MICROWAVE FREQUENCY 
MAGNETOACOUSTIC INTERACTIONS 
IN FERROMAGNETIC THIN FILMS

Master’s thesis 
Matthias Clemens Mühlenhoff

Supervisor: Prof. Dr. Rudolf Gross 
Advisor: Dr. Mathias Weiler

Garching – November 2, 2017
Introduction

Exploiting the electron charge is a foundation of today’s information technology. With the invention of the semiconductor transistor [1–3], computational capabilities have continued to double every two years together with a decrease in transistor size, in agreement with Moore’s law. To proceed with this development, future processors need feature sizes below 10 nm. This downscaling becomes increasingly complicated due to Joule heating and tunneling effects, and will eventually approach its physical limits [4]. Therefore much effort is put into researching alternative or complimentary technology, including efforts to exploit another fundamental property of electrons: the spin.

The electron spin was first discovered in 1922 by O. Stern and W. Gerlach [5], but only later correctly interpreted as such in 1927 [6]. Around the same time, in 1925, W. Pauli wrote about a double entendre as a quantumtheoretical property of electrons [7] and introduced the Pauli exclusion principle [8]. Prominent applications of spin properties are the Nuclear Magnetic Resonance spectroscopy (NMR) and the Giant MagnetoResistance (GMR), both of which were awarded with the Nobel Prize [9, 10]. Over the recent years, the growing fields of spin electronics (spintronics) [11], spin caloritronics [12] and spin mechanics [13–16] seek to further incorporate the spin degree of freedom as an essential building block of modern technology.

A detailed understanding and manipulation of magnetization dynamics will be essential for this purpose. In this context, Ferromagnetic Resonance (FMR), which describes the resonant precession of a magnetic moment about an effective magnetic field, provides promising opportunities [17]. The theoretical foundation of FMR was established by L. Landau and E. M. Lifshitz in 1935 [18] and in 1946 J. H. E. Griffiths presented its experimental discovery [19]. In the following years many well-known physicists like J. H. Van Vleck [20] and C. Kittel [21,22] have further developed our understanding of FMR.

For the generation of the microwave-frequency magnetic driving fields, different approaches were made, including using a resonant cavity [23] or coplanar waveguides (CPW) [24] or applying an alternating current that runs through a ferromagnetic structure [25]. The latter field generation results from the combined effect of spin-orbit coupling and exchange interaction [26,27]. Generally, current induced spin-transfer and spin-orbit torques have gained huge interest, due to their capability to efficiently manipulate nanoscale magnets, used in e.g., Magnetoresistive Random-Access Memory (MRAM) [28,29].

In this thesis, spin-torques are induced by a dynamic lattice deformation. It has been shown that such magnetoelastic effects can generate virtual magnetic driving fields [30–33]. This enables acoustic excitation of FMR without the use of resonant cavities, CPWs or the need of electrical contacts to the ferromagnetic film. However, the coupling between coherent acoustic waves (phonons) and quantized spin waves (magnons) has so far only been measured indirectly by studying the acoustic attenuation at FMR without spatial resolution. Furthermore, the Acoustically Driven FMR (ADFMR) has not yet been measured at frequencies above 4.5 GHz [34].
For this thesis, we characterize magnon-phonon coupling in ADFMR at frequencies up to 5.95 GHz. To this end we use established microwave spectroscopy as well as optical measurement techniques for a spatially resolved study of magnon-phonon interactions. Brillouin Light Scattering (BLS) enables us to distinguish between the detection of magnons and phonons, while a Frequency Resolved Magneto-Optic Kerr Effect (FRMOKE) setup provides phase resolution for measurements of traveling magnetoacoustic waves.

The contents of this thesis are as follows:
Chapter 1 introduces the fundamentals of ADFMR by first approaching FMR in general and subsequently outlining magnon-phonon coupling as a result of magnetostriction. The fundamentals of Surface Acoustic Waves (SAW) as source of coherent phonons for ADFMR are presented and their generation on piezoelectric substrates is described. In this context we explain the design and working principles of InterDigital Transducers (IDT). Thereafter, the fabrication process of IDTs with electron-beam lithography is illustrated.

Chapter 2 focuses on microwave spectroscopy measurements of delay lines consisting of two IDTs. The measurement setup that uses a Vector Network Analyzer (VNA) is presented. We then explain our data processing, based on a time gating algorithm. We vary and characterize IDT design parameters and compare our results to theoretical calculations in order to fabricate IDTs that operate at high frequencies (up to 13.78 GHz). Finally, we use these optimized IDTs in SAW delay lines with a ferromagnetic thin film to study ADFMR. The ADFMR results are compared to a theoretical model based on a Landau-Lifshitz-Gilbert approach. It is shown that at high frequencies, which go beyond previous work on ADFMR, the four-fold symmetry of ADFMR is broken and non-reciprocal sound wave propagation corresponding to an acoustic diode is found.

