All-Electrical Spin Wave Spectroscopy

Bachelor’s Thesis
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Chapter 1

Introduction

The human brain, the most powerful computing machine for the largest part of our history, has remained unchanged for the last tens of thousands of years. As the scale and complexity of scientific problems became too vast, we began to outsource some of the information processing to computers, first purely mechanical, but soon replaced by electrical circuits. With that, computing machines became artificial, and thus improvable. A rapid series of breakthroughs followed, accompanied by progress in almost every scientific area, starting with the invention of the transistor by Bardeen, Brattain and Shockley in 1947 [1]. The transition to integrated circuits led to modern computer chips based on complimentary metal-oxide-semiconductors (CMOS), which can fit billions of transistors on a few square millimeters. However, further miniaturization of digital electronic circuits is constrained by thermodynamic effects [2], and scientists search for alternative approaches which would give us even greater information processing power.

The field of spin-electronics (spintronics) attempts to exploit the spin degree of freedom of electrons along with their charge. The field has emerged with the discovery of magnetoresistive effects, i.e. the capability of a material to change its electric resistance depending on the external magnetic field, such as the giant magnetoresistance effect (GMR). For this discovery, Albert Fert [3] and Peter Grünberg [4] were awarded the Nobel Prize in 2007. Magnetoresistive effects have already found applications in hard disc drives and magnetic random access memories. Recent research is focused on information transport via pure spin currents, i.e. spin transport without net charge flow, which are predicted to be dissipationless [5] and are, therefore, not affected by Joule heating. Collective magnetic excitations, or spin waves, provide a powerful means for such spin transport.

In order to integrate spintronic devices into a traditional CMOS environment, effective spin wave detection techniques have to be developed. The commonly used ferromagnetic resonance spectroscopy with a vector network analyzer (VNA-FMR) allows to investigate magnetization dynamics in a ferromagnetic material [6], but the technique is not spatially resolved and is not suitable for micro-patterned devices. Alternatively, optical methods such as time-resolved magneto-optic Kerr effect (TR-MOKE) [7, 8], Brillouin Light Scattering (BLS) [9] or the novel frequency-resolved magneto optic Kerr effect (FR-MOKE) [10] can locally probe the magnetization dynamics, but the optical nature of these techniques makes them hard to integrate into a CMOS environment.

In this thesis, we implement an alternative, all-electrical spin wave detection technique, as first demonstrated in Ref. [11], which deploys two antennas for spin wave excitation and...
detection. We perform measurements of propagating spin waves in a magnetic Co$_{25}$Fe$_{75}$-strip and compare the results from all-electrical spectroscopy to optical BLS measurements on the same sample. The thesis is structured as follows: Chapter 2 gives a short overview of the physics of magnetization dynamics. We discuss the spin wave excitation and detection processes via microwave antennas and explain the physics behind both measurement techniques. In chapter 3, the design and the fabrication process of the spintronic device are presented. We explain the choice of Co$_{25}$Fe$_{75}$ for the magnetic waveguide and compare it to alternatives. Finally, the results of our measurements are given in chapter 4. We compare the findings from the electrical technique and optical BLS spectroscopy to a theoretical model, based on the Kalinikos-Slavin equation. Using the results of both measurements, we estimate signal loss due to the excitation and detection process and compare it to the loss due to spin wave damping. Chapter 5 gives a summary of our experimental results and a short outlook on possible future experiments involving all-electrical spin wave spectroscopy.
Chapter 2
Theoretical Background

2.1 Magnetization Dynamics

The following section provides a brief overview of the magnetization dynamics in an external magnetic field. First, we consider a small current loop, which can symbolize either orbital motion of electrons in an atom or their spin, placed in an effective magnetic field $H_{\text{eff}}$. The effective field is a combination of the external field $H_0$ and the anisotropy field $H_{\text{aniso}}$:

$$ H_{\text{eff}} = H_0 + H_{\text{aniso}}. \quad (2.1) $$

The current produces a magnetic moment $\mu = IA\hat{n}$, where $A$ is the surface of the loop and $\hat{n}$ a unit vector normal to the surface. In an effective magnetic field, the loop experiences a torque:

$$ T = m \times \mu_0 H_{\text{eff}}. \quad (2.2) $$

The flow of charged particles in the loop also produces an angular momentum $J$, which is oriented along the normal and is proportional to the magnetic moment:

$$ m = -\gamma J. \quad (2.3) $$

The constant of proportionality $\gamma$ is the gyromagnetic ratio equal to $\gamma = \frac{g\mu_B}{\hbar}$, where $g$ is the Landé-factor and $\mu_B = \frac{e}{2m_e}\hbar$ the Bohr magneton. In the case of negative charge carriers, the angular momentum and the magnetic momentum are antiparallel. Now, since the torque is defined as the derivative of the angular momentum with respect to time, we can combine Eq. (2.2) and (2.3):

$$ \frac{dm}{dt} = -\gamma (m \times \mu_0 H_{\text{eff}}). \quad (2.4) $$

This equation is similar to that of a rapidly spinning top in a gravitational field. It describes a precession of the magnetic moment around the field axis at an angular frequency $\omega = \frac{1}{J \sin \theta} \frac{dJ}{dt} = \gamma \mu_0 H_{\text{eff}}$, where $\theta$ is the angle between the magnetic field and the angular momentum.

If we now consider the entire solid-state body, then the individual magnetic moments
can be averaged over the volume to obtain the macroscopic magnetization:

\[ M = \frac{1}{V} \sum_{m_i \in V} m_i. \]  

(2.5)

Since this equation is linear, we can simply plug it into Eq. (2.4). We end up with the Landau-Lifshitz equation [12]:

\[ \frac{dM}{dt} = -\gamma (M \times \mu_0 H_{\text{eff}}). \]  

(2.6)

The Landau-Lifshitz equation describes a precessional motion of the magnetization around the effective field axis as shown in Fig. 2.1. In the real world, the magnetization will slowly relax after some time and orient itself parallel to the magnetic field. To account for that relaxation, we here follow the convention introduced by T. Gilbert, who added an additional damping term to Eq. (2.7) pointing towards the field axis. This damping term depends on the phenomenological damping parameter \( \alpha \) [13]. The resulting Landau-Lifshitz-Gilbert equation then becomes:

\[ \frac{dM}{dt} = -\gamma (M \times \mu_0 H_{\text{eff}}) + \frac{\alpha}{M_s} \left( M \times \frac{dM}{dt} \right). \]  

(2.7)

Figure 2.1: Precessional motion of a magnetization vector in an effective magnetic field. The magnetic field creates a torque on the magnetization and excites circular motion. A phenomenological Gilbert damping term describes the gradual relaxation of the precession. Figure adapted from [14].

