devices. Analytical models for STOs generally predict the FWHM linewidth of the spectral line, which is the frequency-domain average consequence of the frequency fluctuations. A simulator typically works in the time domain and hence needs the time-domain representation of the STO signal. In this section we describe in more detail the contribution to [39] (Paper IV of this thesis), about the method for generating a time-domain waveform with a specified frequency-domain linewidth.

The generation of noise is a research topic in itself – in particular for the case of $1/f$ noise, where only generation schemes generating an approximate result exists [63]. White noise is however easily generated from a chosen probability distribution. In physical systems, noise is often approximated as white noise with a Gaussian (or normal) distribution of its amplitudes. In the case of frequency noise, the noise signal is the random frequency fluctuations $\nu(t)$ of an oscillating signal with a specific nominal frequency $f_0$.

Since most literature on STOs utilize white noise sources (in the form of a stochastic internal magnetic field), it is not surprising (although not immediately obvious) that the predicted frequency noise also obtains a white power spectral density, $S_\nu(f) = S_\nu,\text{white}$. A signal with white frequency noise obtains a spread in the frequency domain described by a Lorentzian lineshape with the FWHM linewidth given by the relationship $\Delta f = \pi S_\nu,\text{white}$ [59].

In order to generate a signal in the time-domain with the frequency-domain characteristic linewidth $\Delta f$, a relationship between the statistics of the phase noise $\phi(t)$ or the frequency noise $\nu(t)$ and $\Delta f$ is required. One such relationship is given for the phase diffusion constant $D$, describing the time evolution of the phase variance (for white frequency noise) as a function of time $t = n\Delta t$ for the discrete case, where $\Delta t$ is the time step:

$$\langle \phi(t)^2 \rangle = Dt = D \cdot n\Delta t,$$

namely $D = 2\pi \Delta f$ [64]. The discretized random phase walk is given by $\phi(n\Delta t) = \sum_{i=1}^{n} \Delta \phi_i$, where $\Delta \phi_i$ are the individual, random phase noise steps. This can be described also in terms of the discretized random frequency $\nu_i$, given by a normal
3.1. FREQUENCY NOISE THEORY

distribution \(N(0, \sigma_\nu)\) with the standard deviation \(\sigma_\nu\) given by:

\[
\langle \phi(t)^2 \rangle = \text{Var} (\phi(t)) = (3.7a)
\]

\[
\text{Var} \left( \sum_{i=1}^{n} \Delta \phi_i \right) = (3.7b)
\]

\[
\text{Var} \left( \sum_{i=1}^{n} \Delta t 2\pi \nu_i \right) = (3.7c)
\]

\[
\text{Var} \left( 2\pi \Delta t \sum_{i=1}^{n} \nu_i \right) = (3.7d)
\]

\[
(2\pi \Delta t)^2 \text{Var} \left( \sum_{i=1}^{n} \nu_i \right) = (3.7e)
\]

\[
(2\pi \Delta t)^2 \sum_{i=1}^{n} \text{Var} (\nu_i) = (3.7f)
\]

\[
(2\pi \Delta t)^2 \sum_{i=1}^{n} \sigma_{\nu_i}^2 = (3.7g)
\]

\[
(2\pi \Delta t)^2 n \sigma_{\nu_i}^2 = (3.7h)
\]

\[
(2\pi \sigma_{\nu_i} \Delta t)^2 n = (3.7i)
\]

\[
(2\pi \sigma_{\nu_i})^2 \Delta t \cdot n \Delta t = (3.7j)
\]

resulting in

\[
\sigma_\nu = \frac{1}{2\pi} \sqrt{\frac{D}{\Delta t}} = \frac{1}{2\pi} \sqrt{\frac{2\pi \Delta f}{\Delta t}} = \sqrt{\frac{\Delta f}{2\pi \Delta t}}. (3.8)
\]

Similarly, it is possible to obtain for the standard deviation of the discretized angular frequency deviations \(2\pi \nu_i\):

\[
\sigma_{\omega} = \sqrt{\frac{D}{\Delta t}} = \sqrt{\frac{2\pi \Delta f}{\Delta t}} = \sqrt{\frac{\Delta \omega}{\Delta t}}. (3.9)
\]

Equation (3.9) constitutes the basis for the frequency noise generation in [39] (Paper IV), with the difference that the FWHM angular frequency linewidth there is defined as \(2\Delta \omega\) (as opposed to \(\Delta \omega\) in this thesis). In theory, one generates just the series \(\Delta \phi_i\) in a discretization where the only points in time are \(i \Delta t\). However, in many cases, such as in system- and circuit-level design tools such as Cadence SpectreRF, the circuit simulator needs to be able to simulate the device output at any arbitrary time \(t\). In such cases, when one needs to know \(\phi(t)\) also at points in between \(i \Delta t\), the phase has to be linearly interpolated or else the discontinuities in the phase \(\phi(t)\) will result in discontinuities in the device waveform \((\sim \sin(2\pi f_0 t + \phi(t)))\).
Such interpolation is identical to utilizing the instantaneous frequency deviation $\Delta \nu_i$. Since the simulator has to be able to go both forward and backward in time in order to reach convergence for the simulated voltages and currents, the actual noise realization has to be stored in memory and may not be allowed to be regenerated (in which case the device could give different output for the same time $t$ depending on the history of the back- and forward-stepped solution).

3.2 Frequency noise in spin torque oscillators

Spin torque oscillators differ from many other oscillators in the way that there is a strong coupling mechanism between the oscillation amplitude (the opening angle of the precessional cone) and its frequency [65]. STOs are also comparatively small, increasing the relative impact of thermal noise impulses. In magnetic materials, the noise impacting the magnetization is usually modelled as random internal field impulses which act to realign the magnetization towards their particular (randomized) direction [66].

The magnetization precession can be perturbed by a thermal field impulse in two perpendicular directions; parallel and perpendicular to the trajectory. Any perturbation along the trajectory simply results in an instantaneous phase shift, whereafter the oscillation continues with the same frequency. If the magnetization is however kicked perpendicularly to its trajectory, its phase is initially unchanged but its position will now be at a trajectory with a different amplitude. This amplitude change is coupled into a change in the frequency, resulting in the effect pictured in Figure 3.1: as the magnetization precession relaxes back to its steady-state trajectory, the oscillator will pick up a phase shift compared to the nominal, steady-state frequency. This phase difference is visible in Figure 3.1(b) as the difference between the unperturbed (blue) and perturbed (red) motions. This type of phase noise induced by the amplitude-frequency coupling does not exist in ordinary electrical oscillators [67].

Theoretical work based both on the general nonlinear auto-oscillator model [69, 70, 71] and direct macrospin dynamics [64] show that the latter effect, of amplitude-frequency coupling, is the clearly dominating contributor to the resulting phase noise. This means that the same coupling that provides the high frequency tunability also inherently comes with intensified levels of frequency noise.

Another aspect of frequency noise in STOs, that might be even more critical, is the mode-jumping phenomenon that has been observed in time-domain experiments [72, 73]. Here, the STO toggles or jumps between different, well-separated frequencies which are generally associated to different precessional modes or trajectories. Such mode-jumping can in theory be obtained even at zero temperature in systems with complex dynamics (through chaotic or weakly chaotic behavior [74]), but is in most cases simply viewed as thermal fluctuations kicking the magnetization from one steady trajectory to another [75]. In the process, the phase coherence
3.2. FREQUENCY NOISE IN SPIN TORQUE OSCILLATORS

Figure 3.1: Phase shift acquired from a perpendicular perturbation at time $t = 0$ in an oscillator with the nominal frequency $f_0$ and red shift; i.e. having lower frequency for larger oscillation amplitudes. (a) Magnetization trajectory for the unperturbed (blue) and perturbed (red) motion. (b) Phase shift acquired by the perturbed motion as it relaxes to the steady-state trajectory. ©2016 IEEE, reprinted from [68].
is completely or partially lost, leading to an increase in the linewidth [47, 76].

In nano-pillar STOs, the origin of different-frequency modes has been explained micromagnetically as various oscillation patterns in the laterally constrained thin film [77, 78]. For nano-contact STOs, the origin of various submodes within the propagating mode is more unclear; their presence is indicated by discontinuous transitions in the frequency versus current [79, 80, 81] but whether mode-jumping occurs or not has just recently been investigated in the work presented within this thesis. The case of operation in magnetic fields below the critical angle, where the solitonic “bullet” mode can be excited, has been the topic for investigations showing that in the cases when both modes are excited, they can co-exist in time due to spatial localization underneath the nano-contact [82].

Most of the studies related to STO frequency stability report measurements of the spectral linewidth. As for actual measurements of the phase or frequency noise spectral density, the progress has been hindered by the inability of commercial phase noise analyzers to lock to the relatively strongly fluctuating STO frequency. This random frequency fluctuation on the level of MHz per second is of course an unwanted behavior, but it has yet not been characterized in a systematic manner. So far, time-domain techniques have been implemented as in [83] (Paper II) and [59, 84, 85, 86, 87, 88], with measurement times restricted to ranges of µs to ms depending on the measurement bandwidth and the oscilloscope memory depth. These studies in general show the expected white frequency noise for most of the range of the obtained frequency noise spectrum. Four of the studies ([83] (Paper II) and [84, 85, 87]) report the presence of low-frequency $1/f$ frequency noise, which is likely the same noise that can be observed on the timescale of seconds. Another of the studies, where vortex-mode oscillation below 200 MHz was measured, a low-frequency slope of $1/f^{1/2}$ was observed.

On the high-frequency end of the frequency noise spectral density, a fall-off from the white level towards $1/f^2$ has been observed in the high-bandwidth MTJ experiments [85, 86, 88] and used to obtain values for the amplitude relaxation rate $f_p$, which are found to be in agreement with the fall-off frequency in the actual amplitude noise spectrum [85]. A white noise level at even higher fluctuation frequencies was identified as the linear frequency noise [85, 86, 88], not stemming from amplitude noise but the perturbations parallel to the trajectory. The relationship between the two white frequency noise levels in these measurements gives the nonlinearity parameter $(1 + \nu^2)$ defined in the general nonlinear auto-oscillator model.
Part II

Experimental work
Chapter 4

Electrical DC and microwave measurements

In the spin torque oscillator, an electrical current is used for both of the two purposes of 1) exciting the magnetization dynamics through the spin torque and 2) producing a corresponding output voltage signal through the magnetoresistance effect. The device resistance reflects the state of the free layer magnetization in terms of its angle relative to the fixed layer, and hence constitutes only a one-dimensional signal. Thus, it is in general not possible to use the resistance signal to reconstruct the full spatially dependent spin wave dynamics in the STO. However, the information carried in the resistance signal can be compared with the corresponding output of a selected model and can thus serve as confirming evidence for the modelled magnetization configuration.

In this chapter, we will describe the various methods used in this work for electrical characterization of both the DC and AC parts of the resistance signal, and the results that have been obtained using the methods.

The work is focused on the propagating spin wave mode, since it provides the highest frequency stability available in NC-STOs and blue-shifts (i.e. increases its frequency) with the magnitude of the drive current, thus enabling operating frequencies in a span of several GHz from the FMR frequency and upwards. The propagating mode is also of interest for magnonic devices, since the NC-STO provides local generation of spin waves that can carry information several µm.

4.1 Device structure

The devices investigated in this chapter have been fabricated jointly at the KTH Royal Institute of Technology and the University of Gothenburg. We will here present the device structure; the fabrication has not been part of this thesis and
has been described in further detail elsewhere [89].