Chapter 3 provides the first results for optically measured ADFMR. The measurement technique presented in this chapter is Brillouin Light Scattering (BLS). After describing the fundamentals, we give a detailed explanation of the measurement setup and its working principles. BLS does not allow for phase resolved measurements, but is able to distinguish between phonon-photon and magnon-photon scattering. We characterize the spatial resolution and sensitivity of the setup, and then demonstrate the resonant generation of magnons by coherent phonons. Our results represent the first ADFMR measurements with spatial resolution. We can show magnon generation is in fact accompanied by an overall attenuation of the sound wave, while the local magnon-phonon interaction shows a complex pattern.

Chapter 4 presents measurements using our Frequency Resolved Magneto-Optic Kerr Effect setup (FRMOKE). The setup provides phase resolved measurements of SAWs and magnons, but cannot differentiate between the two, because the detection is based on light polarization rotation due to birefringence and Magneto-Optic Kerr Effect (MOKE). We show measurement results that demonstrate phase resolved imaging of traveling SAWs and provide a first magnetic field dependent measurement of magnetoacoustic FRMOKE.
1 Acoustically driven ferromagnetic resonance

Throughout this thesis, Acoustically Driven Ferromagnetic Resonance (ADFMR) [30–38] and its realization are the principle topics. In this section, we introduce the basic principles of ferromagnetic resonance and magnon-phonon coupling. A key element for ADFMR are Surface Acoustic Waves (SAWs) that drive the ferromagnetic resonance. We discuss the fundamentals of SAWs, and present their generation by InterDigital Transducers (IDTs) [39–43]. Thereafter the IDT fabrication process using electron beam lithography is illustrated.

1.1 Ferromagnetic resonance

Below a material specific temperature, ferromagnetic materials experience spontaneous ordering of magnetic moments [44] causing a macroscopic magnetization \( \mathbf{M} \) in the material. Magnetic fields, e.g., external magnetic fields \( \mathbf{H}_0 \) or anisotropy fields, control orientation. The sum of all fields is called effective magnetic field \( \mathbf{H}_{\text{eff}} \). If the net magnetization is tilted by an angle \( \theta \) to \( \mathbf{H}_{\text{eff}} \) it subsequently describes a precessing motion about \( \mathbf{H}_{\text{eff}} \) [18,21,22]. Because of damping effects the magnetization eventually relaxes along \( \mathbf{H}_{\text{eff}} \), if no recurring driving field is applied [45]. An illustration of this process is shown in Fig. 1.1a) and it can be described by the Landau-Lifshitz-Gilbert equation (LLG) [18,45]:

\[
\partial_t \mathbf{m} = -\gamma \mathbf{m} \times \mu_0 \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \partial_t \mathbf{m},
\]

where \( \mathbf{m} = \mathbf{M}/M_s \), with the saturation magnetization \( M_s \) in a macrospin model. The first term on the right side of the equation expresses the precession of the magnetic moment, where \( \gamma \) is the gyromagnetic ratio and \( \mu_0 \) is the vacuum permeability. The second term describes the damping, which is proportional to the material dependent damping factor \( \alpha \).

Fig. 1.1: Precession of magnetization \( \mathbf{M} \) about \( \mathbf{H}_{\text{eff}} \). Fig. a) illustrates precession and damping without driving field. In Fig. b) a driving field for FMR conditions is provided by the magnetic field of coherent photons. Fig. c) illustrates ADFMR, established by coherent magnon-phonon coupling. Figure is reproduced from PhD thesis by M. Weiler [32].

If a driving field \( h_1(t) \) is applied in resonance with the precession to counter the damping effect, the system is in Ferromagnetic Resonance (FMR) and stays in precession with resonant angle \( \Theta_{\text{res}} \).
and resonant angular frequency \( \omega_{\text{res}} = \gamma \mu_0 |H_{\text{eff}}| \). \( \tag{2} \)

For experimentally easily accessible external magnetic fields, the frequencies needed for FMR lie in the gigahertz regime. Conventionally, the driving field is provided by the magnetic field of coherent photons, as illustrated in Fig. 1.1b). It has been shown that also phonons can provide a driving field that fulfills conditions for FMR, thus establishing ADFMR, as illustrated in Fig. 1.1c) \[30\]. Here, the magnetic field emerges from the link between elastic strain of a magnetic material and its magnetic anisotropy field, which is described as magnetoelastic coupling \[46\] or inverse magnetostriction \[44\]. In this way, phonons can excite magnetization dynamics. Because the phonon possesses a non-zero wave vector, it can also excite non-zero wave vector magnetization dynamics. The resulting spin wave is called magnon \[46\]. Because of the coupling between phononic and magnonic degrees of freedom, the origin of the magnetoelastic driving field \( H_{\text{magel}}(t) \) is denoted as magnon-phonon in Fig. 1.1c).