### 2.2 Ferromagnetic Resonance

To excite spin dynamics and to counteract the Gilbert damping, we need to apply an additional oscillating magnetic field \( h_{\text{rf}}(t) = h_{\text{rf},y} \hat{e}_y + h_{\text{rf},z} \hat{e}_z \) perpendicular to the external magnetic field \( H_0 \) pointing along the x-axis (in the coordinate system of Fig. 2.5). If the oscillating frequency of \( h_{\text{rf}} \) is equal to the resonance frequency of the magnetization, the system will absorb the energy of the oscillating field, thereby tilting the magnetization vector away from its equilibrium orientation (here assumed to point along the x-axis). It is useful to separate the magnetic field and the resulting magnetization in a time-independent and a time-dependent part:
\[ H(t) = H_0 - N M_s + h_{rf}(t) = H_{\text{eff}} \hat{e}_x + h_{rf}(t) \]  
\[ M(t) = M_s + m(t) = M_s \hat{e}_x + m(t). \]  

For simplicity, we only consider the contribution of the shape anisotropy to the total anisotropy field \( H_{\text{aniso}} \). It depends on the demagnetization tensor \( N \) and can be diagonalized under the assumption of ellipsoidal geometry. If the magnitude of the rf-field \( h_{rf} \) is small compared to \( H_0 \), and \( m(t) \) is much smaller than \( M_s \), the non-linear spin dynamics can be neglected. The resulting linear relation between the rf-field \( h_{rf}(t) \) and \( m(t) \) is described by the Polder susceptibility tensor [15]:

\[
\begin{pmatrix}
  m_y \\
  m_z
\end{pmatrix}
= \chi
\begin{pmatrix}
  h_{rf, y} \\
  h_{rf, z}
\end{pmatrix}
\]  
\[ \chi = \frac{M_s}{\det(\chi^{-1})}
\begin{pmatrix}
  A_{11} + \frac{i \omega}{\gamma \mu_0} & \frac{i \omega}{\gamma \mu_0} \\
  -\frac{i \omega}{\gamma \mu_0} & A_{22} + \frac{i \omega}{\gamma \mu_0}
\end{pmatrix}
\]  

with

\[
A_{11} = H_0 + M_s \cdot (N_z - N_x)
\]
\[
A_{22} = H_0 + M_s \cdot (N_y - N_x),
\]

where \( N_y \) and \( N_z \) are the diagonal components of the demagnetization tensor. In the case of a thin magnetic film, we can neglect the in-plane demagnetization and set the component pointing perpendicular to the film to equal one. A more detailed derivation can be found in [16].

### 2.3 Spin Wave Resonance

When magnetic moments exist in a solid-state material, we additionally have to consider the interactions between them. We will simplify the discussion by assuming that the magnetic moment is entirely due to the spin of the electrons, which can be described in a semi-classical way by an angular momentum \( S \). In the Heisenberg model, the interaction energy of electrons on a lattice is given by:

\[ E = -\frac{2 J_A}{\hbar^2} \sum_i \sum_{j \in \text{NN}} S_i \cdot S_j, \]  

where the second sum is evaluated over all nearest neighbors of the \( i \)-th electron. \( J_A \) is the exchange integral, which describes whether a parallel or antiparallel orientation of the neighboring spins is more favorable. Additionally, electrons experience a classical dipole interaction between their magnetic moments. If a single electron is disturbed from its equilibrium position, it excites precession in its neighboring electrons via exchange and dipolar interactions, thereby distributing the excitation energy over a larger number of
electrons. The case where all electrons rotate in phase is called the ferromagnetic resonance (FMR). If, however, spins precess with a constant phase difference, a spin wave is formed. An example of a one-dimensional spin wave with a wave length of four lattice constants is shown in Fig. 2.2.

\[ \begin{align*}
\phi &= 0 \\
\phi &= \frac{\pi}{2} \\
\phi &= \pi \\
\phi &= \frac{3\pi}{2} \\
\phi &= 0
\end{align*} \]

Figure 2.2: A schematic illustration of a spin wave. A single precessing magnetic moment can induce precession in its neighbors through the exchange and dipole interactions, thereby propagating the oscillation through the material. When the phase of the oscillation is slightly shifted, a spin wave is formed. Figure adapted from [17].

In general, the exchange interaction is much stronger than the dipole interaction, but its range is so short that we typically only need to consider the interaction between the nearest neighbors. If the wavelength of a spin wave is very long and spans over thousands of lattice constants, then the neighboring spins are oriented nearly parallel to each other, and the long-range dipole interaction dominates. Due to their wavelength in the micrometer range, experiments with dipole spin waves are much easier, so they will be the main focus of this thesis.

An important characteristic of dipole spin waves is their anisotropy: the behavior of spin waves strongly depends on the orientation of the wave vector with respect to the magnetization direction. Assuming a thin magnetic film, three fundamental configurations exist (Fig. 2.3) [18]. In Damon-Eshbach configuration, the magnetic field (and thus the magnetization) lies in the film plane and points perpendicular to the wave vector. The excited spin waves exist only on the surface of the film and their amplitude decreases exponentially along the normal to the surface. On the contrary, in the case of both volume modes the amplitude stays constant inside the volume. In forward-volume configuration the magnetic field is applied perpendicular to the magnetic film; in backward volume configuration the field lies in-plane but parallel to the wave vector.

Most experimental setups choose the Damon-Esbach or the backward volume configuration, because the widely used microfocused Brillouin Light Scattering (BLS) measuring technique is sensitive only to the dynamic out-of-plane component of magnetization. This component vanishes for out-of-plane magnetized films. Thus, the external magnetic field has to be applied in-plane. The travelling spin wave spectroscopy technique, discussed at length in this thesis, works in all configurations, but since we would like to use BLS for comparison, an in-plane geometry is employed. An analytical expression for the dispersion relation in an in-plane magnetized magnetic film of thickness \( d \) was derived by Kalinikos
2.4 Microwave Antennas

The high frequency magnetic field \( h_{\text{rf}} \), used to drive spin dynamics (see Eq. (2.9)), can be produced by connecting an AC current source to a microwave antenna, placed directly on the surface of the ferromagnet. If we assume that the antenna is very thin compared to its width, we can use the Karlqvist equations [21, 22] to describe the magnetic field in the cross section plane of the antenna. The external static magnetic field points along the

\[
 f = \frac{\mu_0 \gamma}{2\pi} \sqrt{H_0 + Jk^2 + H_i - H_k + M_s \left(1 - e^{-kd} \right) \times \left(1 - e^{-kd} \right) \sin^2(\phi)}.
\]

(2.12)

Here, \( H_i \) is an in-plane anisotropy field, \( H_k \) is the out-of-plane anisotropy field and \( \phi \) is the angle between the in-plane field and the propagation direction. The \( f \) vs. \( k \) dispersion obtained from Eq. (2.12) is plotted in Fig. 2.4 in the range of \( k \) which is relevant to our experiments. The group velocity in Damon-Eshbach geometry, given by the slope of the dispersion relation \( v_g = \partial \omega / \partial k \), is noticeably higher than in the backward volume configuration; hence, the propagation length of spin waves \( \lambda_{\text{prop}} = v_g \tau \) is higher for a given spin wave lifetime \( \tau \). Sufficiently long spin wave propagation length is essential for travelling spin wave spectroscopy. Therefore, all measurements in this thesis are performed in Damon-Eshbach configuration.