Images of the device structure are shown in Figure 4.1. The thin film stack configuration of the devices characterized in this chapter is Si/SiO$_x$/1000/Pd$_8$/Cu$_{30}$/Co$_8$/Cu$_3$/NiFe$_{4.5}$/Cu$_{3}$/Pd$_2$ (thicknesses in nm). The free layer NiFe alloy is the commonly used Ni$_{80}$Fe$_{20}$, also known as permalloy (Py). For each device, the stack has been patterned into a rectangular mesa with the size 16*8 $\mu$m$^2$ and then covered with an insulating 30 nm thick SiO$_2$ layer. In the center of the mesa, the circular nano-contact is defined using electron beam lithography and larger vias are defined using optical lithography for making the ground connections on the far sides of the mesa. In the stack between the ground vias and the nano-contact, the current primarily flows in the thick and relatively highly conductive Cu bottom electrode. This device structure provides a current path for driving the STO and sensing the GMR signal with the same drive current.

4.2 Pulse-delta DC measurement

The dual utilization of the electrical current in STOs constitutes a problem for reading the magnetization state without affecting it. This problem is typically circumvented by reducing the magnitude of the current so that the induced spin torque no longer induces magnetization dynamics. The approach works well as long as the resulting magnetoresistive voltage signal $U_{\text{MR}} = R_{\text{MR}} \cdot I_{\text{DC}}$ is large compared to that of the noise voltage. Here, we decompose the total device resistance $R_{\text{STO}}$ into two parts excluding and including effects of the magnetization state as $R_{\text{STO}} = R_{\text{non-MR}} + R_{\text{MR}}$. For a typical GMR NC-STO, $R_{\text{non-MR}} = 3\, \Omega$ and $R_{\text{MR}} \sim 1\% \cdot R_{\text{non-MR}} = 0.03\, \Omega$. This value for $R_{\text{MR}}$ and a measurement current $I_{\text{DC}} = 1\, \text{mA}$ leads to $U_{\text{MR}} = 30\, \mu\text{V}$ for the maximum signal swing induced by magnetization-dependent effects. For a detailed measurement of any magnetization configuration-dependence, the desired measurement accuracy needs to be within only a fraction of this voltage – i.e. on the order of $1/100 \cdot 30\, \mu\text{V} = 0.3\, \mu\text{V}$.

The so called thermal voltage can constitute a significant source of error in this voltage range. One way to considerably reduce the influence of the thermal voltage is simply to measure and compensate for it. Since one reason for compensating for the thermal voltage is to remove its effect of drift and fluctuation during the measurement, the thermal voltage needs to be continuously monitored and compensated for. Depending on the type of the measurement, there exist several measurement schemes for this. The schemes that are available in the Keithley 6221/2182A precision current source and nanovoltmeter combo, are the differential conductance, delta and pulse delta modes. A differential conductance measurement is performed around a sweep of the current involving back-and-forward stepping, while the delta and pulse delta modes are performed at fixed current level. The delta mode operates a square-wave current source with 50/50 time division between the two current levels (usually ON and zero, or ON and the reverse ON-current),
4.2. PULSE-DELTA DC MEASUREMENT

Figure 4.1: Scanning electron microscopy of the top contact structure and the mesa with the etched nano-contact and ground vias. Also shown is the stack schematic.

while the pulse delta allows a configurable wave (usually between ON and zero) so that the OFF-state can be chosen considerably longer than the ON-state. This configurable duty-cycle is desirable in order to be able to investigate and control effects induced by sample heating during the ON-state. These effects include both thermal voltage and temperature-induced sample resistance increment. For probing the magnetic state of NC-STOs without altering it by spin torque or inducing sample temperature effects, we found pulse delta to be the most appropriate measurement scheme.

An example of a magnetoresistance measurement is shown in Figure 4.2. As the
in-plane magnetic field is swept from left to the right (forward sweep, red curve), there is a gradual resistance increase as the free layer starts to rotate an align with the changed direction of the magnetic field, while the fixed layer, due to its higher coercivity, stays aligned with the original negative field direction. Upward jumps in the resistance curve are caused by regions of the free layer that is switching coherently. In the high-field saturated state, both magnetizations are pointing in the positive direction. During the reorientation of the both magnetizations, resistance jumps of both upward and downward direction can result from coherent switching of regions both in the free and the fixed layer. The regions can consist of magnetic domains or, potentially, of crystalline grains formed by the sputter deposition technique. By re-measuring the same sample up to ten times, however, the discontinuous switching fields showed no or low consistency, indicating that the region switching is a domain phenomenon. On the other hand, the effective field experienced by a grain consists both of the external field and the dipolar and exchange fields from the surrounding grains, meaning that if the first movement of the initial grain is not the same between the measurements, the collective switching can take an entirely different route – also resulting in random switching behavior with random switching fields. Such a system potentially has very high sensitivity to any small differences in the saturated initial state or noise. In order to use magnetoresistance measurements as a tool for measuring film homogeneity, the problem of separating random domain switching from random grain switching needs to be solved.
4.3 Frequency-domain measurement

A straightforward way of characterizing an oscillator is to do a frequency-domain measurement of its oscillating voltage. This is typically done with a spectrum analyzer, which basically consists of a narrow bandpass filter with a tunable center frequency. The analyzer measures the transmitted electrical power on a RF diode, and hence gives a measurement of the power spectral density in terms of the power within the filter bandwidth. The width of the bandpass filter is called the resolution bandwidth. In order to obtain a stable measurement of the power spectral density, there is an additional filter before the RF diode that performs configurable time-averaging of the signal. This averaging is performed on the so-called intermediate frequency (IF) of the spectrum analyzer and is controlled in terms of the IF bandwidth. The lower the selected IF bandwidth is, the more averaging will be done. This also leads to longer measurement times.

The microwave circuit used for both frequency- and time-domain measurement is shown in Figure 4.3.

4.4 Time-domain measurement

By its nature, a frequency-domain measurement represents the long-time average behavior. The acquired spectrum contains information about the frequency stability of the signal, mainly in terms of the linewidth. However, a frequency-domain
measurement can in general not be used to unambiguously probe whether two or more visible spectral peaks at different frequencies are created by two signals that coexist in time or one signal that jumps between the frequencies.

### 4.4.1 Bandwidth and noise

A time-domain measurement system such as an oscilloscope has a frequency-domain bandwidth that specifies how quick signal variations that can be accurately represented, without time-domain smoothing. In this sense, high bandwidth is typically desired. However, high bandwidth inherently also increases the Johnson-Nyquist RMS voltage noise $v_n$:

$$v_n = \sqrt{4k_B TR\Delta f},$$

where $k_B \approx 1.381 \cdot 10^{-23}$ J/K is the Boltzmann constant, $T$ is the absolute temperature, $R$ is the resistance producing the noise and $\Delta f$ is the bandwidth. At room temperature $T = 300$ K, the voltage noise on a $R = 50$ Ω microwave measurement load is approximately

$$v_n = 0.91 \frac{nV}{\sqrt{Hz}} \cdot \sqrt{\Delta f},$$

which at $\Delta f = 10$ GHz corresponds to 91 µV. In comparison, GMR NC-STOs typically deliver an electrical power in the order of -70 dBm (0.1 nW) to a 50 Ω measurement load, corresponding to 71 µV. Hence, the STO signal is buried in noise already at the measurement load. In most cases, the measurement load is the input of an amplifier and this active circuit generally produces additional noise (characterized by its noise figure) which is added to the amplified input noise and signal. The SNR is hence additionally reduced by the amplifier.

The only solution for measuring the real-time signal is to reduce the bandwidth so that the bandwidth noise reduces to acceptable levels. Bandwidths of $\Delta f = 1$ GHz or 100 MHz results in noise levels of $v_n \approx 29$ µV or 9.1 µV, respectively.

### 4.4.2 Down-mixing

Due to the bandwidth noise, the measurement bandwidth for GMR STO signals at 10 GHz and above needs to be restricted. One way of doing this is by adding a bandpass filter after the amplifier, which then attenuates the noise outside its bandwidth. Since the STO is an oscillator with high frequency tunability, it is desired that the center frequency of the bandpass filter also is tunable. However, the available tunable bypass filters operating at 10 GHz and above are based on YIG crystals and provide a maximum bandwidth around 100 MHz. However, reducing the bandwidth also reduces the possibility of observing fast changes in the signal, such as frequency or amplitude fluctuations. The fastest changes that can be observed are on the timescale of the inverse bandwidth, so a filter bandwidth of 100 MHz limits the observable fluctuations to timescales on the order of 10 ns.
Due to the time-averaging performed by a filter, there is no additional information that can be obtained by sampling the signal at a rate much higher than the filter bandwidth. However, a 100 MHz wide filter centered at 10 GHz still requires accurate sampling of the 10 GHz signal, resulting in an inefficient use of the oscilloscope memory. It would hence be desirable to subtract the known carrier frequency (∼10 GHz) and only sample the fluctuations with a rate corresponding to the filter bandwidth. For this purpose, RF mixers are typically employed; our down-mixing setup is depicted in Figure 4.3.

An RF mixer has three ports: the RF port carrying the incoming signal, a local oscillator (LO) port to which a reference carrier signal is supplied and an intermediate frequency (IF) port where the output is obtained. The frequency of the down-mixed signal at the IF port will be the difference between the RF signal and the LO signal. The signal at the IF port can then comparatively easily be amplified to a level that can be measured with an oscilloscope. An advantage of down-mixing is that the signal filtering can be performed at the IF and hence does not need frequency tunability. This opens up for using filters with bandwidths higher than the YIG-limit of 100 MHz. This is particularly useful in the case of mode- (or frequency-) hopping STO signals, which typically occurs between frequencies separated by more than 100 MHz for GMR NC-STOs.

The GMR STO signal levels typically require amplification of the IF signal. The bandwidth of this amplifier can then be considered as the filtering bandwidth. Further filtering can be achieved with filters in the oscilloscope, but in the case of the LeCroy WaveMaster 825Zi the high-frequency fall-off of these filters was comparatively slow.

### 4.5 Results

#### 4.5.1 Device-to-device variability

In order to draw solid, general conclusions about the physics of a particular type of device, it is important to base the analysis of any particular phenomenon on a behavior that can be reliably reproduced. For the case of nano-contact spin torque oscillators produced by both Everspin Technologies, Inc. and our research group at the KTH Royal Institute of Technology and the University of Gothenburg, the oscillation properties as a function of current and magnetic field can be reproduced to within the accuracy of the sample placement within the magnetic field, which always contains slight inhomogeneity. This holds true as long as the bias current is not increased to too high levels, in which case the oscillation becomes worse defined or simply ceases to exist. This type of sample degradation is typically observable also in the device resistance, which usually goes up for such an event. However, as long as the bias current is kept below the critical current value, the device can be measured for many hours while showing a consistent behavior.
Although the device-level reproducibility is sufficient, the device-to-device variability is significant. In terms of resistance, for 100 nm diameter NC-STOs the mean value and standard deviation was found to be around 2.85 $\Omega$ and 0.19 $\Omega$, where the mesa and top contact pads constitute 1.63 $\Omega$ and the nano-contact 1.22 $\Omega$. If the entire standard deviation is assumed to stem from variations in the nano-contact, this leads to a 0.19/1.22 $\approx 16\%$ relative NC resistance deviation. This resistance variation can stem from area variation or interface resistivity variation. A possible source for the latter could be the NC etching and the pre-etching and deposition during the NC metallization process.

The variability in terms of RF characteristics is more complex. We have focused on the device behavior as a function of the bias current, since the bias current is the controllable acting force that excites the dynamics that is pre-defined by the magnetic field landscape. An example of the RF output from nine NC-STOs with 100 nm diameter nano-contacts is shown in Figures 4.4 and 4.5. Concentrating at the frequency as a function of the current, it is apparent that the behavior varies qualitatively. Differences exist in the form of varying number of simultaneously excited frequencies, the current and frequency position of discontinuous transitions from one frequency to (generally) a higher one, and the curvature (or non-linearity). The comparatively weak resemblance in the qualitative behavior significantly complicates a quantitative comparison, but it is apparent that the curves are not simply rescaled with respect to the current, as would be the naively assumed behavior in the case of NC area variation. It is instead more likely that the variation in RF characteristics stems from various sources of inhomogeneity in the oscillating regions; i.e. the NC via and the metallic layers underneath it.