In this thesis, we use magnon-phonon coupling to establish ADFMR. In section 2.4.2 a mathematical model for the coupling mechanisms based on a LLG approach \[33\] is further discussed in connection with computational simulations of our experimental results.

1.2 Fundamentals of surface acoustic waves

SAWs are elastic waves in solid matter that do not propagate through the solid’s bulk, but at its surface. This phenomenon was first described in 1885 by Lord Rayleigh \[47\]. A figure that illustrates the nature of SAWs is shown in Fig. 1.2.

![Fig. 1.2: 3D illustration of a surface acoustic Rayleigh wave with compressional wave components \( \epsilon_{xx} \) \( |k_{\text{SAW}} \) and \( \epsilon_{xz} \) \( \perp k_{\text{SAW}} \). Positive and negative strain of the shear vertical component \( \epsilon_{xz} \) is illustrated in blue and red, respectively.](image)

The SAW can be understood in terms of strain components \( \epsilon_{ij} \) with \( \{x, y, z\} \) indicating the spatial dimension of strain. The first index, here denoted as \( i \), expresses the propagation direction, whereas the second index, here denoted as \( j \), points to the direction of strain. SAWs are classified in respect to these strain components. Generally any SAW traveling in \( x \)-direction consists of a compressional wave with \( \epsilon_{xx} \), a shear vertical wave with \( \epsilon_{xz} \), and a shear horizontal wave \( \epsilon_{xy} \). In
1.3 Interdigital Transducer

A convenient way of SAW generation is the periodic electrical excitation of a piezoelectric material. Piezoelectricity is the property of a material to respond to mechanical stress with a change in electric polarization and thereby with the occurrence of a voltage \([44]\). The inverse piezoelectric effect causes mechanical strain under the influence of an externally applied voltage. Excitation is therefore possible by exciting a periodic conducting structure with a radio frequency (rf) source. This structure is called an InterDigital Transducer (IDT). Its key elements are conductive electrodes, which we call fingers, separated in periodic displacement. An illustration is shown in Fig. 1.3.

As illustrated in Fig. 1.3a), a surface charge on the IDT fingers establishes strain in the piezoelectric substrate. The periodicity \(L\) of the IDT fingers determines the periodicity of mechanical strain. Since electric charge does not only induce strain, but also the reverse process is possible, meaning that strain in the piezoelectric substrate induces charges in the IDT fingers, an IDT can
be used for both creation and detection of SAWs, as illustrated in Fig. 1.3b). The input IDT on the left side is powered by an rf source, which creates a SAW with $k_{\text{SAW}}$ parallel to the IDT finger displacement direction. In terms of (quasi-)particles, the input IDT converts photons to phonons. At the output IDT on the right side, the reverse process takes place, so that a power $P_{\text{IDT}}$ can be measured. This design consisting of two IDTs is called a SAW delay line.

1.4 Fabrication

In this thesis we will focus on the well established piezoelectric material for SAWs, Lithium Niobate – LiNbO$_3$ (LNO). As a material for our IDTs we use 70 nm thick aluminum (Al), covered by a 5 nm thick layer of titanium (Ti). The Ti is not strictly necessary, but useful for contacting purposes. Adhesive forces between Al and LNO are weak, because of which the Al can be easily scraped off the LNO when using contact probes. A thin Ti layer prevents the Al from losing contact to the LNO. For the fabrication of IDTs on LNO we use electron beam (e-beam) lithography, e-beam physical vapor deposition (EBPVD) for Al and sputtering for Ti. IDTs are manufactured in a lift-off process.

Figure 1.4 shows fabrication steps in consecutive order. First, a cleaned LNO substrate is spin coated with resist in a clean room and baked on a hot plate. Besides e-beam sensitive PMMA 33%, we also use a conductive resist (CR). The CR is necessary, since LNO is not conductive itself, which would lead to electric charging by the e-beam and thereby fabrication defects. The designed pattern is then written in the e-beam and afterwards developed. The CR is removed with water. The PMMA is removed by the developer only where it was previously exposed to the e-beam. In EBPVD and sputter chamber the Al and Ti are deposited on the sample surface. Removing the remaining resist with acetone then also removes the Al and Ti on top, leaving only the desired pattern. For the deposition of a ferromagnetic thin film the procedure is repeated. Figure 1.5a) shows an optical microscopy picture of one of our samples. As ferromagnetic material we use cobalt (Co) that is deposited by EBPVD. Further details including all lithography parameters are summarized in Appendix A.
Since we fabricate the samples ourselves, we have the freedom to adjust design parameters. In this thesis we want to create SAWs of high frequencies and optimize signals for specific frequencies

\[ f = \frac{v_{\text{SAW}}}{\lambda}, \]