2.4 Microwave Antennas

Figure 2.3: Three fundamental configurations of dipole spin waves in the case of a thin magnetic film. a) Damon-Eshbach configuration: the external field lies in the film plane and is perpendicular to the wave vector. In this case, the spin waves exist only on the surface. b) Forward volume configuration: the external field is applied perpendicular to the magnetic film. The characteristics of the spin waves are independent of propagation direction. c) Backward volume configuration: the field lies in-plane and is parallel to the wave vector. In the case of both volume modes b) and c) the spin waves exist inside the volume of the film. Figure adapted from [19].

and Slavin [20]:

Here, \( H_i \) is an in-plane anisotropy field, \( H_k \) is the out-of-plane anisotropy field and \( \phi \) is the angle between the in-plane field and the propagation direction. The \( f \) vs. \( k \) dispersion obtained from Eq. (2.12) is plotted in Fig. 2.4 in the range of \( k \) which is relevant to our experiments. The group velocity in Damon-Eshbach geometry, given by the slope of the dispersion relation \( v_g = \partial \omega / \partial k \), is noticeably higher than in the backward volume configuration; hence, the propagation length of spin waves \( \lambda_{\text{prop}} = v_g \tau \) is higher for a given spin wave lifetime \( \tau \). Sufficiently long spin wave propagation length is essential for travelling spin wave spectroscopy. Therefore, all measurements in this thesis are performed in Damon-Eshbach configuration.
Figure 2.4: Dispersion relation of dipole spin waves in Damon-Eshbach geometry ($\mathbf{H}_0 \perp \mathbf{q}$) and backward volume geometry ($\mathbf{H}_0 \parallel \mathbf{q}$) at an external field $H_0 = 50 \text{ mT}/\mu_0$ [20]. The exchange interaction was neglected by setting $J = 0$. Material-specific parameters in this plot match those of the later used 20 nm-thick CoFe-multilayer: $M_s = 2.36 \text{ T}/\mu_0$, $H_k = 356 \text{ mT}/\mu_0$, $H_i = 0$, $g = 2.095$.

x-axis and the time-dependent magnetic field should lie in the y-z plane, so we orient the antenna along the x-direction as shown in Fig. 2.5. The magnetic field induced by current $I$ flowing through a thin conductor of width $w$ is then given by:

$$h_{\text{rf}, y}(y) = \frac{I}{2w} \left( \Theta \left( y + \frac{w}{2} \right) - \Theta \left( y - \frac{w}{2} \right) \right) = \frac{I}{2w} \text{rect}_w(y) \quad (2.13)$$

$$h_{\text{rf}, z}(y) = \frac{I}{2w} \ln \left( \left| y + \frac{w}{2} \right| / \left| y - \frac{w}{2} \right| \right) \quad (2.14)$$

We only consider the impact of the parallel component $h_{\text{rf}, y}$ since the perpendicular component couples less efficiently to the highly elliptical magnetization precession found in ferromagnets with $M_s \gg H_0$. The rf-field excites precession of magnetic moments in the area below the antenna. Neglecting the damping, the amplitude of the resulting wave at a distant point is proportional to the Fourier transform of the source, which in the case of a rectangular function is a sinc-function:

$$m_y(k) \propto \frac{I}{2} \text{sinc} \left( \frac{wk}{2} \right) = \frac{I \sin(wk/2)}{2 \cdot wk/2}. \quad (2.15)$$

A plot of this function is given in Fig. 2.6b. Since the amplitude of the magnetic response $m$ depends linearly on the field, which in turn depends linearly on the current, we can interpret this function as the excitation efficiency of the antenna as a function of $k$.

A downside of this configuration is that it mainly excites spin waves near the FMR at $k = 0$, whereas we want to maximize the magnitude of the wave vector to increase the
Figure 2.5: A schematic illustration of the Oersted magnetic field in the case of a thin antenna on the surface of a magnetic spin wave conductor. Current flows perpendicular to the image plane along the x-axis.

Figure 2.6: a) Magnetic field induced by a single-strip antenna, b) its excitation efficiency. This antenna mainly excites FMR. A meander-shaped antenna c) is more suitable for our purposes as the excitation efficiency d) is more selective and excites spin waves with $k \neq 0$.

propagation length. A much better result is achieved by using a meander-shaped antenna. It can be modeled as a convolution of multiple Dirac delta functions with a rectangle function. The $(-1)^n$-term accounts for alternating directions of current flow:

$$h_{hf, y}(y) = \frac{I}{2w} \cdot \sum_{n=1}^{N} (-1)^n \cdot \delta(y - nd) \otimes \text{rect}_w(y),$$  \hspace{1cm} (2.16)
where $d$ is the distance between the centers of the strips and $N$ is the number of strips. As shown in Fig. 2.6d, the Fourier transform of this function exhibits multiple sharp peaks but suppresses the excitation of FMR, which is desirable for our application. The width of the peaks depends on the ratio of the meander strips to the gaps: a perfect square wave without gaps would best approximate a sine wave and therefore produce the sharpest peaks in the k-space. Of course, this is not technically feasible since the neighboring strips have to be electrically isolated from each other, but we can make the gaps as small as possible.

A meander-shaped antenna with three strips has already been successfully tested at WMI [23]. However, an even number of strips is more favorable for travelling spin wave spectroscopy as it reduces the far-field electromagnetic signal and, hence, suppresses the cross-talk between both antennas. We thus use an antenna with four strips in this thesis.

2.5 Brillouin Light Scattering

Brillouin Light Scattering (BLS) a commonly used spin wave detection technique [9], based on an effect of the same name [24], which measures the frequency shift of photons scattered inelastically from quasiparticles, in this case the spin wave’s quanta magnons. Since both the energy and the momentum are conserved during BLS, a difference in energy of a scattered photon is attributed to the creation or annihilation of a quasiparticle. Photons scattered off magnons additionally gain a $\pi/2$ polarization rotation due to conservation of angular momentum, which allows to distinguish them from photons scattered off phonons. The small difference in frequency is measured using a tandem-Farby-Perot interferometer, which scans the scattered light at different frequencies by changing the distance between mirrors with piezo crystals. Photons with a positive shift in frequency indicate the annihilation of magnons of the same frequency.

The experimental setup involves a laser with a wavelength of $\lambda = 532$ nm as a photon source. The light is linearly polarized and focused on the sample, which is mounted on a movable stage in an external magnetic field. Scattered photons are filtered out by a polarizing beam splitter and sent into the tandem-Farby-Perot interferometer; the remaining photons are then detected by a photon counter.