We can identify a comparatively well-defined behavior for the devices in Figures 4.4(a,b,c,e,f) and 4.5(a) in terms of current intervals with a single, sharp linearly increasing frequency, connected either by nonlinearities or discontinuous transitions. The samples in Figures 4.4(d) and 4.5(b,c) have intermediate-current regions where more than one frequency is excited and the peaks are worse defined at most currents. In all the samples at low currents, there is a low-power interval with low, zero and even negative tunability $df/dI$. The frequency of this pre-threshold mode varies greatly between the samples, and may or may not connect to the main mode once it is excited.

### 4.5.2 $1/f$ and white frequency noise

Historically, the frequency stability of STOs has been characterized primarily by the linewidth, i.e. the full width at half maximum (FWHM) of the peak in the power spectral density. The linewidth gives a rough measurement of how much the frequency varies during the measurement time, but it does not per se give information about what the time scale of the fluctuations is. Theoretical treatment of noise in STOs mostly considers white noise sources modelled as a stochastic device internal magnetic field. Such a white noise source results in frequency noise
that is also white over a wide range of fluctuation frequencies and falls off as $1/f^2$ for high fluctuation frequencies.

For lower fluctuation frequencies, however, experimental results show the pres-
Figure 4.5: Device-to-device variation for nine devices, part 2 of 2. Power spectral density versus current for NC-STOs with 100 nm diameter nano-contacts, all located next to each other on the same chip. (a-c) Devices 7-9. $H = 10$ kOe, $\theta = 70^\circ$.

Little is known about the origin of the colored (non-white), low-frequency frequency fluctuations in STOs. Available studies have been restricted to reporting its presence, and being one order of magnitude stronger in devices with a Co/Ni multilayer (5x(Co(0.2)/Ni(0.4))+Co(0.3)) as free layer compared to a NiFe free layer. In [83] (Paper II), we studied both the $1/f$ and white frequency noise levels as a function of current for nominally identical NiFe devices in a set of magnetic field strengths. This investigation of a range of adjacent operating points with low as well as high linewidths was made possible by use of the high-bandwidth time-domain
measurement system described in Chapter 4.4.

The ability to measure also the high-linewidth peaks is important, since these operating points usually are the ones that show the highest frequency versus current nonlinearity. The general non-linear auto-oscillator theory predicts a larger impact of the white magnetic noise on the white frequency noise as a function of increased nonlinearity, and although this impact of the nonlinearity had been verified experimentally only in terms of the linewidth, our study shows that the relation indeed holds for the actual white frequency noise. This is exemplified in Figure 4.6(d-f).

In fact, the frequency-domain linewidth implied by our measurement of the white frequency noise was found to be close to, but always below the measured linewidth for the measurement conditions typically employed in the spectrum analyzer.

Measuring the low-frequency $1/f$ frequency noise as a function of the bias point made it possible to see that its behavior in most cases follows the same trend as the white frequency noise and goes up at the operating points showing nonlinearity in $df/dI$. This finding indicates that low-frequency $1/f$ noise is present also in the amplitude of the magnetization precession, and that this $1/f$ precession amplitude noise is a root cause of the $1/f$ frequency noise. This is consistent with the general notion of the STO as an oscillator with coupling between the oscillation amplitude and oscillation frequency, in the sense that the frequency is controlled by the amplitude. The amplitude, in turn, is controlled by the spin torque provided by the spin current.

There is however a region in which the $1/f$ frequency noise does not follow the same trend as the white frequency noise, as indicated in Figure 4.7(f). In this
Figure 4.7: (a,b) Power spectral density, (c,d) spectrum analyzer linewidth and white frequency noise and (e,f) 1/f frequency noise for the dual-mode sample B. (a,c,e) \( H = 10.5 \, \text{kOe} \) and (b,d,f) \( H = 11.5 \, \text{kOe} \), \( \theta = 70^\circ \). (g-i) Waveforms measured at the indicated current values in (a). Reprinted from [83] with the permission of AIP Publishing.

region we see an elevated level of 1/f frequency noise. It was found that this region, when biased in a slightly weaker magnetic field, showed the presence of an additional excited mode, at a higher frequency. In this dual-mode region, the oscillation waveform of the original, lower frequency mode was no longer continuous but showed an ON/OFF-toggling behavior on a timescale of hundreds to a fraction of a \( \mu \text{s} \) (Figure 4.7(g-i)). We interpret this finding as a second cause of 1/f frequency noise, and suggest that the higher-frequency additional mode exists also at the higher magnetic field strength as a perturbing element inducing 1/f-type instability in the magnetization precession.

4.5.3 Mode-jumping

The appearance of the high-current additional mode was studied more extensively in [90] (Paper I).

In this investigation, a measurement bandwidth of 2.5 GHz was obtained by using a 2.5 GHz bandwidth IF amplifier after the mixer. This high bandwidth made it possible to observe, in real time, how the oscillator randomly changed its frequency by several GHz in a mode-jumping behavior. The study determined that these high-current additional propagating modes were not excited at the same time, i.e. that they were not coexisting as had been determined for magnetic field conditions where both the propagating and localized “bullet” modes existed simultaneously [82].

More information about the nature of the high-current modes than what could
be presented in [90] (Paper I) was obtained by examining their dependence on the magnetic field strength, displayed in Figures 4.8 and 4.9. Figure 4.9(a) depicts the behavior in the field strength $H = 10.0$ kOe, where the high-current mode-jumping was investigated in Paper I. In this field strength, the two additional modes at high current have different tunability $df/dI$ and join at $I = 25$ mA. However, going down in field strength to $H = 9.4$ kOe (Figure 4.8(a)) the three modes have an almost identical tunability and oscillate comparatively freely. By increasing the field strength by just 0.2 kOe (Figure 4.8(b)), the situation has changed; here there are not three independent modes, but a domination behavior where the dominating mode is consecutively shifted up as a function of increasing current. In Figure 4.8(c) at $H = 9.7$ kOe, the middle mode and top mode bend their frequencies curves to form a continuous but nonlinear relationship visible in Figure 4.8(d) at $H = 9.8$ kOe. This is accompanied by a visible graininess in the spectra, which is caused by mode-jumping. Comparing this Figure 4.8(d) to Figure 4.9(a), where the time-domain measurements were done, we see that the origin of the different $df/dI$ for the top two modes is the bending of the middle mode, which has been “pulled” up to the top mode. In some aspect, the middle and top modes are closer to each other in the sense that the middle mode is pulled towards the top mode. This is supported from an energy viewpoint based on the timescales of the mode-jumping presented in Paper I. The oscillation at $H = 10.0$ kOe, $I = 22.5$ mA has a sub-$\mu$s timescale for the mode-jumping between the middle and top modes, while the timescale is on hundreds of $\mu$s for the toggling between the lower mode and the higher two-mode state. This indicates that the top two modes are energetically closer to each other than the bottom mode is to both of them. One might consider that it is more probable that two magnetization configurations that resemble each other more closely have more similar energies. If two configurations are more similar to each other, it is also more likely that the energy barrier that separates them is lower. Going to even higher field strengths, first the middle mode and eventually also the top mode disappears (Figures 4.9(b-d)), leaving the bottom mode in a steady oscillating state with no apparent mode-jumping at $H = 10.4$ kOe.

In the micromagnetic simulations performed in [82], the coexistence of the propagating and localized bullet modes was found to be facilitated by localization of the two modes to different regions underneath the nano-contact. In the case of the propagating mode-jumping in Paper I, the absence of coexistence makes possible a scenario where only one propagating mode is allowed at any given point in time, and the active mode is free to extend over the entire nano-contact region. In the electrical measurements, it is however not possible to determine whether these modes are localized (or centered) in different regions underneath the nano-contact, or all emerge in the same active region.

This type of high-current additional propagating mode is however not the most common behavior for the GMR NC-STOs fabricated at KTH, which implies that its origin is connected to the device-to-device variability. If the additional modes were
alternative solutions for the LLGS equation of motion for a nominal, homogeneous device, their appearance would likely be present more often than it would be absent.

A type of multi-mode situation that however frequently occurs in the fabricated samples is when there is a discontinuous upward step in the frequency versus current. Such a situation was encountered at $H = 10.0 \text{ kOe}$, $I = 17.3 \text{ mA}$ (Figure 4.9(a)) and recorded in the time-domain. The short-time Fourier transform [91] of the signal is shown in Figure 4.10. Also in this type of much more common multi-mode situation, we see that the STO is jumping between the modes so that only one mode is excited at a time. This indicates that the propagating mode might, in general, only be able to excite one of its various sub-modes at a time.

Mode-jumping and thereby frequency-hopping is obviously not desirable in an RF oscillator, where one typically needs a stable reference frequency that can be modulated in subsequent components. Mode-jumping in STOs is also considered to be accompanied with loss of phase coherence, so that the phase at the onset has no

Figure 4.8: Power spectral density versus current for the device in Paper I in $H =$ (a) 9.4 kOe, (b) 9.6 kOe, (c) 9.7 kOe, (d) 9.8 kOe, $\theta = 70^\circ$. 
4.5. RESULTS

Figure 4.9: Power spectral density versus current for the device in Paper I in $H =$ (a) 10.0 kOe, (b) 10.2 kOe, (c) 10.3 kOe, (d) 10.4 kOe, $\theta = 70^\circ$.

or little correlation to the phase at the previous offset. Such incoherence increases the measured linewidth in the power spectral density for the individual peaks. From a general time-domain frequency noise perspective it can be discussed whether frequency-hopping or, if observed within a bandwidth covering only one mode, ON/OFF-toggling should be treated as frequency noise per se, since there cannot be noise in the frequency of a signal if the signal with that frequency temporarily does not exist. It is of course possible to treat any excursion of the frequency to another mode as a large and long-time frequency fluctuation of the original signal, but one might also choose to consider the different sub-modes as different oscillators.

When the signal is observed after a bandpass filter, the timescale of any signal fluctuations that can be observed is limited to the inverse bandwidth. This means that if the oscillator is turned on and off on a timescale faster than the inverse bandwidth, the toggling will not be readily observed. In that sense, mode-jumping will seemingly not matter from an application point of view, assuming that the
application uses a similar or even lower bandwidth. However, the phase noise of such a filtered signal will be greater than that of a continuous oscillator.

In either way, random mode-jumping is an unwanted phenomenon. In the case of the GMR NC-STOs studied in this thesis, there exist many ranges of bias conditions with single-mode operation. For complete tunability and maximum stability, however, the current-wise discontinuous frequency transitions need to be suppressed.
Figure 4.10: Short-time Fourier transform (STFT) of the waveform during mode-jumping in a discontinuous frequency transition for the sample in Figures 4.8 and 4.9, with STFT window length 20 ns. $I = 17.3$ mA, $H = 10.0$ kOe, $\theta = 70^\circ$. (a) 0 – 100 $\mu$s, (b) 0 – 10 $\mu$s.
Chapter 5

Micromagnetic simulations

In order to gain insight about the spin wave dynamics in nano-contact STOs, micromagnetic modelling has to be employed. The single-spin, macrospin model can by its nature not take into account the magnetic exchange field and the resulting spin waves that arise from the spin-to-spin interaction. Although the macrospin model cast into the form of general nonlinear oscillator theory has been found to show agreement with experiments, the agreement relies upon fitting of phenomenological parameters. A complete, self-contained description and prediction of the magnetization dynamics hence still requires the employment of computationally heavy micromagnetic simulations. Fortunately, the development of algorithms for calculating the dipolar field based on the fast Fourier transform (FFT) [92] has reduced the complexity of the calculations. Furthermore, the advent of implementations of these methods on graphics processing units (GPUs) has brought an additional speed-up in the order of one to two orders of magnitude. This means that micromagnetic simulations now constitute an available and viable tool that allows a detailed observation of the spin wave dynamics.