where \( v_{\text{SAW}} \) is the SAW velocity and \( \lambda \) the SAW wavelength. \( \lambda \) depends on the periodicity \( L \) and the harmonic \( n \) that is being excited by the rf source with \( \lambda = L/n \). Designing IDTs with specific \( f \) is therefore a matter of choosing \( L = 2(w + g) \), where \( w \) is the IDT finger width and \( g \) the gap width in between fingers. Other parameters are expected to have an influence on the SAW signal strength. These parameters contain the number of finger pairs \( N \) (= half the number of electrodes) and the overlap \( O \) of oppositely charged fingers. For clarification, the parameters are illustrated in Fig. 1.5b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abbr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of finger pairs</td>
<td>( N )</td>
</tr>
<tr>
<td>Overlap</td>
<td>( O )</td>
</tr>
<tr>
<td>Finger width</td>
<td>( w )</td>
</tr>
<tr>
<td>Gap width</td>
<td>( g )</td>
</tr>
<tr>
<td>Metallization ratio</td>
<td>( \eta )</td>
</tr>
<tr>
<td>Periodicity</td>
<td>( L )</td>
</tr>
<tr>
<td>Wavelength</td>
<td>( \lambda )</td>
</tr>
<tr>
<td>Harmonic index</td>
<td>( n )</td>
</tr>
<tr>
<td>Frequency</td>
<td>( f )</td>
</tr>
</tbody>
</table>

Table 1.1: IDT design parameters.

Finally, the metallization ratio \( \eta \) is an important parameter for SAW creation [40]. In this thesis we define \( \eta \) as follows:

\[ \eta \equiv \frac{w}{g}. \]

An optimization of these parameters is conducted in section 2.3. Table 1.1 gives an overview of the different parameters that can be adjusted in our design.
2 Microwave spectroscopy

In this chapter we present the measurement setup, data processing and results, obtained from microwave spectroscopy of SAW delay lines. After the description of the applied methods, we will show that by optimizing IDT design parameters (introduced in chapter 1) we can fabricate SAW delay lines with operating frequencies well above 10 GHz. Additionally, our analysis reveals which IDT design is preferable for operation at specific frequencies and harmonics. Finally, this chapter presents Acoustically Driven FerroMagnetic Resonance (ADFMR) spectroscopy results in the gigahertz regime as well as corresponding simulations.

2.1 Setup

In this section, we present the measurement setup that is being used to characterize SAW delay lines. The transmission signal $S_{21}$ from IDT 1 to IDT 2 is detected as a function of frequency with a Vector Network Analyzer (VNA). The complex valued $S_{21}$ describes the ratio between radio frequency (rf) voltage at port 2 to rf voltage at port 1 [51]:

$$S_{21} = \frac{Ae^{i\phi_1}}{Be^{i\phi_2}},$$

where $A$ and $B$ are the amplitudes of transmitted and emitted waves, respectively. $\phi_1$ and $\phi_2$ are the corresponding signal phases. For better readability the magnitude of $S_{21}$ is often given on a logarithmic scale representing a power ratio:

$$|S_{21}| \text{ (dB)} = 20 \log_{10} |S_{21}|.$$

VNAs used in this thesis are either of model ROHDE & SCHWARZ ZVA 24 GHz (2 port) or AGILENT PNA-X 26.5 GHz (4 port). Figure 2.1 shows the general measurement setup used to obtain the presented data in sections 2.2 and 2.3.

![Fig. 2.1: Measurement setup for IDT characterization and optimization. Two IDTs form a SAW delay line, fabricated with electron beam lithography as described in chapter 1. The delay line is electrically connected to a VNA in order to measure the transmission signal $S_{21}$.]

Later, in section 2.4, an external magnetic field is added to the setup to investigate the interaction of the SAW with a ferromagnetic thin film deposited in the delay line.
2.2 Time gating

This section presents an outline on the data processing, applied for all measurements obtained from microwave spectroscopy within this thesis. For more details on the mathematics taking part in the processing see diploma thesis by C. Heeg: *Spin mechanics at radio frequencies* [36]. A schematic is shown in Fig. 2.2: After obtaining $S_{21}$, the data runs through an algorithm where each major step is represented in a box. Thereafter the data is saved as the processed transmission signal $\hat{S}_{21}$.

![Schematic of data processing using (inverse) Fourier transform with time gating algorithm. The data is measured by a Vector Network Analyzer and forwarded containing frequency and signal in form of real and imaginary part.](image)

Figure 2.3a) shows the magnitude $|S_{21}|$ of the signal traveling through a SAW delay line from port 1 to port 2. The acoustic signal is often masked by spurious signals. However, a majority of these spurious signals, e.g., electromagnetic crosstalk, bulk waves, and higher transits, can be excluded from the measured data by exploiting the fact that these signals will have different transit times. Hence time gating allows to separate the SAW contribution from the $S_{21}$ data. For this operation we make use of (inverse) Fourier transform and appropriate window functions, which is explained in the following.