2.6 Travelling Spin Wave Spectroscopy

An alternative all-electrical approach to detection of spin waves is investigated in details in this thesis. An illustration of the setup is presented in Fig. 2.7. It involves two parallel antennas on the surface of the magnetic film, one for excitation of spin waves and one for detection, which are connected between the ports of a vector network analyzer (VNA) and ground. An AC current flowing through the first antenna excites a spin wave by an induced magnetic field; the spin wave propagates to the second antenna and generates an electric response via a reverse mechanism. The VNA takes over both tasks of excitation and detection: it injects a wave into port $i$ and measures the magnitude and the phase shift of the response in port $j$, where $i, j \in 1, 2$. The output of a VNA is given in terms of a matrix with four scattering parameters, or S-parameters, where each parameter $S_{i,j}$ is
2.6 Travelling Spin Wave Spectroscopy

A schematic illustration of the measurement setup. Two antennas are placed on the surface of a magnetic film and are connected to the ports of a VNA. An external field $H_0$ is applied perpendicular to the magnetic strip in the Damon-Eshbach configuration. Spin waves propagate from the excitation antenna to the detection antenna and excite an electrical response, which is captured with the VNA. Overall, four S-parameters can be measured: $S_{12}$ and $S_{21}$ characterize the transmission from one port to the other, while $S_{11}$ and $S_{22}$ describe the reflection of the signal back to the same port.

Defined as the ratio of the incident (complex) voltage $V_{i}^{\text{in}}$ at port $i$ and the output voltage $V_{j}^{\text{out}}$ at port $j$:

$$S_{11} = \frac{V_{1}^{\text{in}}}{V_{1}^{\text{out}}}$$
$$S_{12} = \frac{V_{1}^{\text{in}}}{V_{2}^{\text{out}}}$$
$$S_{21} = \frac{V_{2}^{\text{in}}}{V_{1}^{\text{out}}}$$
$$S_{22} = \frac{V_{2}^{\text{in}}}{V_{2}^{\text{out}}}.$$  \hspace{1cm} (2.17)

Diagonal S-parameters $S_{11}$ and $S_{22}$ give the reflection of the signal at the corresponding port, while the antidiagonal components $S_{12}$ and $S_{21}$ describe the transmission of the signal from port 2 to port 1 and vice versa. Each S-parameter can also be expressed in terms of relative amplitude loss and phase shift:

$$S_{i,j} = \frac{V_{i}^{\text{in}}}{V_{j}^{\text{out}}} = \left|\frac{V_{i}^{\text{in}}}{V_{j}^{\text{out}}}\right| \cdot e^{i\Delta \phi}.$$  \hspace{1cm} (2.18)

The transmission between antennas in our setup consists of two superimposed signals: the largest contribution comes from an unwanted direct antenna-to-antenna coupling, which is field-independent and can be extracted during data processing. The spin waves produce a much smaller signal at their resonance frequency, which depends on the external magnetic field as described by the Kalinikos-Slavin equation (2.12). The reflection S-parameters can be used to evaluate the excitation efficiency of a single antenna.


Chapter 3

Sample Fabrication

3.1 Device Structure

Figure 3.1: The device consists of two layers: a CoFe-strip (orange) and a 50 nm thick aluminum layer with contact pads and two antennas (gray). Each antenna is connected to its corresponding port of the VNA on one end and to ground on the other. The antennas are 1 µm wide with a 1.4 µm gap between strips.

Having taken all theoretical requirements into consideration, we end up with the design presented in Fig. 3.1. The structure is written on a silicon $12 \times 12$ mm$^2$ substrate with a 1 µm-thick SiO$_2$ layer on the surface for electrical isolation. The magnetic waveguide, drawn in orange, consists of a series of layers (SiO$_2$)/Ta(3)/Cu(3)/Co$_{25}$Fe$_{75}$(20)/Cu(3)/Pt(3) (numbers in brackets stand for the thickness of the layers in nm), with Co$_{25}$Fe$_{75}$ being the crucial component (referred to as CoFe in the following). The details of this heterostructure and the characteristics of CoFe will be discussed in the chapter 3.3. Two meander-shaped aluminum antennas are deposited on top of the magnetic CoFe-strip and are connected to the two ports of a VNA as detailed in chapter 4.1. The CoFe-strip is surrounded by...
aluminum ground planes to reduce electromagnetic cross-talk between antennas, which would otherwise mask the signal from the spin wave. It would be even more beneficent to cover the whole magnetic strip with aluminum, but this would make optical BLS measurements impossible. We chose the length of the gap between the antennas in the same range as the propagation length of spin waves $\lambda_{\text{prop}} = (20.9 \pm 1.0) \mu m$ measured in a 30 nm-thick CoFe film [25]. The width of the meandering antenna is constrained by the resolution of optical lithography and was set to 1 $\mu m$ with a 1.4 $\mu m$ gap between lines. This results in a wavelength of 4.8 $\mu m$ (a period contains two antenna strips since the direction of the current flow alternates).

### 3.2 Lift-off Lithography Process

![Lithography Process](image)

Figure 3.2: A typical manufacturing process via optical lithography. a) The substrate is cleaned with acetone and isopropanol, b) a thin film of a photoresist is dispersed on the surface by a spin-coater, c) a laser writer writes the pattern, d) the photoresist is developed, e) a thin layer of material is sputter deposited on the surface, f) the photoresist is dissolved in aceton, leaving the desired structure.

The most challenging part of the structure are the antennas. We aim to achieve efficient excitation of spin waves with wavelengths in the low $\mu m$ range. In this wavelength regime, both dipolar and exchange interactions contribute to the spin wave dispersion resulting in high group velocities. This regime is favorable for magnonic applications, where it is desirable to maximize the number of spin wave wavefronts within one propagation length. We chose photolithography with a direct laser writer PicoMaster200 due to its high writing speed of 1.7 mm$^2$/s compared to electron beam lithography at a sufficient resolution up to 300 nm [26].

The photolithography and the lift-off process is schematically shown in Fig. 3.2. The fabrication process has to be carried out in a cleanroom. In the first step, the substrate has to be very thoroughly cleaned as any surface contaminations result in an uneven photoresist film. The silicon substrate is initially covered with a layer of protective varnish, which is removed by placing the substrate in acetone and cleaning it an an ultrasonic bath
3.3 Characterization of Co$_{25}$Fe$_{75}$

for two minutes at the highest power. After that, the sample is transferred to a second vessel with new acetone and ultrasonic cleaning is repeated at the same settings. This procedure removes the varnish from the surface but not the acetone, which can leave streaks on the substrate. This is prevented by repeating the two-step cleaning procedure with isopropanol. Then, the substrate is dried using a N$_2$-gun. If the substrate is used for the first time, an adhesion promoter TI Prime is applied to improve resist adhesion (see Appendix A for application parameters). A thin layer of a photoresist AZ MIR 701 is dispersed on the surface by a spin-coater, operating at 4000 rpm for 60 s, which, according to the manufacturer, should result in a 1 µm-thick layer [27]. After that, the substrate is baked at 90 °C for 90 s to reduce residual solvent concentration in the photoresist [28]. The quality of the resulting resist film can be evaluated with the bare eye as any minor changes in thickness produce visible interference patterns.