In our work, we focus on the propagating spin wave mode in GMR NC-STOs. We investigate its spatial extent since recent studies have shown deviations from the theoretically predicted cylindrical propagation. We also investigate inhomogeneity in the magnetic free layer as a possible source for the experimentally observed but hitherto unexplained presence of device-to-device-variation and nonlinear frequency versus current behavior.

5.1 Simulation setup

The simulations were set up utilizing the open source micromagnetic simulation package mumax³ [93]. mumax³ utilizes fast Fourier transform (FFT) techniques accelerated by GPUs (in our case either Nvidia Tesla K80 cards available on a number of the Tegnér nodes at the PDC Center for High Performance Computing.
at KTH, or on the local office workstation with consumer Nvidia GeForce GTX cards). A typical simulation of 10 ns on a $N = 512^2$ grid takes roughly 15 minutes on a Nvidia Tesla K80 and one hour on a GeForce GTX 750 Ti. The performance is mainly limited by the GPU memory bandwidth. A full output of the free layer with 10 ps time resolution consists of around 3 GB of binary data. This amount of data is manageable, but for an entire current sweep of 0–40 mA with a 0.5 mA resolution, the data set will be 240 GB – roughly a quarter of today’s standard hard disk drive volume of 1 TB. Since we in this work are interested in exactly the behavior when sweeping the current and storage space has a finite limit, we instead primarily use the mumax\textsuperscript{3} output table file, in which the mean values of specified regions of the magnetization is recorded. The primary region of interest is that of the free layer underneath the nano-contact, where the GMR signal is also produced. We hence focus on the magnetization averaged over a square region with the side $d_{NC}/\sqrt{2}$, such that the entire square fits inside the NC. The coordinate system has its $z$-axis perpendicular to the $xy$-plane of the thin films, and the in-plane component of the applied field is directed along the $x$-axis.

The main physical parameters obtained from FMR measurements of unpatterned thin film stacks (performed by S. Jiang), along with ± one standard error of the FMR fits are: $\mu_0 M_{s,NiFe} = 1.01 \text{ T} \pm 3.5 \text{ mT}$, $\mu_0 M_{s,Co} = 1.98 \text{ T} \pm 10.4 \text{ mT}$, $\alpha_{NiFe} = 0.0135 \pm 0.0008$, $\alpha_{Co} = 0.0088 \pm 0.0003$. The values for $\mu_0 M_s$ are around 18 % higher than the corresponding values for NC-STOs with the same stack, obtained from homodyne-detection utilizing an injected microwave current [94, 95]: $\mu_0 M_{s,NiFe} = 0.85 \text{ T}$ and $\mu_0 M_{s,Co} = 1.65 \text{ T}$. The discrepancy is to large part explained by the values for the gyromagnetic ratio $\gamma/2\pi$ which was set to 28 GHz/T in the film measurements and 31 GHz/T in the homodyne-detection; the difference is 10 %. From previous FMR measurements on unpatterned films, values of $\mu_0 M_{s,NiFe} = 0.88 \text{ T}$ and $\mu_0 M_{s,Co} = 1.7 \text{ T}$ was found to give good correspondence between simulations and experimental measurements on NC-STOs in the active regime [82]. Given the uncertainties in the determination of the saturation magnetization, the values selected for the simulations presented here are $\mu_0 M_{s,NiFe} = 0.85 \text{ T}$ and $\mu_0 M_{s,Co} = 1.7 \text{ T}$ along with $\gamma/2\pi = 28 \text{ GHz/T}$ in the homodyne-detection; the difference is 10 %. From previous FMR measurements on unpatterned films, values of $\mu_0 M_{s,NiFe} = 0.88 \text{ T}$ and $\mu_0 M_{s,Co} = 1.7 \text{ T}$ was found to give good correspondence between simulations and experimental measurements on NC-STOs in the active regime [82]. Given the uncertainties in the determination of the saturation magnetization, the values selected for the simulations presented here are $\mu_0 M_{s,NiFe} = 0.85 \text{ T}$ and $\mu_0 M_{s,Co} = 1.7 \text{ T}$ along with $\gamma/2\pi = 28 \text{ GHz/T}$ to mimic the simulated situation in [82]. Literature values were utilized for the exchange stiffness constant $A_{ex,NiFe} = 1.1 \cdot 10^{-11} \text{ J/m}$ and $A_{ex,Co} = 2.1 \cdot 10^{-11} \text{ J/m}$. No anisotropy was assumed for the free NiFe layer but also for the Co layer. Co has crystalline anisotropy but since the exact properties of the sputtered and hence polycrystalline Co films is not known (in particular the degree of alignment), this effect has been excluded. Finally, we used values for the spin polarization $\epsilon = 0.3$ and Slonczewski spin torque asymmetry parameter $\Lambda = 1.0$ based on previous works. The values of these parameters are hard to determine experimentally, but the spin polarization $\epsilon$ has a direct, inversely proportional influence on the threshold current.

It was detected that in the simulations, the values for the damping constants $\alpha_{NiFe}$ and $\alpha_{Co}$ had become interchanged, so that the NiFe free layer dynamics were
simulated with the value $\alpha_{\text{NiFe}} = 0.0088$ instead of 0.0135. A brief simulative investigation showed that the behavior presented in this chapter stays the same qualitatively and to a large extent also quantitatively. A quantitative significant difference was observed only for the long-term stability simulations presented in section 5.2.5, where the high-current grain case no longer showed a dramatic linewidth increase. This can be explained by the more highly attenuated spin wave propagation resulting in a lower intensity for the grain-boundary-reflected spin waves and the consequent lower impact of the multiple reflection interfaces. We still expect that the dramatic linewidth increase can result if the model for the inter-grain exchange coupling is altered into a distribution with more weakly coupled boundaries. Since the exact nature of the grain-to-grain exchange coupling is not known and difficult to determine experimentally, it is justified to alter the details of the inter-grain coupling, explore the resulting dynamics and compare with the experimental results. Since the difference in spin wave propagation efficiency regretfully appears to have a highly significant impact only on the highly time-consuming linewidth simulations, such an investigation is postponed to future research. We here primarily focus on the concept of reflected spin waves and their general impact on the STO dynamics.

5.2 Results

5.2.1 Periodic versus absorbing boundary conditions

The $O(N \cdot \log N)$ computational complexity of micromagnetic problems puts effective limits on the system size $N$ that can be simulated within a reasonable amount of time even on the best available hardware. On modern GPUs with hundreds of cores, a manageable system size is on the order of $N = 512^2 \sim 2.5 \cdot 10^5$ computational cells. Depending on the cell spacing and the simulated material, any spin waves may be powerful enough to propagate all the way from the point of excitation (the nano-contact) to the border of the simulation space. Therefore, it is essential to consider the boundary conditions. With periodic boundary conditions, the computational cells on one border are directly connected to the ones on the opposite side in a wrap-around fashion. This leads to spin waves that, at the same time as they exit the simulation space on one side, enters again on the opposite side. In our simulations with 1.28 $\mu$m sides, the propagating spin waves were powerful enough to circulate all the way around the simulation space and reach the nano-contact region with a still significant amplitude. This is directly observable in the generated movies of the magnetization and, in a perhaps more evidential way, as spatial interference patterns in the oscillation amplitude.

Many alternative boundary conditions easily result in spin wave reflection, and designing perfectly absorbing boundary conditions are in general impossible without advance knowledge of the incoming wave – which is the unknown object under study. The most successful absorbing boundary conditions that have been employed
in STO simulations involve a gradual increase in the Gilbert damping close to the border. We found that in our simulations of space \( N = 512^2 \), the boundary conditions employed in [96] (Paper V) resulted in a highly reduced interference pattern. These boundary conditions are specified in terms of three encapsulating frames, each with a width of 5% of the simulation space (in this case the width was 64 nm), where the Gilbert damping is successively raised from \( \alpha_{Py} = 0.0088 \) to \( \alpha = 0.05, 0.15 \) and 0.45.

Reducing the simulation space to \( N = 256^2 \) or \( 640^2 \) nm\(^2\) while retaining the percentual boundary conditions resulted in interference effects. In this case, a combination of the proximity to the borders and the reduced width of the encapsulating frames (now 32 nm) likely lead to both increased reflection and higher incoming spin wave amplitude. Fixating the width of the encapsulating frames to the previous value of 64 nm likely reduces the reflection but now places the innermost frame only 128 nm away from the center of the NC and therefore still results in interference effects. This reduced, \( 640^2 \) nm\(^2\) simulation space with narrow (32 nm) encapsulating frames did however show sufficient for simulating STOs with grainy free layer, with reduced inter-grain exchange coupling. The reason for the absence of visible interference effects in this case is the reduction of the propagated spin wave amplitude as it passes from grain to grain. There are, however notable effects from the sought-for reflections at the grain boundaries.

We use two methods for checking for interference effects induced by the boundary conditions. The first one is useful when simulating a largely homogeneous system, where the magnetization precesses in the form of smooth spin waves. The method, illustrated in Figure 5.1, is to perform point-wise analysis of the motion and look for spatial interference patterns. The analysis can be either in the form of calculating the time-wise standard deviation of one of the three magnetization components (Figure 5.1(a)) or calculating the power spectral density at the frequency of the spin wave (Figure 5.1(b)). This method is not appropriate when analyzing the magnetization precession in a heterogeneous system, where the heterogeneity itself results in patterns in the spin wave amplitude.

The second method for identifying interference induced by the boundary conditions is to compare the frequency vs current behavior between simulations with different simulation space and/or boundary conditions. We noted that the interference of the generated and reflected spin waves could shift the STO frequency in order to provide a better match between the wavelength and the propagated distance, so any changes in the frequency that we could induce by changing the boundary conditions is an indicator that spin wave interference is at play. It is important to note that this comparison needs to be performed at a number of bias currents since the possible frequency shift itself depends on the original, unperturbed frequency and its wavelength. If the tested free-running wavelength matches the propagation distance of the reflected waves, no frequency shift will be observed even though there is interference.
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Figure 5.1: Spatial maps of (a) the standard deviation of the $y$-component of the magnetization and (b) the oscillation power at the main frequency $f = 22.7$ GHz. $H = 10$ kOe, $\theta = 70^\circ$, $I_{dc} = 20$ mA. The Oersted field has been excluded. Periodic boundary conditions.

5.2.2 Homogeneous free layer

A striking difference between the simulations of a device with totally homogeneous thin films and all experimental, electrical measurements is that, when sufficiently absorbing boundary conditions are employed, no or very little nonlinearity exists in the frequency as a function of current once above the low-tunability low-current regime in the vicinity of the threshold current. This is shown in Figures 5.2(a,b) for the cases without and with the current-induced Oersted field, where the propagating mode with frequency $f_{\text{prop}}$ increases linearly as a function of the current. These simulations show that there is no inherent mechanism for the propagating spin wave mode of exhibiting the experimentally obtained nonlinear frequency versus current behavior.

The same simulations (Figure 5.2) also show the frequency of the transient, natural FMR-type oscillation $f_{\text{FMR}}$. Short-time Fourier analysis (not shown here) shows that the transient FMR-type oscillation evanesces within $\sim 5$ ns. The addition of the Oersted field in Figure 5.2(b) results in a faster decay of the FMR-type oscillation especially at higher drive currents. Due to the temporal and spatial coexistence of the two frequencies, intermodulation products appear with the most evident one being the third-order product $2f_{\text{prop}} - f_{\text{FMR}}$. Also this intermodulation product is transient, in agreement with $f_{\text{FMR}}$ being transient.