![Fig. 2.3: a) Magnitude of VNA signal $|S_{21}|$ before time gating. Before the time gating algorithm is applied the SAW is difficult to differentiate from spurious noise, e.g., electromagnetic crosstalk, higher transits and bulk waves. b) Hamming window amplitude over frequency.](image)

The VNA measurement output consists of a complex-valued $S_{21}(f)$ signal at positive frequencies ($f > 0$). Depending on the IDT frequency, a frequency Region Of Interest (ROI) is selected. To
avoid sharp step-like cutoff of the $S_{21}(f)$ data, which would result in ringing-artifacts in the inverse Fourier transform $B^{-1}[S_{21}(f)](t)$ (due to the Gibbs phenomenon [52]), a window-function for the ROI with smooth boundaries is multiplied on top of the data. Generally, a Hamming window $w(f)$, plotted in Fig. 2.3b), is used in this thesis to suppress ringing-artifacts [53,54]:

$$S_{21}^*(f) = S_{21}(f) \cdot w(f)$$

with

$$w(f) = 0.54 - 0.46 \cos \left( \frac{2\pi f}{F - 1} \right),$$

where $f$ represents a discrete frequency index of a function in Fourier space with the total number of frequencies $F$.

At this point the frequencies of $S_{21}^*(f)$ are still all positive. To correctly carry out the Inverse Discrete Fourier Transform (IDFT) the positive frequency spectrum therefore must be extended to the negative spectrum. To do so, at first the output array is filled with zeroes from 0 GHz up to the first frequency in the ROI [36]. This step also expands the total frequency range. Mathematically a larger span in the frequency domain yields a better time resolution in the inverse Fourier transform due to interpolation. This step is well established and referred to as zero-padding [55]. Subsequently, the array is filled once more with zeroes, this time at higher frequencies than the ROI, to contain a total of $2^n$ entries with $n \in \mathbb{N}$. The reason for this lies in the algorithm for fast Fourier transform (Cooley-Tukey radix-2 decimation-in-time [56]), where the input array is assumed to have a number of entries with the power of two. Finally, the zero-padded array is mirrored to the negative spectrum. We define $S_{21}^{\text{ex}}(f)$ as the expanded array.

![Fig. 2.4: a) Real part of inverse Fourier transform of VNA signal with window $\tilde{w}$ (red area) for time gating. The applied window is of rectangular function, setting everything outside of it to zero whereas signal inside the window is not changed. b) Magnitude of VNA signal after time gating $|\hat{S}_{21}|$. Shown is the first harmonic detected in a SAW delay line. After the time gating algorithm is applied, the SAW signal is clearly visible.](image-url)
With the complete frequency spectrum including negative and positive entries the array is fully prepared for an IDFT and time gating:

$$\hat{S}_{21}^s(f) = \mathcal{F}^{-1} \left[ \mathcal{F} \left[ S_{21}^{s,ex}(f) \right] \cdot \tilde{w}(t) \right](f).$$  \hspace{1cm} (9)

The signal $\mathcal{F}^{-1} \left[ S_{21}^{s,ex}(f) \right](t)$, now depicted in the time domain, can be separated with respect to the transit time from port 1 to port 2 of the VNA. A SAW traveling with the speed of sound through the substrate arrives with a significant time delay relative to an electromagnetic crosstalk, given that the distance between output IDT and input IDT is sufficiently large ($\geq 250 \, \mu m$). Using a rectangular window $\tilde{w}(t)$, everything except for the SAW signal is set to zero as shown in Fig. 2.4a). The SAW delay line used for the measurement shown in Fig. 2.4a) has an IDT distance of 1 mm and is built on a substrate with a speed of sound of 3775 m/s. Therefore the measured SAW arriving time of approximately 0.28 $\mu$s fits near perfectly to the expected value. Transforming back to the frequency domain via a discrete Fourier transform (DFT) allows de-embedding the previously applied Hamming window:

$$\hat{S}_{21}(f) = \hat{S}_{21}^s(f)/w(f).$$  \hspace{1cm} (10)

After applying the algorithm illustrated above, the magnitude $|\hat{S}_{21}|$ of the time gated signal shows significantly less background as seen by comparing Fig. 2.4a) and Fig. 2.4b). Figure 2.5 displays an extended frequency range. When using the time gating algorithm not only the fundamental IDT frequency is well visible but also higher harmonics $n$, i.e., signals up to $n = 9$, are clearly separated from spurious signals.