AZ MIR 701 is a positive resist and is sensitive to ultraviolet and near-ultraviolet light. The areas which have been exposed to light are dissolved in the developer, while the unexposed areas remain on the substrate. For the exposure, the substrate is placed on the stage of the laser writer, which then scans the surface of the substrate and writes the desired structure. An additional red laser is used to check the focus at each point and slightly correct the height of the writing stage. The evenness of the resist film is very important at this step since any change in thickness scatters the light of the red laser resulting in a failed focus capture procedure, which terminates the writing process. Finally, the substrate is developed in AZ 726 MIF developer for 60 s, rinsed in two vessels with distilled water and dried using a N$_2$-gun.

A thin film of the desired material is deposited on the substrate using the SUPERBOWL ultrahigh vacuum sputtering system. The photoresist is then removed with acetone in the so-called lift-off process, leaving material only on exposed areas.

### 3.3 Characterization of Co$_{25}$Fe$_{75}$

In order to successfully detect the spin wave at the second antenna, it has to propagate across the distance between antennas, which requires a ferromagnet with sufficiently low magnetic damping. Insulating ferrimagnets such as yttrium-iron-garnett (YIG) have very low Gilbert damping in the order of $\alpha \approx 10^{-5}$ due to absence of free electrons which could otherwise cause magnon-electron scattering [29, 30]. However, insulators cannot be used in spintronic devices which require an electric current through the magnetic material. Furthermore, YIG exhibits low saturation magnetization in the order of $M_s \approx 100 \text{ mT}/\mu_0$, which leads to low spin wave group velocity as well as a low amplitude of the spin wave’s magnetization, compared to metallic ferromagnets, and thus to a weaker signal [30, 31]. Finally, YIG is incompatible with the lift-off process used to manufacture the spin-wave waveguide as it requires epitaxial growth at elevated temperatures.

A promising alternative to insulating ferrimagnets is Co$_{25}$Fe$_{75}$ (CoFe) as it combines the advantages of high electrical conductivity with ultra-low magnetic damping. Its Gilbert parameter $\alpha = (5.0 \pm 1.8) \times 10^{-4}$ approaches the regime of insulating ferrimagnets and its high saturation magnetization of $M_s = 2.36 \text{ T}/\mu_0$ [32] produces strong magnetic signal and
high spin wave group velocity. Propagation lengths as high as $\lambda_{\text{prop}} = (21 \pm 1) \mu m$ have been measured in a 26 nm-thick CoFe film [25], which allows us to separate the antennas by tens of micrometers. The fabrication process of CoFe-structures is relatively simple compared to YIG since it can be sputtered at room temperature and patterned using optical or electron beam lithography.

Direct deposition of CoFe on SiO$_2$ leads to a significant increase in magnetic damping, which has been attributed to unwanted oxidation of CoFe [17]. The problem is solved by enclosing CoFe in a suitable seed and cap layers. For this thesis, the sequence (SiO$_2$)/Ta/Cu/Co$_{25}$Fe$_{75}$/Cu/Pt was used.
Travelling spin wave spectroscopy and BLS

The core idea of this thesis is to compare an all-electrical spin wave detection technique to results from optical spin wave spectroscopy. To this end, we perform a series of VNA and BLS measurements at similar settings using the same sample.

4.1 VNA Measurements

In order to connect the antennas to the VNA, we glue the sample to a sample holder consisting of a coplanar waveguide (CPW) with a gapped center conductor (CC). The ends of the CC are bonded to the corresponding antennas’ contact pads thereby connecting the antennas, shown in Fig. 3.1, to the end launches of the sample holder. These are in turn attached to high frequency cables leading to port 1 and port 2 of the VNA. Both ground planes of the CPW are also bonded to the ground pads of the sample. After that, we mounted the CPW with the sample between the pole pieces of an electromagnet in Damon-Eshbach geometry, i.e. orientating the external magnetic field perpendicular to the CoFe-stripe and within the film plane.

The first objective is to find approximate values for the magnetic field at which spin waves are created and to capture the relationship between the spin wave’s frequency and the external magnetic field. To this end, we perform linear frequency scans for all four S-parameters while varying the external field between $-11.6$ and $271.8$ mT. To enhance the signal-to-noise ratio, we repeat the measurement multiple times and average the results. Data processing using the derivative divide algorithm [33] is performed on all four signals to eliminate the frequency-dependent spurious background.

The results can be seen in Fig. 4.1. The transmission parameters contain multiple field-dependent resonances slightly shifted with respect to each other. These resonances are attributed to the excitation and detection of spin waves traveling between the two antennas. A resonance is also visible in the reflection parameters, especially in the less contaminated $S_{22}$-parameter. By comparing $S_{22}$ to the transmission $S_{21}$ (or $S_{12}$), we find a few broad resonances in the reflection parameters and multiple narrow resonances in the transmission parameters for any given field strength. The reason for this behavior will become evident after analyzing our BLS data (see chapter 4.2).

In order to resolve the magnetic resonances more clearly, we perform a second measurement of the $S_{21}$-parameter in continuous-wave mode (CW-mode). In this mode, the VNA frequency is fixed, which allows to increase the measurement time for each point...
and thereby decrease the noise. We select six frequencies from 9 to 21 GHz and sweep the magnetic field in the range where the resonances occurred in the previous measurements. Fig. 4.2 shows the norm of the complex $S_{21}$-parameter. All six curves exhibit a V-shaped dip with a minimum roughly in the middle of the field range; however, at frequencies 9 to 18 GHz multiple peaks to the left of the minimum are visible. A low $S_{21}$-parameter indicates low transmission of the microwave; therefore, there exists a field-dependent process which increases absorption but allows transmission at specific values of the field. This behavior can be explained by magnetic properties of the ferromagnet: when the frequency of the microwave approaches the FMR frequency of CoFe, the microwave excites precession of magnetic moments and its energy is absorbed. A spin wave is produced at each point and, since the excitation frequency is fixed, its wave vector depends only on the magnetic field according to the Kalininok-Slavin equation (2.12). Depending on the geometry of the
antenna, some wave vectors lead to constructive interference as described in section 2.4. If this is the case, a spin wave propagates to the other antenna leading to an increase of the microwave transmission.

According to the Kalinikos-Slavin equation, a larger magnetic field moves the spin wave’s dispersion relation to higher frequencies. Therefore, as we increase the magnetic field, while keeping the frequency fixed, the length of the wave vector must decrease. This explains why all the peaks lie to the left of the minimum, which corresponds to the FMR, i.e. $k = 0$.

### 4.2 BLS Measurements

In the BLS setup, only one antenna is connected to a microwave source, so we repeat every measurement with each antenna to ensure that they behave similarly. Throughout this section, we refer to each antenna by the number of the VNA port it was previously connected to. Due to geometrical constraints of the BLS setup, the CPW has to be rotated by $180^\circ$ to connect the second antenna. This is different to the VNA measurement, where the CPW was fixed during the entire experiment, and has to be taken into consideration during evaluation.