The mode structure of the main peak is shown for the mid-range current $I_{\text{DC}} = 20$ mA in the spatial maps of the power spectral density in Figures 5.3(a,b). We see in Figure 5.3(a) that without taking the Oersted field into account, the oscillation mode forms a highly cylindrically symmetric amplitude envelope, in agreement with
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Figure 5.2: Simulation of a device with homogeneous thin films: power spectral density of the $y$-component of the magnetization. $H = 10$ kOe, $\theta = 70^\circ$. (a) Without Oersted field, (b) with Oersted field. The frequencies of the steady-state propagating mode ($f_{\text{prop}}$) and the transient, natural FMR-type oscillation ($f_{\text{FMR}}$) and their third-order intermodulation product ($2f_{\text{prop}} - f_{\text{FMR}}$) are indicated in (a).

the theoretical prediction for the case of a completely out-of-plane field made by Slonczewski. By the addition of the Oersted field (Figure 5.3(b)), the downward-propagating spin waves are greatly diminished or extinct. This extinction occurs at the side of the nano-contact where the Oersted field adds constructively to the in-plane component of the applied field. Similar results have been obtained previously [97, 82, 98, 54, 99], in all verifying the impact of the Oersted field on the oscillation mode structure.

5.2.3 Spin wave reflection-induced frequency shift

Since the micromagnetic simulations presented above show very little nonlinear frequency versus current dependence, the question arises what the origin of the nonlinearity in the experimental samples is. A clue to this was actually found already when setting up the simulations of the devices studied in this thesis: before implementing the absorbing boundary conditions, the simulated current sweeps actually showed discontinuous frequency steps. It was found that in these simulations, due to the completely periodic boundary conditions and relative small size of the simulation space, spin waves exiting the simulation space on one side and re-entering on the opposite, were strong enough to survive a complete circulation and arrive back at the nano-contact a second time. This was also visible as interference patterns in the spatially plotted power spectral density at the primary oscillation frequency. Due to the spin wave dispersion relation, as the STO is driven with higher currents and thereby higher frequency, the wavelength changes. In order for the STO to reach a steady state, it appears natural that it should approach an oscillation state.
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Figure 5.3: Simulation of a device with homogeneous thin films: oscillation power of the $y$-component of the magnetization at the main peak with frequency $f$. $H = 10$ kOe, $\theta = 70^\circ$, $I_{dc} = 20$ mA. (a) Without Oersted field ($f = 20.5$ GHz), (b) with Oersted field ($f = 21.3$ GHz).

such that its self-generated propagating spin waves interfere constructively with the oscillation source underneath the nano-contact. This leads to the result that frequencies with certain wavelengths – and thereby certain frequencies – will be less probable for the STO to sustain.

Spin wave self-interference hence appeared as a plausible source for the frequency discontinuities, motivating further exploration of the phenomenon. Spin waves do not encounter periodical boundary conditions in real systems, but it is known that they can be reflected at interfaces with abrupt changes in the Gilbert damping parameter. This is the reason why absorbing boundary conditions are implemented with a gradual increase in the damping \cite{100}. We therefore added to the simulation with absorbing boundary conditions a highly damping ($\alpha = 1.0$) wall with a width equal to the nano-contact diameter (100 nm) and thickness 50 nm, at distances of 50 nm and 150 nm from the nano-contact edge. The distance has two implications on the self-interference: 1) it alters the spin wave propagation path and thereby the number of complete or fractional wavelengths and 2) the reflected spin wave will be weaker for larger distances due to the spin wave attenuation.

The current sweeps from the simulations with the damping- and exchange-type walls are shown in Figure 5.4. Although the low-current regime in the vicinity of the threshold current generally shows a more unstable behavior, the appearance of discontinuous steps in the frequency is notable in Figure 5.4(a) (damping-wall, $d_{sep} = 50$ nm) and Figure 5.4(2) (exchange-wall, $d_{sep} = 150$ nm. There is also a small discontinuity or nonlinearity visible in Figure 5.4(b) (damping-wall, $d_{sep} = 150$ nm). We hence conclude that there exists an effect of the spin wave
Figure 5.4: Simulations with (a,b) a $\alpha = 1.0$ damping wall and (c,d) a wall with no exchange coupling to the remaining free layer: power spectral density of the $y$-component of the magnetization. $H = 10$ kOe, $\theta = 70^\circ$. The separation between the NC edge and the wall is (a,c) $d_{sep} = 50$ nm and (b,d) $d_{sep} = 150$ nm.

self-interference that works to introduce discontinuities or nonlinearities in the frequency as a function of current.

5.2.4 Grain microstructure in the free layer

Having identified spin wave self-interference as a possible source of the frequency nonlinearities, we next turn our attention to identifying a realistic source of spin wave reflection. In order to reproduce the device-to-device variability, this realistic source needs to be of a random nature. When it comes to reflection phenomena, we can identify three parameters that can provide randomness in the system: the distance from the nano-contact, the angle facing the nano-contact (or, in general, the shape of the interface) and the strength of the spin wave reflection. One system that can provide this type of variation is that of the grain microstructure that is
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Figure 5.5: Top view of the surface of the Si/SiO$_x$/Pd8/Cu30/Co8/Cu8/NiFe4.5/Ta3 GMR stack. (a) Atomic force microscopy (phase contrast mode) and (b) scanning electron microscopy.

generally the result of sputtering processes [101, 102, 103, 104], where atoms add to the sample surface one by one, combining to form single-crystalline grains. In this process, the gaps between the grains will not constitute perfect interfaces and hence it can be assumed that the magnetic exchange coupling will not be perfect. A simulation study has shown that the exchange coupling is almost completely broken already when inter-atom distances are increased by 50 % [105]. This rapid fall-off is consistent with the fact that the exchange interaction originates from overlapping electron orbitals.

In-house measurements of the GMR stack used in the electrically characterized devices are shown in Figure 5.5. Both the atomic force microscope (Figure 5.5(a)) operated in phase-contrast tapping mode [106, 107] and the scanning electron microscope (Figure 5.5(b)) show the presence of metallic grains with a typical lateral size around 30 nm. We utilized a mumax$^3$ extension to create a (random) Voronoi tesselation of 30 nm grains in the free layer, and rescaled the grain-to-grain exchange coupling. This technique has been used in the works by Leliaert et al. [108, 109, 110] to simulate material effects on domain wall mobility. In these works, a grain-to-grain reduction in the exchange stiffness to 30 % of the nominal value was used for reaching agreement with experimental work on vortex domain wall pinning potentials in NiFe films [108].

Our simulation tests showed that for 30 nm sized grains, well-defined oscillation existed for inter-granular exchange couplings of 30–100 % for the case of $H = 10$ kOe, $\theta = 70^\circ$ in a 100 nm diameter nano-contact. At 20 % coupling,
the oscillating current range was reduced to below 30 mA. For higher currents or 0–10 % coupling, the obtained state was characterized by broadband noise. We however consider it to be a more physical situation if the inter-grain exchange coupling is randomly reduced, motivated by the fast fall-off with separation distance (on the order of one missing atom) and the very probable variation in this inter-grain (interface) distance. Due to the rapid fall-off, there should be a number of highly exchange-broken inter-grain interfaces (close to 0 % coupling) while at the same time too many such interfaces result in a non-oscillating device behavior. We therefore implemented a random inter-grain exchange coupling within the interval 0–100 %, following a uniform distribution.

The chosen inter-grain exchange distribution might be considered as a first-approach approximation of the actual (unknown) distribution, but nevertheless shows a frequency versus current with the nonlinearity features observed experimentally. Two devices with different randomizations are displayed in Figure 5.6(a,b). These simulated devices show both continuous and discontinuous nonlinear behavior, similar to the experimentally measured devices in Figures 4.4 and 4.5. Moreover, the nonlinearities occur at different current levels and frequencies, resulting in device-to-device variation in the frequency as a function of current.

We next calculate the mean frequency and its standard deviation at each current for nine simulated devices and compare to the same calculation performed on the nine experimentally characterized devices. The results are plotted in Figure 5.6(c). The mean frequencies agree well at currents below 20 mA, whereafter the simulated frequencies increase faster than the experimental. By further comparing the mean frequency of the grain simulations to the perfect (homogeneous) film case, it can be seen that the effect of the grain structure is to increase the frequency by 1–2 GHz for current levels above 25 mA. One possible explanation is that as the oscillation amplitude grows (by increasing the current), the impact of the reflected spin waves increases on the current-driven, active region and is hence able to shift its frequency.

Moreover, at the same current levels as the grain-induced frequency shift becomes notable, the device-to-device standard deviation (plotted separately in Figure 5.6(d)) grows from ～300 MHz to ～600 MHz, close to the standard deviation obtained for the experimental devices. The experimental devices, however, sustain a standard deviation of around 600 MHz over the entire current range, not just above 25 mA. This indicates that if the experimental standard deviation is due to inter-grain spin wave reflection, the reflection has to have higher impact already at low current. This can possibly be obtained in the model by a more aggressive reduction in the inter-grain exchange coupling, such that small-amplitude spin waves have a higher probability of being reflected close to the active region and hence return with a less diminished amplitude. Nevertheless, we can conclude that inter-grain spin wave reflection is a mechanism that can explain a device-to-device variation of the experimentally obtained magnitude.
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Figure 5.6: Simulations where the free layer consists of 30 nm grains with random, 0–100 % exchange coupling. (a,b) Power spectral density of the y-component of the magnetization, (c) mean frequency (error bars represent +/- 1 standard deviation) of simulations and experimental measurements of nine devices and simulations with perfect films and (d) the standard deviation in (c).

A spatial plot of the oscillation power for the device in Figure 5.6(a) at $I_{DC} = 30$ mA is shown in Figure 5.7(a). At this current level, the device experiences the spin wave reflection induced frequency shift, since the frequency is 26.1 GHz instead of 23.5 GHz for the homogeneous-film simulated case. There are two striking phenomena visible in the spatially resolved oscillation power: 1) the appearance of discontinuous interfaces, such as at $(x, y) = (0.25, 0.15)$ and $(0.5, 0.1) \mu m$ and 2) an oscillatory power leading to these discontinuities. An oscillatory power is characteristic of a standing wave produced as the interference between a propagated wave and its reflected counterpart. That there is a spin wave reflection is supported by the discontinuities in the oscillation power. Comparing to the exchange coupling configuration of the same device, shown in Figure 5.7(b), we see that the reflecting edges visible in Figure 5.7(a) coincides with grain boundaries with low exchange coupling.
Figure 5.7: Simulation of a device with 30 nm grains with random, 0–100 % exchange coupling. (a) Oscillation power of the $y$-component of the magnetization and (b) normalized exchange coupling in the free layer for the same device. $I_{\text{DC}} = 30$ mA, $H = 10$ kOe, $\theta = 70^\circ$. 
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coupling (below 20\%) that are close to perpendicular to the radial path to the nano-contact. The multiple scattering interfaces create a complex environment for the nano-contact STO, where each of these interfaces enforces a particular wavelength and thereby frequency. The final selected frequency will be the frequency corresponding to the wavelength that results in the strongest overall resonance.

5.2.5 Frequency stability

In the previous section, we saw that spin wave reflection against weakly exchange-coupled metallic grain boundaries results in a complex oscillation landscape, giving rise to frequency shift and device-to-device frequency variability. It is also plausible that the multiple scattering interfaces can give rise to instability in the system and hence induce frequency instability. To test this idea, we performed simulations with a duration of 1 $\mu$s (instead of 10 ns) in order to obtain a 1 MHz spectral resolution for the linewidth determination. We also included the effect of temperature in the cases with and without grains. The time required to simulate an STO with grain structure and temperature for 1 $\mu$s is just over four days using a high-performance Nvidia Tesla K80 GPU. This long computation time prevents an exhaustive investigation of the linewidth versus current, but allows for simulations of selected operating conditions. We have performed simulations at $I_{DC} = 20$ mA, where the grain-induced frequency shift and frequency variability is low, and at $I_{DC} = 30$ mA, where the impact of the grain boundaries is high.

The results are presented in Figure 5.8. At zero temperature, we note that the perfect-film simulation as well as the grainy film at both 20 and 30 mA is below the 1 MHz spectral resolution. Hence, also in the grain structures the oscillation settles at a state that is stable over the 1 $\mu$s simulation. At finite temperature, the linewidth at $I_{DC} = 20$ mA increases slowly and reaches a value of $\Delta f = 4$ MHz at room temperature for the grain structured film. Interestingly, the simulation of a perfect free layer at the same temperature reaches $\Delta f = 6$ MHz. In other words, it appears as if the grain structure acts to stabilize the oscillation and make it less sensitive to thermal fluctuations. This can possibly be an effect of the reflection induced spin wave resonance structure, but the difference is also close to the spectral resolution and in order to verify such a grain-induced stabilizing effect, simulations of even longer time will be needed.