**Fig. 2.5:** VNA spectrum before (red) and after (black) time gating.

### 2.3 IDT characterization and optimization

In order to investigate the physics of magnon-phonon interactions through ADFMR, an IDT design that creates a high output of acoustic waves with frequencies in the gigahertz regime is required. High frequency SAWs can either stem from an IDT with small finger periodicity or from higher harmonics of an IDT with wider spacing. To characterize the IDT designs, delay lines of two identical IDTs were connected to the two ports of a VNA, as illustrated in Fig. 2.1. All data provided in this section has been processed with the time gating algorithm described in section 2.2.
2.3.1 LiNbO$_3$ substrate and SAW alignment with crystalline axes

In addition to systematically varying the design of the IDT fingers, illustrated in Fig. 1.5, we also study the impact of different substrates and of the SAW delay line alignment with the substrate crystalline axes. This thesis focuses on the two commonly used crystalline structures of LiNbO$_3$ (LNO) substrates: the YZ- and the 128° rotated Y-Cut. Additionally, the YZ-Cut allows multiple orientations of SAW traveling direction in respect to the crystalline z-direction of the substrate [40].

![Graph showing maximum magnitude $|\hat{S}_{21}|$ of IDT signals in a SAW delay line with number of finger pairs $N = 20$. Various frequencies of multiple higher harmonics are detected. a) and b) show the results for a SAW on a 128° rotated Y-Cut with the full spectrum shown for finger periodicity $L = 4 \mu m$ in a) and extracted peak heights including other values for $L$ in b). Extracted data for YZ-Cut LNO substrate is shown in c) with 0° orientation to the z-direction and d) with a 90° orientation. The scale of the signal is in decibel thus maximum magnitude decays exponentially with frequency. The 128° rotated Y-Cut and the 0° oriented YZ-Cut sample show very similar behavior with a suppressed 3rd harmonic but generally higher signals than the 90° oriented YZ-Cut sample.](image)

Figure 2.6 shows the results for SAW delay line measurements comparing those crystalline structures and orientations for various periodicities.

Figure 2.6a) shows $|\hat{S}_{21}|$ (dB) data obtained for $L = 4.0 \mu m$ on 128° LNO. $n = 1, 3, 5, 9$ harmonics are visible as peaks and marked by symbols. Figure 2.6b) shows extracted peak heights vs. frequency for different values of $L$. As visible from Fig. 2.6b), $|\hat{S}_{21}|$ decays exponentially with frequency. For a given frequency, similar $|\hat{S}_{21}|$ are obtained for either using higher harmonics.
with larger $L$ or using lower harmonics with smaller $L$. The frequency dependent signal loss is attributed to interactions with thermally excited elastic waves in the substrate and energy lost to air adjacent to the surface (air loading) [57–59] as well as impedance mismatch [40].

Figures 2.6c) and d) show extracted peak heights for the YZ-Cut LNO with a $0^\circ$ and $90^\circ$ orientation respectively. The YZ-Cut substrate with a $0^\circ$ orientation and the $128^\circ$ rotated Y-Cut show a very similar behavior regarding signal strength to frequency relation. In both substrates the third harmonic is suppressed, whereas this is not the case for the $90^\circ$ YZ-Cut. The $90^\circ$ YZ-Cut, however, generally yields smaller signal strengths, which agrees with reference [40]. In all three cases the same periodicity does not result in the same frequency. This is due to different speeds of sound $v_{\text{SAW}}$ [40]:

$$f_n = \frac{v_{\text{SAW}}}{\lambda} = \frac{v_{\text{SAW}}}{L/n},$$

where

$$v_{\text{SAW}}^{0^\circ} = 3488 \text{ m/s}, \quad v_{\text{SAW}}^{90^\circ} = 3775 \text{ m/s}, \quad v_{\text{SAW}}^{128^\circ} = 3996 \text{ m/s}.$$

The measured frequencies in Fig. 2.6 fit expected values from the IDT designs very well.

2.3.2 Metallization ratio $\eta$

The suppression of some harmonics can be related to the metallization ratio $\eta$ of the IDT design. In Fig. 2.7 signal strength over frequency is summarized comparing various metallization ratios on a $0^\circ$ oriented YZ-Cut LNO substrate. Periodicity $L$ is kept constant by reducing the finger width $w$ while simultaneously increasing the gap between fingers by $g = (L/2) - w$.

![Figure 2.7: Signal magnitudes $|\hat{S}_{21}|$ as a function of harmonic number for samples with various metallization ratios $\eta$ are shown. For $\eta = 1$ every second odd harmonic is suppressed. For smaller $\eta$ more complicated patterns appear.](image)

We conclude from the graph that for a metallization ratio of $\eta = 1$ the signal strengths for higher harmonics show an alternating pattern with every second odd harmonic being suppressed. The
suppression strength decreases with higher frequencies. However, the 1st and 5th harmonic have the highest maximum magnitude for $\eta = 1$ compared to every other metallization ratio. For the other metallization ratios more complicated patterns emerge [40].

The same behavior was found for $f_1 = 0.2$ GHz IDT designs, as shown in Fig. 2.8a), with an alternating pattern for $\eta = 1$ ($w = g = 4.36 \, \mu m$) and Fig. 2.8b) with a more complicated pattern for $\eta = 0.13$ ($w = 1.0 \, \mu m$, $g = 7.72 \, \mu m$). The IDTs are fabricated with an overlap $O = 100 \, \mu m$ and number of finger pairs $N = 5$ on $0^\circ$ oriented YZ-Cut LNO.