First, we measure the field dependency of the BLS intensity at a constant excitation frequency. The range of the magnetic field is chosen in order to capture the resonance of the spin wave according to Fig. 4.1.
Figure 4.3: BLS field sweep at the excitation frequency $f = 12$ GHz at a fixed position in the middle between antennas. For the measurement (a), the first antenna is used for excitation of spin waves, after that, the sample is rotated by 180° and the second antenna is connected to the microwave source for the measurement (b). The resonance of the first antenna occurs at a slightly higher field compared to the second antenna and the signal is weaker. (c) shows both signals integrated over frequency.

frequency of 12 GHz analogous to the CW-sweeps. The laser spot is focused in the middle between the antennas, i.e. at a distance of approximately 11 µm from the excitation antenna. The BLS intensity is plotted for both antennas as a function of BLS frequency and the
magnetic field in Fig. 4.3a and 4.3b. Fig. 4.3c shows both signals integrated over BLS frequency. There are two peaks in the first plot and three in the second, and the highest peaks are slightly shifted with respect to each other. As described in section 2.5, the intensity of the BLS signal corresponds to the density of the excited magnons. The shift in signals indicates that the antennas are not identical, possibly due to the imprecision of the fabrication process.

In contrast to the CW VNA-sweep at \( f = 12 \, \text{GHz} \) (see Fig. 4.2), here we observe only two large resonances; nevertheless, the position of the peaks along the field axis matches that from the CW-sweeps. The first BLS resonance spans from approximately 45 mT to 70 mT for both antennas; in the CW-sweep we observe four peaks in the same region. Moreover, another peak occurs in the BLS signal from 70 mT to 80 mT; again, we find corresponding peaks in the CW-sweep, but their intensity is much lower. These results are discussed in more details in chapter 4.3 and 4.5.

![Spatial scans at a fixed frequency \( f = 12 \, \text{GHz} \) and a fixed magnetic field, which is determined from the field sweeps (Fig. 4.3). In all four images the left antenna is connected to the microwave source. Antenna #1 is drawn in green, antenna #2 in orange. The external magnetic field is applied in the positive x-direction.](image)

In the next experiment, we measured the BLS intensity as a function of position on the magnetic strip on both sides of the excitation antenna. The magnetic field is fixed at the value corresponding to maximal BLS intensity, obtained from the field sweep, and the scan
is repeated for both peaks. This experiment allows us to calculate the propagation length of the spin wave in the CoFe-stripe and from that to estimate the efficiency of the VNA method as described in chapter 4.5.

The results of the four scans are shown in Fig. 4.4. It is evident from those images that the antennas excite multiple modes of spin waves, which result in interference patterns. The patterns are especially visible on the right side of the exciting antenna and can be caused by interference with the spin wave reflected from sides of the magnonic waveguide and the unconnected antenna. The BLS intensity from the second antenna is noticeably higher, which supports the suspicion that the antennas are not identical. The $S_{11}$-parameter in the VNA-measurement also suffers from many artifacts, possibly because the antenna was somehow damaged during fabrication or bonding.

Furthermore, the spin wave is not symmetrical: the intensity of the spin wave propagating in the negative y-direction is in all four cases higher than of the spin wave in the other direction. This effect is caused by antenna non-reciprocity as discussed in Ref. [34].

### 4.3 Kalinkos-Slavin Model

In order to use the Kalinikos-Slavin equation (Eq. (2.12)) to model the behavior of spin waves, we need the material-specific parameters such as the Landé-factor $g$ and the effective magnetization. We determined these by performing broadband FMR measurements (bbFMR) on an unpatterned reference sample sputtered at the same settings as the CoFe-stripe. The experimental setup and the theoretical background of bbFMR are described in Ref. [35]. We obtain following values: $g = 2.0957 \pm 0.0005$, $M_{\text{eff}} = (2.0039 \pm 0.0013) \, T/\mu_0$, $\alpha = 0.003591 \pm 0.000018$. The effective magnetization $M_{\text{eff}}$ is defined as $M_{\text{eff}} = M_s - M_k$. The saturation magnetization of CoFe is equal to $M_s = 2.36 \, T/\mu_0$ [25], so we obtain $M_k = 356 \, mT/\mu_0$. Using these values, we can calculate the theoretical resonance frequency as a function of magnetic field at a constant wave vector, which is defined by the geometry of the antenna. As shown in the right small panel in Fig. 4.5, our antennas most efficiently excite and detect spin waves with $k \approx 1.1 \, \mu m^{-1}$.

The resulting function for $k = 1.1 \, \mu m^{-1}$ is plotted in Fig. 4.5 (black solid line) over the previously shown $S_{21}$-measurement. We observe good agreement with the measurements; however, at high frequencies the slope of the theoretical model is slightly smaller than that of the measured resonance. Of all experimentally measured values, only the $g$-factor is included in the linear coefficient of $H_0$ and can tilt the slope; however, large deviations of the $g$-factor from 2 are unphysical and its uncertainty is very small. The deviation could be caused by the inaccuracy of the analytical model at high frequencies or the mismatch between the measured magnetic field and the actual field near the sample.

The wave vectors of the dashed lines are chosen manually in such a way that all measured resonances lie between them. The resulting range $0.5 \, \mu m^{-1} < k < 1.5 \, \mu m^{-1}$ perfectly matches the width of the highest peak in the antenna excitation efficiency curve. The multiple narrow resonances in $d_D S_{21}$ in Fig. 4.1c are due to spin wave interference, the presence of which is evident from the spacial BLS scan (Fig. 4.4). These oscillations do not occur in the reflection signal (Fig. 4.1d), which, as discussed in chapter 2.6, measures the
power loss in a single antenna. In this case, the signal interferes only with weak secondary waves reflected from the second antenna; therefore, the measured signal most closely matches the antenna excitation efficiency curve.

The FMR at \( k = 0 \) is plotted as a sanity check of the model: since higher values of the magnetic field correspond to shorter wave vectors, we shouldn’t see any resonances to the right of the red line. This is indeed the case.

We use the same model to relate the peaks in the BLS field sweeps to wave vectors. For the first antenna, the signal has local maxima at approx. \( \mu_0 H_0 = 58 \) and \( 77 \) mT, which correspond to wave vectors \( k = 0.96 \) and \( 0.11 \) \( \mu m^{-1} \). The second antenna has three visible maxima at \( \mu_0 H_0 = 54, 64 \) and \( 74 \) mT, which correspond to wave vectors \( k = 1.15, 0.69 \) and \( 0.23 \) \( \mu m^{-1} \). The highest peaks match the expected excitation efficiency, while the lower peaks are most likely artifacts of spin wave interference or additional modes of excitation. These additional peaks are not as visible in VNA transmission-measurements, because the detecting antenna also selects for wave vectors matching the excitation efficiency.

### 4.4 Symmetries

It is a consequence of the reciprocity theorem of electromagnetism, that the receiving pattern of an antenna is identical to its radiation pattern in a symmetrical system. However, surface spin waves in Damon-Eshbach geometry exhibit non-reciprocal wave propagation:
when the direction of the spin wave is reversed, the wave shifts from one surface to the other and changes its amplitude [36]. This causes the asymmetrical excitation pattern, visible in the spatial BLS scans (Fig. 4.4). We now want to discuss the non-reciprocity of the receiving pattern of an antenna and of the combined two-antenna system.