On the contrary, for the grain structure at the higher current level of $I_{DC} = 30$ mA, the linewidth substantially increases in the presence of thermal fluctuations. We obtain $\Delta f = 38$ MHz at room temperature, which corresponds to the middle of the experimentally obtained linewidth range (Figures 4.6(d-f) and 4.7(c,d)). The linewidth is almost one order of magnitude larger than the 4 MHz obtained for the homogeneous film case at the same current. This current level, 30 mA, is in the current regime where the grain structure induces the highest frequency shift and device-to-device variation, so we can relate also this considerably higher linewidth to grain-induced effects. Specifically, in this current regime the grain structure induces
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Figure 5.8: FWHM linewidths obtained from Lorentzian fits to the power spectral density of the $y$-component of the magnetization from micromagnetic simulations of duration 1 $\mu$s. $H = 10$ kOe, $\theta = 70^\circ$. $d_{\text{NC}} = 100$ nm. The Oersted field has been included in all simulations. The linewidths at 0 K were all below the 1 MHz resolution, set by the duration of the simulation.

a substantial degree of frequency instability triggered by thermal fluctuations.

5.3 Discussion

This numerical experiment has shown that the propagating spin wave mode in NC-STOs with a homogeneous free layer by nature has a highly linear frequency versus current behavior once away from the threshold region. This means that the cause of the experimentally observed nonlinear behavior has to be investigated in terms of a model that deviates from the ideal, homogeneous-film case. We have included the experimentally characterized microstructural grain structure in the free layer, with reduced magnetic exchange coupling across the grain boundaries.

This structure provides spin wave reflection at the grain boundaries, and the reflected waves from different grains result in a number of spin wave resonators with different resonance wavelengths and thereby frequencies. As the drive current is increased, the frequency of the propagating mode increases and the wavelength decreases. Thereby, the configuration of possible resonators change. There are two primary outcomes of this process: 1) the dominating resonator changes its standing wave pattern to accommodate one extra wavelength (thereby shifting the
resonance frequency upwards) and 2) another resonator becomes dominant due to better matching between its total wave path and the wavelength. This directly provides a modelling framework for the discontinuous nonlinearities (steps) in the frequency as a function of the drive current. The experimentally measured mode-jumping in such a transition (Figure 4.10) thus represent the toggling between different spin wave reflection resonances. The continuous nonlinearities in the frequency versus current likely arise from coupling between the modes [111] of two or more spin wave resonators. This is to be more highly expected in the case of reflections from different grains (where several resonances can coexist in time due to the localization of the resonances) than from higher-order excitation against one single grain.

The origin of the nonlinear frequency versus current dependence has previously been investigated with simulations of a homogeneous free layer in [112]. In [112], as opposed to in the work presented in this thesis, the nonlinearity was observed and then identified as an effect of the Oersted field, based on the observation that each particular nonlinearity shifted towards lower current for magnetic fields directed more out of the film plane. The argument was that since the in-plane component of the applied field decreases as the field is directed more out-of-plane, a smaller Oersted field (and hence current) is required to balance the in-plane field component. This finding was also supported by the reduction of the nonlinear behavior for smaller NC diameters, in which the Oersted field is smaller. However, the nature of this field balance and the reason for it actually generating the nonlinearity was not described in [112]. Since we do not observe nonlinearity for the case of a homogeneous free layer, we investigated the boundary conditions employed in [112] and found that although the boundary condition consists of a continuously increasing Gilbert damping, the rather high slope $\alpha(r)$ (where $r$ is the distance from the center of the NC) together with the increased cell size (compared to those authors’ previous works) of $5^5$ nm$^2$ resulted in steps in the damping of 0.12 between adjacent cells. We implemented this boundary condition in a corresponding circular geometry and in the spatial analysis of our simulation we found a strong interference pattern, indicating that the implemented boundary conditions were insufficiently absorbing. We therefore advocate the possibility that the nonlinearities observed in the simulations in [112] are actually due to interference of reflected spin waves rather than an unknown mechanism of balance between the in-plane field components. The observed shift of the nonlinearities towards lower current for more out-of-plane field angles is then a consequence of the shift of the dispersion relation with field angle, and the decrease in nonlinear behavior for smaller NCs a consequence of the shorter wavelength (which is proportional to the NC diameter). The shift in frequency between the resonance of $n$ and $n + 1$ wavelengths can be expected to be smaller for larger $n$, i.e. for shorter wavelength.

In terms of frequency stability, the most striking simulation result of this thesis is the substantial increase of the linewidth for the grain structured free layer. More-
over, that this difference occurs only at finite temperature indicates that at least for that particular situation, the instability stems from more than one magnetization configuration with energy levels separated by potential barriers. Since we do not observe more than one peak for the propagating mode in this case, the situation closely resembles the one investigated in [76] where it was shown how the linewidth increases due to mode-hopping. The work presented in this chapter and Paper VI provides a physical model for the existence of the various spin wave (sub-)modes that give rise to such mode-hopping in the case when only the propagating spin wave mode can be excited.
Chapter 6

X-ray microscopy

The number of techniques available for an experimental, micromagnetic observation of the STO dynamics at GHz frequencies is fairly limited. One technique is the utilization of Brillouin light scattering (BLS) [113, 114], where a laser with an optical wavelength is used as a probe of the amplitude and frequency of the magnetization precession. The optical wavelength of available lasers limits the obtainable resolution to around 200 nm (set by the spot diameter of the focused laser beam, which is diffraction limited). A fundamental restriction is that BLS does not resolve the phase of the oscillation, which is a requirement for a measurement of the wavelength of the propagating spin wave mode.

In contrast to BLS, X-rays in the so called soft X-ray energy range have an achievable spatial resolution of only a few tens of nanometers (limited by the minimum feature size in the fabrication technology for the X-ray focusing optics) and are also sensitive to the direction of the magnetization. Furthermore, synchrotron light sources such as the Stanford Synchrotron Radiation Lightsource (SSRL) produce a pulsed X-ray beam, where the pulse length is on the order of tens of ps. In order to capture the magnetization oscillation at 10 GHz, it is necessary with a time resolution of the probe that is better than 0.5 \cdot (10 \text{ GHz})^{-1} = 0.05 \text{ ns} = 50 \text{ ps}. The time resolution of synchrotron pulses is hence compatible with the requirement for observing GHz-dynamics in STOs, making X-ray microscopy using synchrotron light sources a viable route towards time- and space-resolved imaging of the magnetization dynamics.

6.1 Experimental setup

A measurement of this type relies on many systems operating at the limit of their capability, at the same time. One system is the sample itself, which has to be wire-bonded to a printed microwave circuit board since there is not room for a probe solution inside the measurement vacuum chamber. The requirement of operating
the sample in vacuum is dictated by the specific photon energy that is necessary to probe the specific absorption edges that give rise to magnetic contrast. The quality of the vacuum is also essential, since the photon beam deposits contaminants onto the sample and reduces the photon transmission. The generation of the X-ray photons relies on the synchrotron where electrons circulate with a speed comparable to the speed of light in an ordered manner with a certain degree of stability. To achieve the required spatial resolution, the X-ray beam has to be focused using X-ray optics, and the sample needs to be moved in front of the beam with high precision to scan it and generate a pixelated image. The transmitted photon beam is so weak that the photons need to be detected one by one basis. Finally, the recorded photons need to be kept track of for averaging out noise.

Figure 6.1(a) shows a photograph of the beamline and electronic equipment used for the experiment. A complete description of the scanning transmission X-ray microscope (STXM) has been published in [115]. We will in this section give a brief introduction to the technique and provide a description of the specific measurement scheme; more elaborate than space permitted in [115] and [96] (Paper V).

6.1.1 Scanning transmission X-ray microscope

The high energy and thereby short wavelength $\lambda$ of X-ray photons allow focusing the beam to smaller spot sizes than what is possible when using optical light. In theory, the spot size diameter is limited by diffraction to the Abbe diffraction limit diameter $d$ given by

$$d = \frac{\lambda}{\text{NA}} = \frac{2\pi \hbar c}{\hbar \omega \cdot \text{NA}} \approx \frac{1.240 \cdot 10^{-6} \text{ eV} \cdot \text{m}}{\hbar \omega \cdot \text{NA}}$$

where $\hbar \omega$ is the photon energy and NA is the numerical aperture of the optical system (dimensionless and on the order of one). For soft X-rays in the regime around $\hbar \omega = 1000$ eV, the Abbe diffraction limit diameter $d$ is approximately 1 nm. However, in practice the quality of the focusing lens can be a limiting factor. At beamline 13-1 at SSRL, focusing is done with a Fresnel zone plate [116] with an outermost ring width $\Delta r$ of 30 nm, limiting the nominal resolution to $1.22 \Delta r \approx 36$ nm [115].

A photograph of the STXM is displayed in Figure 6.1(b), showing the focusing Fresnel zone plate and the order sorting aperture (OSA) used to block out the unfocused zero-th order light. The photons that are transmitted through the sample (placed at the focal point of the zone plate) are detected using an avalanche photo diode, placed at a distance behind the sample that is short enough for the converging beam to cover the detector area, hence utilizing the entire available part of the focused beam.

The number of photons, or the intensity of the transmitted beam, depends primarily on the materials that are penetrated and their thickness. If the photons
6.1. EXPERIMENTAL SETUP

Figure 6.1: (a) The end station of beamline 13-1 at SSRL with the electronics (partly custom-built) for time-resolved imaging and phase-locking of the STO to the synchrotron. (b) The STXM inside the vacuum chamber (without the magnet). The length of the assembly is \( \sim 20 \) cm. (c) Sample microwave PCB. (d) Wire-bonded STO sample (\( \sim 5 \times 5 \) mm\(^2\)).
CHAPTER 6. X-RAY MICROSCOPY

have circular polarization, it is possible to obtain a portion of the transmission that is dependent on the direction of the magnetization in one of the (chemical) elements. This is facilitated by the X-ray magnetic circular dichroism (XMCD) effect, which intensity $I_{\text{XMCD}}$ is proportional to $\cos \Theta$, where $\Theta$ is the angle between the magnetic moment and the photon angular momentum [117]. The direction of the photon angular momentum is set by the undulator in the synchrotron to either parallel or anti-parallel to the beam direction, so $I_{\text{XMCD}}$ will in our measurement depend on the size of the sample's magnetization component that is pointing out of the sample plane.

6.1.2 STXM samples and their preparation

The samples investigated in this experiment have a design that differs slightly from the KTH/University of Gothenburg samples. The STXM samples, fabricated at the Emory University in Atlanta, GA, have an extended NiFe free layer but the current is injected into it through an elliptical nano-contact consisting of a Cu spacer and a CoFe fixed layer (see Figure 1 in Paper V). One advantage of this sample geometry is that the leakage current in the top cap layers is eliminated, hence providing a more efficient generation of spin torque driving the precession in the free layer. This is particularly beneficial when operating the sample in the STXM vacuum chamber due to the absence of air that can cool the sample as it becomes resistively heated by the drive current.

Another advantage of the STXM sample geometry is the disalignment of the elliptical nano-contact with the major axis pointing 45° away from the externally applied in-plane magnetic field. This results in a shape anisotropy field for the fixed layer that provides disalignment between it and the free layer magnetization, hence increasing the amplitude of the read-out GMR microwave electrical signal. This device design is optimized for operation in in-plane magnetic fields, where well-defined oscillation in the form of the localized solitonic spin wave mode can be achieved at significantly lower field strengths (on the order of hundreds of Oe as compared to several kOe required for the propagating spin wave mode in the samples investigated in Chapters 4 and 5). The lower field strength requirement for in-plane operation allows utilizing an electromagnet instead of a several kOe strong perpendicular, permanent magnet. The electromagnet provides a second possibility (other than the STO drive current) to tune the STO frequency to one of the available frequencies derived from the synchrotron repetition rate as described in the following section (6.1.3).