![Fig. 2.8: Spectrum of a SAW delay line with an IDT of fundamental frequency $f = 200$ MHz and metallization ratio a) $\eta = 1$ b) $\eta = 0.13$. For a) every second odd harmonic is suppressed. The suppression strength decreases with higher harmonics. In b) the pattern of harmonic suppression no longer shows an alternating form.](image)

![Fig. 2.9: Simulation for the influence of metallization ratio on signal strength vs. harmonic. The transconductance transfer function $G_{21}$ is taken from S. Datta [40]. Figure a) shows $|G_{21}|$ from Eq. (12) in dB for $\eta = 0.67$ in comparison to the experimental result $|\hat{S}_{21}|$ (dB), normalized to $n = 1$ respectively. Figure b) shows simulation results for $|G_{21}|$ normalized to $n = 1$ for small metallization ratios $\eta = 0.005$ and $\eta = 0.01$.](image)
A theoretical description of the transconductance transfer function $G_{21}(n)$ between IDT 1 and 2 is given in S. Datta’s *Surface Acoustic Wave Devices* [40]. The transfer function for 2 identical IDTs is given by

$$G_{21}(n) = 2Y \mu^2(n, \eta) e^{-i\varphi},$$  \hspace{1cm} (12)

where $\varphi$ is the phase and the factor $Y$ is proportional to $O/\lambda$. The response function $\mu(n, \eta)$ is given by

$$\mu(n, \eta) = \mu(f_1, \eta) \sin^2(\pi n/2) P_{n/2}^2 \cos \pi \eta,$$  \hspace{1cm} (13)

where $P_{n/2}$ is a Legendre polynomial. Exemplary, Fig. 2.9a) shows $|G_{21}|$ in dB compared to $|S_{21}|$ (dB) of the previous shown measurement (Fig. 2.7) with $\eta = 0.67$, normalized to the first harmonic respectively, here defined as $|G_{21}^\text{norm}|$ and, accordingly, $|S_{21}^\text{norm}|$. Equation (12) can reproduce the measured $|G_{21}^\text{norm}|$ very well, therefore even complicated patterns can be understood with $G_{21}(n)$. In theory, very small metallization ratios ($\eta \leq 0.01$) work particularly well as shown in Fig. 2.9b). However, small $\eta$ can only be achieved by fabricating narrow fingers, which might be challenging if the IDT periodicity is kept too small.

![Fig. 2.10: IDT impedance $Z$ as a function of metallization ratio $\eta$ for $f = 1$ GHz, $L = 600$ μm, and various $N$. The relative permittivity of LNO is $\varepsilon = 29$ [60].](image)

Furthermore, the metallization ratio has a strong influence on the impedance of an IDT [42,43]. In case of an impedance mismatch between microwave cables (50 $\Omega$) and IDT, microwave signals get reflected, resulting in an insertion loss. It is therefore favorable to find a suitable metallization ratio and be aware of other design factors that impact impedance matching. Neglecting the ohmic and inductive resistance of an IDT, the magnitude of impedance $Z$ can be calculated by

$$Z = \frac{2\pi}{fC},$$  \hspace{1cm} (14)

where $C$ is the capacitance of the IDT. An expression for $C$ is given by Igreja et al. [42]:

$$C = (N^*-3) \frac{C_I}{2} + 2 \frac{C_I C_E}{C_I + C_E},$$  \hspace{1cm} for $N^* > 3,$  \hspace{1cm} (15)

where $N^* = 2N$ is the number of electrodes of the IDT. $C_I$ and $C_E$ are functions of $\eta$ and propor-
tional to the length of IDT electrodes $\tilde{L}$ and thus $Z \propto 1/\tilde{L}$. For the full expressions of $C_I$ and $C_E$ see Igreja et al. [42]. In Fig. 2.10, $Z$ is plotted as a function of $\eta$ for different $N$ at $f = 1$ GHz. For $\eta = 0$ the impedance $Z$ has an asymptote with $Z \to \infty$. For higher $\eta$ the impedance decreases and flattens in respect to $\eta$. Also higher $N$ decrease $Z$ significantly. Therefore, $\eta$, $N$, and $\tilde{L}$ can be used for impedance matching. For $f = 1$ GHz, $N = 20$, $\tilde{L} = 600 \, \mu m$, and $\eta = 1$ the impedance of an IDT is approximately $Z_{\text{IDT}} \approx 50.6 \, \Omega$. With the general form of the voltage reflection coefficient,