If damping is neglected, the excitation of spin waves is time-reversal invariant. Therefore, we can obtain a detecting antenna from a radiating one by inverting the time. However, this operation also flips the direction of current flow in electromagnets and thereby the external magnetic field: $H_0 \rightarrow -H_0$. Hence, the spin wave excitation pattern of an antenna is equal to its detection pattern in an inverted magnetic field. This means that if, for instance, an antenna can better excite surface spin waves propagating to its right, it can better detect spin waves approaching from its left and vice versa.

If we combine two antennas as in the VNA-setup, two possible configurations are possible: the strong radiating side of the excitation antenna is facing the strong detecting side of the second antenna or vice versa. Since the direction of the external magnetic field was not changed during the measurement, we expect to see a difference in amplitude between signals $S_{12}$ and $S_{21}$. This is indeed the case: as seen in Fig. 4.1, the intensity of the resonance is higher in $S_{21}$ than in $S_{12}$. If the external magnetic field was flipped between both measurements, we would expect both signals to be equal: $S_{21}(H_0) = S_{12}(-H_0)$. This statement is supported by experimental observations [34].

Importantly, the dispersion relation of spin waves is unaffected by inversion of the propagation direction $k \rightarrow -k$ [36], therefore, the shape of the resonance curve doesn’t change between $S_{12}$ and $S_{21}$.

### 4.5 Efficiency

Finally, we want to estimate how much signal is lost due to excitation and detection processes as opposed to the damping of spin waves in CoFe. The total loss (TL) can be extracted from the magnitude of signal associated with the spin wave in the CW-sweeps (Fig. 4.2). At the excitation frequency $f = 12$ GHz the spin wave produces a superimposed signal equal to approximately $|S_{21,sw}| \approx 5 \cdot 10^{-5}$. This value, as mentioned in chapter 2.6, is equal to the ratio of the input voltage to the output voltage. The voltage ratio is proportional to the oscillating magnetic rf-field $h_{rf}$, which in turn is proportional to the amplitude of the spin wave $m$. Therefore, the total loss of the signal can be expressed in terms of decibels on an amplitude scale:

$$TL = 20 \log_{10} (|S_{21,sw}|) \text{ dB} = 20 \log_{10} (5 \cdot 10^{-5}) \text{ dB} \approx -86 \text{ dB}. \quad (4.1)$$

Two major effects contribute to the total loss: first, the ineffective conversion of electrical energy in magnetization dynamics during the excitation and detection processes, second, the damping of spin waves in CoFe. The latter can be calculated from the BLS spacial scans by fitting an exponential model

$$I = I_0 e^{-2y/\lambda_{prop}} \quad (4.2)$$
4.5 Efficiency

to the BLS signal averaged over the width of the CoFe-strip. Here, $\lambda_{\text{prop}}$ is the distance after which the amplitude of the spin wave decays by the factor $1/e$. As the BLS signal is proportional to the intensity of the spin wave and not its amplitude, we add an additional factor of 2 in Eq. (4.2).

\[
\lambda = (10.85 \pm 0.23) \, \mu m
\]

Figure 4.6: The intensity of the BLS spatial scan signal as a function of distance to the excitation antenna #2. The intensity was averaged over the width of the CoFe-strip. The red line is a fit to an exponential model $I = I_0 e^{-2y/\lambda_{\text{prop}}}$.

From the fit, shown in Fig. 4.6, we extract a propagation length of $\lambda_{\text{prop}} = (10.85 \pm 0.23) \, \mu m$. Since the distance between the midpoints of antennas is equal to $d = 30 \, \mu m$, we can calculate the propagation loss (PL) as follows:

\[
\text{PL} = 20 \log_{10} \left( e^{-d/\lambda_{\text{prop}}} \right) \, \text{dB} \approx -24 \, \text{dB}. \tag{4.3}
\]

This corresponds to a loss in amplitude by about a factor of 0.06 and a loss in intensity by a factor of 0.0036. The loss associated with both antennas (AL) is simply the difference between TL and PL expressed in decibels:

\[
\text{AL} = \text{TL} - \text{PL} = -62 \, \text{dB}. \tag{4.4}
\]

Since the excitation pattern of one antenna is equal to the detection pattern of the other, as detailed in section 4.4, each antenna is responsible for half of the loss:

\[
\text{EL} = \text{DL} = \frac{1}{2} \text{AL} = -31 \, \text{dB}. \tag{4.5}
\]

This calculation shows that the major part of the signal is lost due to excitation efficiency and not spin wave damping. Consequentially, the distance between the antennas doesn’t have a huge impact on the strength of the signal.
Chapter 5

Summary and Outlook

In this thesis, an all-electrical spin wave detection technique was tested and compared with results from established optical spin wave spectroscopy. The results are summarized in the following.

Both techniques were tested on the same sample. Aluminum microwave antennas and a CoFe magnonic waveguide were fabricated via optical lithography and sputter deposition. The fabrication and design parameters are given in appendix A and B.

The all-electrical spectroscopy was tested via a VNA in frequency sweep mode and in continuous wave mode. The frequency sweep mode allows to capture the general shape of the resonance, which showed good agreement with theoretical predictions obtained from the Kalinikos-Slavin model. The resonances in the transmission parameters $S_{12}$ and $S_{21}$ consist of multiple curves, which are caused by spin wave interference and are not observed in the reflection parameters $S_{11}$ and $S_{22}$. The range of excited wave vectors shows good agreement with the expected excitation efficiency of meander-shaped antennas with four strips.

The continuous wave mode gives a detailed view of the magnetic resonances. A field-dependent decrease in transmission was observed in the range near the FMR along with superimposed sharp peaks caused by the spin wave. As in the previous measurement, we suppose that these peaks originate from a single peak in the excitation efficiency curve, and the subdivision is caused by interference or different excitation modes.

A series of BLS measurements was performed at similar settings for comparison, showing good agreement with the VNA results. Additional weak resonances, which were observed in BLS, are strongly suppressed in the VNA measurements due to combined selectivity of excitation and detection efficiency.

We also analyzed the non-reciprocity of spin wave propagation in our device based on fundamental symmetry arguments. The difference between different propagation directions is distinctly visible between the $S_{21}$ and $S_{12}$ signals.

Finally, we estimated and compared the losses in signal associated with antennas as opposed to spin wave damping. We conclude that the antenna loss is much higher than the propagation loss, which implies that the signal can primarily be improved by tweaking the antennas and not by reducing the distance between them. More accurate fabrication of antennas, achieved for example by using the vector mode of the laser writer (see appendix C), can have a strong impact on the quality of the signal.