Since a STXM relies on X-ray transmission through the sample, it is important that the sample is not too thick. Even in order to observe transmission on the order of just one photon per synchrotron electron bunch, a standard silicon wafer has to be avoided since it blocks the photons too efficiently. Instead, the STO devices are fabricated on top of a special layer of SiN (200 nm thickness) on top of the silicon wafer, whereafter the wafer is back-etched to provide an opening for the photons
6.1. EXPERIMENTAL SETUP

through the wafer down to the SiN membrane. The 200 nm thin SiN membrane is comparatively sensitive to mechanical stress such as that encountered when making the wire bonds from the sample GSG contact pads to the microwave PCB (Figure 6.1(c,d)). The microwave PCB has a hole located underneath the sample, in the path of the photon beam. Since the wire bonding proved to be a critical process, the sample resistance was tested both before and after the bonding.

6.1.3 Synchronization of the STO to the synchrotron

Although the SSRL produces light pulses of 50 ps length in its standard operating mode, the time between the pulses is set by the synchrotron clock frequency \( f_s = 476.2 \) MHz and is hence \((476.2 \text{ MHz})^{-1} = 2.1 \) ns, much longer than the STO oscillation period \((< 1 \text{ ns})\). This means that the magnetization trajectory cannot be measured during a single STO period. Instead, the experiment has to rely on measuring the different STO phases on different STO periods (with the order of tens of STO periods in between every light pulse). In order for such a scheme to work, the STO and the synchrotron pulse rate 476.2 MHz have to be phase locked to each other. By phase locking the STO to the \( n = 21 \) harmonic of the synchrotron pulse rate \( (21 \cdot 476.2 \) MHz \( = 10 \) GHz), one would obtain the situation that all the photon pulses arrive at the STO at exactly the same STO phase. This could in theory comprise a viable measurement scheme, provided that the phase delay between the STO and the synchrotron harmonic could be successively adjusted in order to obtain measurements at all the desired phases. In practice, however, this is not an optimal solution due to the long integration times necessary to reach a sufficient signal-to-noise ratio.

An alternative scheme is to phase lock the STO to a frequency different from one of the harmonics, such that the photon pulses will arrive at the STO on different STO phases. The requirement of averaging over many measurements of the same STO phase means that the measurement system needs to keep track of which STO phase that has been measured for every single photon bunch. This can be realized by locking the STO to a frequency \( f_{\text{lock}} = n \cdot f_s \pm f_s/m \) \((n \text{ and } m \text{ being integer numbers})\), such that the photons arrive with a time separation of

\[
T_s = n \cdot T_{\text{lock}} \pm \frac{T_{\text{lock}}}{m}
\]

where \( T_s = f_s^{-1} \) and \( T_{\text{lock}} = f_{\text{lock}}^{-1} \). Every \( m \)th pulse will arrive at an integer multiple of \( T_{\text{lock}} \), and hence be at the same STO phase. The in-between pulses will each arrive at their defined phase position. The number \( m \) defines the number of phase positions that are obtained. A fundamental constraint on \( m \) is that the number of buckets is divisible with it, so that the STO always is at the same phase after a synchrotron revolution. Since the storage ring at SSRL operates with \( 372 = 2 \cdot 2 \cdot 3 \cdot 31 \) buckets, the available values for \( m \) compatible with the frequency conversion microwave board are 2, 4, 6 and 12.
The above described quasi-stroboscopic technique is sufficient in the case where all the photon bunches carry the same intensity (or number of photons). In practice at the SSRL, however, not all buckets carry electrons and hence do not produce x-ray light. Measurement should not be performed at times when there are actually no photons since that will bias and add noise to the measurement. Moreover, the light from the different electron-filled buckets have slightly varying intensity due to their varying number of electrons. Since the goal is to observe how the intensity on the detector varies with the phase of the STO, and different sets of electron bunches probe the \( m \) phases, an under-filled bucket will result in a measured lower intensity for its corresponding STO phase. A related issue is that over time, all the buckets’ relative intensities change as electrons are lost from the synchrotron trajectory and electrons are re-added through so called top-up injection that occurs every 5 minutes. This introduces a long-timescale time-dependence in the recorded intensities so that the intensity of the phase measured at one pixel cannot be compared with the same phase measured at another pixel (at a later time).

The solution implemented to overcome the beam intensity stability issue is to perform a direct normalization of the STO-phase intensity with the intensity of that bucket without the intensity effect induced by the magnetization precession. Since the conventional beam monitoring intensity sensors do not provide bucket-wise intensities, this has to be done using the detection system itself. Using the detector system present at beamline 13-1 at the SSRL, we implemented a normalization scheme where the STO phase intensity and the bucket intensities were measured at odd and even revolutions of the synchrotron, respectively. The synchrotron cyclic repetition rate \( f_{\text{cyc}} = 1.28 \text{ MHz} \) corresponds to on orbit period \( T_{\text{cyc}} = (1.28 \text{ MHz})^{-1} = 781.25 \text{ ns} \). During this time, the bucket intensity variation is the smallest one obtainable, and considered negligible. The measurement of the normalization signal (without the effect of the coherent STO precession) is obtained through the use of a RF PIN diode that allows ON/OFF toggling of the \( f_{\text{lock}} \) signal supplied to the STO, so that during the RF OFF-state, the STO starts oscillating incoherently and quickly dephases relative to the synchrotron. During the RF OFF-state, the detector measurement at each phase position will average together the intensity from all oscillation phases and hence well represent the intensity with no STO precession.

The odd/even revolution normalization requires twice the number of counters for the ON and OFF states, so that \( 2m \) counters are required. Since the detector at SSRL beamline 13-1 only carries 16 counters, the set of selectable values for \( m \) is reduced to 2, 4 and 6. In order to measure the wavelength of the propagating spin wave mode, all that is required is essentially a phase-resolved image so that any of these values for \( m \) can be used. However, the more phases that can be measured, the greater the understanding will be of any potentially unknown spin wave mode.

The developed measurement scheme puts two requirements on the phase-locking capabilities of the STO. The first requirement is that the STO re-locks to the
injected $f_{\text{lock}}$ signal quickly compared to the synchrotron revolution time $T_{\text{cycl}} = 781.25$ ns. Since the locking-time of GMR NC-STOs has previously been measured to be on the timescale of a couple of ns, this requirement is regarded as fulfilled. The second requirement is that the locking is perfectly stable. Spectrum analyzer measurements of STOs locked to an injected RF signal typically report a finite linewidth or a spectral “tail” indicating fluctuations in the frequency, and thereby in the phase. This tail arises despite the fact that the STO frequency is shifted (“pulled”) to $f_{\text{lock}}$. The available studies hence indicate that even though the STO seems locked to $f_{\text{lock}}$ in terms of a shifted STO frequency, it can occasionally unlock and run incoherently until it re-locks. The degree of unlocking is likely dependent on the power of the $f_{\text{lock}}$ signal.

Attempts made at biasing the STO for exciting the propagating mode, with a magnetic field directed out of the film plane with a strength of 0.8 T typically resulted in STO free-running linewidths at tens of MHz or more and visible spectrum tails in the “locked” state. The STO typically locked better if it had a better defined spectral peak, such as at higher magnetic field strengths and field angles away from the plane normal. Primarily the difficulty in obtaining a strong enough perpendicular field resulted in the decision to perform a measurement of the localized mode, operating with linewidths in the order of 10 MHz already at modest magnetic field strengths $\sim 60$ mT directed in the film plane. The in-plane magnetic field at the STXM at SSRL beamline 13-1 is provided by a cooled electromagnet, providing additional freedom in biasing the STO close to a frequency available with the quasi-stroboscopic measurement scheme.

6.2 Results

6.2.1 Localized spin wave mode with $p$-like symmetry

Prior to our measurement of a GMR NC-STO operating in an in-plane magnetic field in the red-shifting, localized mode, it was expected that the oscillating magnetization region would be largely in a single phase and concentrated within a region in close proximity to just underneath the nano-contact. Besides achieving the first phase-resolved measurement of the STO dynamics with a spatial resolution of 35 nm and thereby constituting a proof-of-concept for the measurement technique, the observed oscillation mode was quite different from the expected one.

The experimental results are displayed in Figure 6.2. The first observation is that the oscillating region has its center not right below the nano-contact but at a point outside it, so that the nano-contact is situated on the border of an oscillating, disc-shaped region that is several times larger than the nano-contact. Moreover, it is clear that this oscillating region is not in a single phase throughout; in two measurement phases we can see two sub-regions, each one pointing either up from or down through the plane. One of the most easily observed and identified
Figure 6.2: Spatial map of the XMCD STXM signal for the STO phase-locked to the synchrotron, at the six measurement phases (a-f). $H = 600$ Oe, $\theta = 0^\circ$. The length of the scale bar in (a) is 200 nm. Reprinted from [96] under the Creative Commons CC-BY 4.0 license.

phases is the transition from out-of-plane to down-through plane, which occurs between $\phi = 120^\circ$ and $180^\circ$ for the lower region adjacent to and including the nano-contact. For the upper region, the transition instead occurs between $\phi = 180^\circ$ and $240^\circ$. Otherwise the pattern for the lower and upper region is identical with three subsequent out-of-plane and three down-through-plane phases. Based on these observations, the measurement results can be interpreted as the upper region being $\sim 60^\circ$ delayed compared to the lower, NC-connected region. This, in turn, is similar to the situation of a spin wave emitted at the nano-contact that propagates to its final end-point over a time corresponding to the $60^\circ$ phase shift, $(6.11$ GHz$)^{-1} \cdot 60^\circ / 360^\circ \approx 27$ ps.

The micromagnetic simulations that were performed by the Barcelona group are in good qualitative agreement with the measured dynamics, capturing the $60^\circ$ phase shift. The simulations also show that as the strength of the magnetic field is increased, the oscillation becomes more localized to the region underneath the nano-contact. This also has the consequence that the behavior is changed into
one without phase shift across the oscillation pattern. The different \( \frac{df}{dH} \) slopes of the low-field and high-field solutions (Figure 3(c) in Paper V) also show that the two different oscillation patterns represent two different wave-solutions. The more localized, low-field mode (showing the 60° spatial phase shift) is referred to as having a \( p \)-like character due to the similarity to the \( p \)-type electron orbital wave functions.

Quantitatively, there is a one order of magnitude difference in the oscillation amplitude between the XMCD measurement and the simulations; the simulated value is around 10° while the experimentally measured value is around 1°. Such a large difference in the dynamics between the experimental and the simulated system is unlikely, considering the qualitative similarity and similar frequencies. The difference cannot be due to phase fluctuations in the generated \( f_{\text{lock}} \), where the jitter was experimentally determined to be around 300 fs – the STO oscillation period is almost three orders of magnitude longer at \( (6.11 \, \text{GHz})^{-1} \approx 169 \, \text{ps} \). Instead, the two main sources are the duration of the light pulse (50 ps) and the unknown phase locking efficiency of the STO. At 6.11 GHz, 50 ps corresponds to 30 % of the oscillation period. Calculating the convolution of a sinusoidal curve with amplitude 1 and a Gaussian curve with height of 1 and a FWHM width of 30 % of the oscillation period results in an oscillation amplitude of 0.73, meaning that the time resolution accounts for 27 % signal loss. Another concern is the exact phase at which the STO is measured; an additional decrease from 0.73 to 0.63 in the measured maximum amplitude can be obtained if the measurement is taken at the worst phase instead of the optimal. Moreover, in the 6-phase measurement scheme the phase with minimum attainable signal has the strength 0 while at the worst phase the amplitude at the minimum point is 0.36. It remains unclear whether insufficient phase locking in this case can account for the remaining 53 % signal loss; this would indicate that the STO is phase locked only 16 % of the time (14 % if the measurement was performed at the optimum phase).

Although the quantitative difference between the X-ray measurement and the simulated magnetization dynamics has not yet been fully investigated and explained, the study effectively demonstrates that it is now possible to experimentally directly image magnetization dynamics at GHz frequencies in nano-scale elements, with phase (i.e. time) resolution. Phase-resolved XMCD STXM measurement is the only technique capable of imaging the oscillating magnetism in STOs and provides the possibility to directly validate, refine or falsify the micromagnetic modelling of the devices. In that sense, this experimental technique is important both for the general understanding of the various spin wave modes, but also as a tool for identifying and investigating the effects of device imperfections on the mode structure.
Part III

Conclusions and future outlook
Chapter 7

Conclusions

The work presented in this thesis has been focused on investigating mainly GMR nano-contact spin torque oscillators and, in particular, their propagating spin wave mode. This mode is of interest for microwave applications due to it having the highest frequency stability in this type of device and due to its high range and tunability in frequency. Propagating spin waves also permit the necessary information transfer for future possible spin wave-based logic circuits. The GMR nano-contact spin torque oscillators constitute a model system for investigating and understanding the properties of this mode.

Many of the conclusions presented herein rely on the effort of developing the experimental techniques used to characterize and model the investigated devices:

- Measuring mode-jumping on the 10 ns-timescale in bandwidths exceeding 2 GHz at microwave frequencies exceeding 20 GHz, for the available GMR-type samples which inherently have sub-nW electrical power output required assembling a custom microwave circuit with performance and analysis capabilities not present in commercial measurement instruments.

- Similarly, this circuit allowed time-domain measurement of the STO frequency noise even at more unstable operating points requiring bandwidths exceeding 100 MHz. Conventional phase noise measurement instruments have not been able to lock to the comparatively unstable STO frequency.

- Using scanning transmission X-ray microscopy for time- and space-resolved measurement of the magnetization dynamics required hitherto unachieved control of the fluctuations in the synchrotron X-ray radiation used to perform the measurement, in order to obtain a sufficient signal-to-noise ratio.

- Micromagnetic simulations as a tool for device modelling need extensive consideration of the implemented boundary conditions and verification that the
CHAPTER 7. CONCLUSIONS

Boundaries do not influence the dynamics. The effects caused by reflected spin waves can be very similar to experimentally measured STO peculiarities, so the source of any reflection in the simulations needs to be well-known and intended. Identifying reflection from the simulation space boundaries involves analyzing the full spatial output as well as sweeping dispersion-connected parameters such as the STO frequency by means of sweeping the drive current.

- Opposite to performing computationally intensive micromagnetic simulations, the general nonlinear auto-oscillator theory for STOs has been condensed into a comprehensive yet compact model for use in hardware description languages for the case of tunneling magnetoresistance (TMR) STOs in the nano-pillar configuration. The model allows circuit- and system-level electronic design with a reasonable degree of accuracy in describing the DC operating point, the frequency, the electrical RF power and the spectral linewidth (i.e. the level of white frequency noise) based primarily on physically measurable quantities. The generality of this model has been verified against three different device designs from different research groups.

- An algorithm has been developed for accurate generation of signals with white frequency noise in the hardware description language Verilog-A. The algorithm is specifically adapted to the lack in Verilog-A of a computation step-writable memory and its non-controllable time step, and thereby avoids discontinuity problems in the generated, stochastic signal.

The main conclusions that can be drawn from this work are:

1. The device-to-device variability of devices fabricated to this date is considerable, both quantitatively and qualitatively. This variability complicates the systematic study of the device physics. In particular, the origin of the variability makes accurate modelling of the devices virtually impossible without resorting to the approximate, general nonlinear auto-oscillator model with device-specific phenomenological parameters.

2. The variability is noticeable in the frequency as a function of the drive current, where linear intervals are joined by compact nonlinear regions. The linear regions have similar slope \( \frac{df}{dI} \) but are shifted upwards in frequency on the high-current side of each nonlinearity. The short nonlinear intervals can be either discontinuous or continuous, supporting mode-jumping between distinct frequencies or the apparent generation at a single, in-between frequency. This behavior is not predicted by the general nonlinear auto-oscillator model.

3. A potential origin of the nonlinear frequency versus current behavior and device-to-device variability has been identified and investigated with micromagnetic simulations. In the simulations of STOs with homogeneous thin
films, a linear frequency versus current relationship was obtained once above the current interval around the onset threshold. It was subsequently shown that the general behavior of more linear segments adjoined by the above mentioned nonlinearities can be recreated as an effect of reflected spin waves. Such reflection can be obtained against a region with high Gilbert damping or with reduced magnetic exchange coupling across its boundary.

4. Measurements using atomic force as well as scanning electron microscopy have shown inhomogeneity in the magnetic films in the form of random grains with a size on the order of 30 nm. Micromagnetic simulations of STOs with this type of material microstructure and a varying degree of reduction in the exchange coupling across the grain boundaries closely resembles the qualitative frequency versus current behavior and variability of the fabricated devices.

5. Time-domain measurement of the electrical STO signal has demonstrated that the level of the white frequency noise increases in the vicinity of the nonlinear operating points. Earlier work has only shown this indirectly in measurements of the spectral linewidth.

6. The same frequency noise measurements have also shown that also the low-frequency $1/f$ frequency noise increases in the vicinity of the nonlinear operating points. This $1/f$ frequency noise also increases at high drive current in case of the presence of “background” modes which are not excited at the particular magnetic field but can be excited with a slight change of the field strength.

7. Mode-jumping between different frequencies can occur in the discontinuous frequency transitions between linear intervals and also when the possible additional, higher-frequency “background” modes become excited. This indicates that there can only be one of the propagating sub-modes excited at any given time in these situations and that they have spatially overlapping oscillating regions. In light of the micromagnetic simulations, the different sub-modes can be regarded as different spin wave resonances against different grain boundaries.

8. Scanning transmission X-ray microscopy can be used to experimentally measure the spatial extent and spatial phase variation of the modes excited in nano-contact spin torque oscillators. This allows direct comparison to predictions from micromagnetic modelling and can be used to test analytical and numerical hypotheses about the spin wave mode structure and thereby the general function of the device.
Chapter 8

Future outlook

The further exploration of nano-contact spin torque oscillators and their propagating spin wave mode remains motivated from an application point of view in terms of microwave radio communication, where the ever-growing need for transmission bandwidth would benefit from a CMOS-integrable on-chip $\mu$m-sized oscillator at frequencies well exceeding 10 GHz and with fast modulation properties. Since the same STO can generate frequencies separated by several GHz only by adjusting its bias current it can be used for agile operation in frequency shared radio environments.

One research direction is the development of NC-STO devices having an insulating tunnel barrier in place of the metallic spacer in order to utilize the stronger, tunneling magnetoresistance (TMR) effect. Since an insulating barrier would shift the electron current flow from the nano-contact away from the bottom electrode and towards the top magnetic and cap layers, the device structure likely needs to be more intricate than the current type of GMR devices and involve patterned fixed and spacer layers.

A parallel problem is that of the modal behavior and the device-to-device variability. Solving this problem of nonlinear frequency versus current behavior is essential for obtaining the lowest possible frequency noise. Even if the existence of more unstable current intervals can be tolerated by excluding them from the actual device operation, those intervals (which are the nonlinear frequency versus current intervals) need to be controlled or at least reproducible. Since the work in this thesis strongly indicates that these effects are due to the non-perfection of the metallic thin films, future work should focus on the deposition techniques and annealing treatment. Ultimately, the films should be single-crystalline but a grain structure can possibly be tolerated if the grain interfaces can obtain a better degree of exchange coupling.

Another potential material quality-dependent issue for STOs is that of the crys-
talline anisotropy for many magnetic metals, including cobalt. In a film with single-
crystal metallic grains, there is always the possibility of misalignment of the crystal
axes between the grains. This would induce an inhomogeneous crystal anisotropy
field, hence resulting in spatial variations of the effective magnetic field and the
spin torque determining the oscillation frequency. Also variations in the thin film
thicknesses will result in different effective fields due to its induced variation in the
shape anisotropy. The effect of these types of spatial variations can be readily ex-
amined at the grain level using micromagnetic methods similar to those developed
in this thesis.

Although the instability-inducing nonlinear operating points can possibly be
greatly reduced by improving the material quality as just described, it remains
to be examined the ultimate limit for the frequency stability in terms of utilizing
perfect-quality and possibly other materials. Theory [64] that has been devel-
oped for homogeneous-film microwave-frequency STOs does however not provide
any clear path to reducing the linewidth much below 1 MHz (corresponding to
$L(f_{offs} = 1 \text{ MHz}) \approx -68 \text{ dBC/Hz}$). That study suggests and experiments show that
the stability is improved with in-plane components of the magnetic field, up to the
point where the localized “bullet” soliton mode is excited; here the two modes inter-
fer with each other and result in a one order of magnitude linewidth increase. Since
it is difficult to treat the extended spin wave oscillations accurately with analytical
models, micromagnetic simulations may become the prominent way of predicting
the possible device performance. A significant drawback with micromagnetic sim-
ulations aiming at investigating the frequency stability is the long simulation times
that are required for acquiring waveforms on the order of $\mu$s needed for sub-MHz
linewidth resolution. Such a simulation today takes around 100 hours for a high-
performance graphics processing unit.

Ultimately, depending on the phase noise requirements of the potential appli-
cations, the case might be that STOs will require frequency stabilization by using
phase locked loop (PLL) techniques. This path is currently being pursued. It
should, however, be investigated whether the complexity induced by such circuits
makes this method worthwhile. Although the levels of frequency noise can be re-
duced dramatically, so will likely the agility of the device be – reducing its inherent
capability of being modulated and possibly also its wide-tunability frequency range.
It might eventually turn out that the achieved performance is on par with that of a
conventional CMOS-based oscillator. Circuit- and system-level design of basically
any electronics containing STO technology will be greatly accelerated by the con-
tinued evolution of STO modelling in hardware description languages, since this
allows immediate testing of the system performance already at the design stage.
It remains an open question of how to incorporate frequency noise generation in
Verilog-A while maintaining signal continuity in the case of dynamical biasing of
the device. Dynamical biasing will be required both for implementing PLL systems
and for direct frequency modulation of the STO; yet, at this stage, the phase mem-
ory of the device is Verilog-A-inherently erased at every new bias condition. The discontinuity problem is diminished (but still existing) in the case of small phase fluctuations, where the phase noise $|\phi(t)| \ll 2\pi$. In the case of free-running STOs, however, for the foreseeable future $|\phi(t)| \gg 2\pi$.

Experimentally determining the wavelength of the spin torque excited propagating spin wave mode remains an interesting measurement case for scanning transmission X-ray microscopy. The simulations presented in this thesis shows that the oscillation trajectory takes the magnetization several tens of degrees in and out of the film plane, meaning that the XMCD signal strength should be comparable to or better than the one obtained in Paper V. There is however a complication in terms of achieving the strong magnetic out-of-plane field required for the propagating mode in STOs with the ordinary free layer materials without crystal anisotropy such as NiFe. This field strength has to be created in vacuum and with the possibility of passing through the X-ray beam along the field axis. This has been solved at beamline 13-1 at SSRL with a custom assembly of permanent magnets but the field is limited to a strength of 8 kOe and highly inhomogeneous, so that the exact field strength and angle at the STO is difficult to determine. In either case, the magnetization precession should be simulated micromagnetically and found to agree with electrical microwave measurements prior to performing the STXM experiment. The STO operation at out-of-plane fields lower than the saturation magnetization is likely a complicated case, with spatial inhomogeneity playing a larger role both for the frequency selection and the frequency stability. The efficiency of the locking of the device to the external microwave signal also needs to be detailedly examined in the presence of thermal noise and the actual time of phase-locking established. This can be performed both with numerical simulations and experimentally using a sampling oscilloscope.
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Part IV

Manuscripts