In conclusion, the investigated all-electrical measurement technique has proved capable
of detecting spin waves and its results compare well with other techniques and theoretical predictions. The technique can already be applied in spintronic experimental setups, where optical access is limited or impossible, for example in low-temperature experiments. In particular, it can be used to study the Dzyaloshinskii-Moriya interaction (DMI) in patterned CoFe multilayer structures. Furthermore, electrical spectroscopy is possible for any orientation of the sample in the magnetic field and can in particular be used in out-of-plane configuration to detect forward volume spin waves. All this makes all-electrical spectroscopy an important tool for future spintronic experiments.
## Appendix A

### Fabrication Parameters

#### Substrate preparation

<table>
<thead>
<tr>
<th>Substrate</th>
<th>12 × 12 Si with a 1μm-thick SiO₂-layer</th>
</tr>
</thead>
</table>
| Cleaning           | 2 min in acetone in the ultrasonic bath at level 9  
|                    | (repeat 2 times)                      |
|                    | 1 min in isopropanol in the ultrasonic bath at level 9  
|                    | (repeat 2 times)                      |

#### Adhesion promoter

<table>
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<tr>
<th>Type</th>
<th>TI Prime</th>
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<tr>
<td>Prebake</td>
<td>10 min at 120°C</td>
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<tr>
<td>Spin coating</td>
<td>2 s at 500 rpm, then 20 s at 4000 rpm</td>
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<tr>
<td>Softbake</td>
<td>2 min at 120°C</td>
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#### Photoresist

<table>
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<th>Type</th>
<th>AZ MIR 701</th>
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<tr>
<td>Spin coating</td>
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<tr>
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<td>90 s at 90°C</td>
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<tr>
<td>Development</td>
<td>AZ 726 MIF for 60 s</td>
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<tr>
<td>Lift-off</td>
<td>2 min in acetone in the ultrasonic bath at level 1</td>
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#### Laser writer

<table>
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<tr>
<th>Spotsize</th>
<th>High Resolution</th>
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</thead>
<tbody>
<tr>
<td>Attenuation</td>
<td>High Reduction</td>
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<tr>
<td>Substrate name</td>
<td>12 × 12 Magnetiker</td>
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<tr>
<td>Exposure energy</td>
<td>90 mJ/cm²</td>
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<tr>
<td>Focus offset</td>
<td>−1 V</td>
</tr>
<tr>
<td>Red laser power</td>
<td>120 μW</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>0.515112 mm</td>
</tr>
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</table>
Threshold current (blue laser) 29.55 mA
Fiducial 10nmPt-MARCH-12-2019-V2

### Sputter deposition

**Markers:**

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<th>Material</th>
<th>Pt</th>
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<tbody>
<tr>
<td>Thickness</td>
<td>10 nm</td>
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<td>Layout</td>
<td>405\All\NG\marker</td>
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**CoFe-strips:**

<table>
<thead>
<tr>
<th>Material</th>
<th>Ta/Cu/Co$<em>{25}$Fe$</em>{75}$/Cu/Pt</th>
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</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>3 nm/3 nm/20 nm/3 nm/3 nm</td>
</tr>
<tr>
<td>Layout</td>
<td>405\All\NG\stripes_CoFe</td>
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</table>

**Antennas:**

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<tr>
<td>Thickness</td>
<td>50 nm</td>
</tr>
<tr>
<td>Layout</td>
<td>405\All\NG\Allround_thick_raster</td>
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</table>
Appendix B

Sample Parameters

<table>
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<tr>
<th>CoFe-strip</th>
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</thead>
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<tr>
<td>Layout</td>
<td>Allround_Thick_raster_Lw.gds, layer #12</td>
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<tr>
<td>Width</td>
<td>5 µm</td>
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<tr>
<td>Measured width</td>
<td>(5.6 ± 0.1) µm</td>
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</table>

<table>
<thead>
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<th>Antennas</th>
<th></th>
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<tr>
<td>Layout</td>
<td>Allround_Thick_raster_Lw.gds, layers #5 and 17</td>
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<tr>
<td>Width</td>
<td>1 µm</td>
</tr>
<tr>
<td>Gap</td>
<td>1.4 µm</td>
</tr>
<tr>
<td>Measured width</td>
<td>(1.6 ± 0.1) µm</td>
</tr>
<tr>
<td>Measured gap</td>
<td>(1.0 ± 0.1) µm</td>
</tr>
<tr>
<td>Distance between antennas</td>
<td>21.8 µm</td>
</tr>
<tr>
<td>Measured distance</td>
<td>(21.4 ± 0.1) µm</td>
</tr>
</tbody>
</table>
Appendix C

Vector Mode

The vector mode of the laser writer PicoMaster 200 was tested for the first time during the work on this thesis and was proved to be capable of writing sub-micron antennas. However, due to bugs in the software, the antennas for the test sample were written in normal raster mode. The results of the tests and the optimal settings for the PicoMaster are given in the following.

The vector mode of the PicoMaster 200 is suitable for writing small structures which require a high degree of precision. However, it is inefficient for designs where a large percentage of the substrate needs to be exposed. In our design, we want the antennas to be as thin as possible, but they should be connected to large contact pads in the mm-range. The most time-efficient way to achieve that is to first use the vector mode for antennas only and then run a second project in raster mode to write the contact pads. We performed several experiments at different settings of the laser writer to find the optimal parameters for the meander-shaped antennas; the results are summarized in Tab. C.1.

<table>
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<tr>
<th>Design</th>
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<tr>
<td>Layout</td>
<td>405\DXF\NG\Merge_Test.gbr</td>
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<tr>
<td>Distance between paths</td>
<td>100 nm (see Fig. C.1a)</td>
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<tr>
<td>Gap</td>
<td>1 µm</td>
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<tr>
<td>Measured width</td>
<td>(400 ± 50) µm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project settings</th>
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<tbody>
<tr>
<td>Max. velocity</td>
<td>25 mm/s</td>
</tr>
<tr>
<td>Max. acceleration</td>
<td>2000 mm/s²</td>
</tr>
<tr>
<td>Max. jerk</td>
<td>10 000 mm/s³</td>
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<tr>
<td>Blending</td>
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<table>
<thead>
<tr>
<th>Exposure settings</th>
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<tbody>
<tr>
<td>Exposure energy</td>
<td>90 mJ/cm²</td>
</tr>
<tr>
<td>Focus offset</td>
<td>−1 V</td>
</tr>
</tbody>
</table>

Table C.1: Optimal settings for writing antennas in vector mode.
The design that has reliably produced successful results is shown in Fig. C.1a. In the vector mode, the PicoMaster moves the laser along the path drawn in red. An antenna consists of two paths shifted with respect to each other by 100 nm. The diameter of the laser spot is equal to 300 nm, so the resulting antenna has a width of 400 nm. The result strongly depends on exposure settings: if the exposure energy is too high, the antenna strips will blend into each other, if it is too low, the photoresist will not be fully exposed, and the antennas will not be written. For our sample, values in the range of 90-80 mJ/cm² have produced the best result. The focus offset is less important than exposure energy, but values in the range from −1.5 to −0.5 V resulted in slightly better antennas. Fig. C.1b shows the result after lift-off at the settings given in Tab. C.1.

Figure C.1: a) Design of the tested antennas. The PicoMaster writes the antenna twice with a 100 nm shift between both paths. Since the spot size of the laser is equal to 300 nm, this design should produce 400 nm-wide antennas. b) The final result after lift-off.
Bibliography


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