$$\Gamma_{12} = \frac{|Z_2 - Z_1|}{Z_2 + Z_1}, \quad (16)$$

$\Gamma = 0.6\%$ for $Z_1 = 50 \, \Omega$ and $Z_2 = Z_{\text{IDT}}$. Thus, the voltage transmission is $T = 1 - \Gamma = 99.4\%$. Since power is proportional to the square of the voltage, insertion loss is given by

$$IL_Z (\text{dB}) = 20 \log_{10}[T] \approx -0.05 \, \text{dB}. \quad (17)$$

In Figs. 2.6a) and b), measurements of a SAW delay with such IDT design show an insertion loss of 9.6 dB. This is because of capacity independent insertion loss, such as insertion loss due to the bidirectional behavior of both input and output IDT (3 dB loss each). Additionally, air loading and thermal effects contribute to losses along the delay line as well as insertion losses of microwave cables and microwave probes. It is to be noted that an ideal impedance matching by adjustment of $\eta$, $N$, and $\tilde{L}$, only works for one previously chosen frequency as stated in Eq. (14). Thus, applying the calculation above for the same parameters at frequency $f = 10$ GHz results in an impedance related insertion loss of 14.7 dB.

2.3.3 Number of finger pairs $N$

Our results for varying the number of IDT finger pairs $N$ are presented in Fig. 2.11. We experimentally investigate the influence of $N$ on signal strength and Full Width Half Maximum (FWHM). In Fig. 2.11a), showing signal magnitude and FWHM for the fundamental frequency $f_1$, the increase in signal magnitude and decrease in FWHM with higher $N$ is evident. In Fig. 2.11b) $|\mathbf{S}_{21}|$ (dB) is displayed for $N = 5$ and $N = 20$ around the fundamental frequency and the 7th harmonic (7.9 GHz). The maximum magnitude at the 7th harmonic is now higher for $N = 5$ than it is for $N = 20$. In Fig. 2.11c) signal strengths are presented for various numbers of finger pairs for 4 different harmonics set in relation to $N = 5$ with $\delta |\mathbf{S}_{21}^N|$ (dB) = $20 \log_{10}[|\mathbf{S}_{21}^N| / |\mathbf{S}_{21}^5|]$. At low harmonics signal strengths increase with increasing $N$. From the 3rd to the 5th harmonic the scaling of peak height with $N$ inverts, resulting in higher maximum magnitudes for less finger pairs rather than more. For the FWHM, shown in Fig. 2.11d), the relation does not change significantly over harmonic index. For the last two plots a Gaussian fit was used on the linear scale to determine peak height and FWHM at the 7th harmonic where sidelobes are not that prominent anymore but noise level is increased. Up to the 5th harmonic the value of FWHM for each $N$ stays approximately at a constant level. Only at the 7th harmonic the FWHM shows a significant increase. However, we attribute this last behavior to the poor signal-to-noise ratio.
In an earlier work on IDT optimization at the Walther-Meißner-Institute using optical lithography [35] it is stated that IDT designs with higher numbers of finger pairs \( N \) yield greater maximum magnitudes for the transmission of the fundamental frequency signal. At the same time the FWHM is reduced. In this thesis we can confirm these relations also for IDTs fabricated with electron beam lithography. However, the investigation of higher harmonics shows that the FWHM stays nearly constant with harmonic index. Furthermore, IDTs with smaller \( N \) perform better in higher harmonics in regard to signal strength.

The constant FWHM for \( f_1 = 1.13 \text{ GHz} \), \( f_3 = 3.39 \text{ GHz} \), and \( f_5 = 5.65 \text{ GHz} \) means that the quality factor \( Q \) increases for higher harmonics [61]:

\[
Q_n = \frac{f_n}{\text{FWHM}}.
\]

Fig. 2.11: Influence of number of IDT finger pairs \( N \) on signal magnitude and FWHM. Figure a) shows maximum magnitude and FWHM of the first harmonic for various \( N \). Maximum magnitude increases with an increasing number of finger pairs while FWHM decreases. Figure b) shows the spectrum for the 1\(^{st} \) and 7\(^{th} \) harmonic at 1.2 GHz and 7.9 GHz respectively. The red lines indicate Gaussian fits necessary for evaluation of the 7\(^{th} \) harmonic. Figures c) and d) show maximum magnitude in respect to \( |S_n| \) and FWHM for all harmonics and numbers of finger pairs. For higher harmonics, i.e., 5\(^{th} \) and 7\(^{th} \), smaller \( N \) become preferable for high signal strengths. The FWHM stays the lowest for higher \( N \).
Exciting higher harmonics in an IDT results in an increase of the number of wavefronts within this IDT by the same factor as the index of the harmonic that is excited. This leads to a better defined frequency spectrum of excited SAWs which is a possible reason for the increasing $Q$ factor. An increase in the number of finger pairs should therefore have the same effect. This agrees well with the data presented in Fig. 2.11d) where the FWHM at $n = 1$ for $N = 5$ is approximately three times as high as for $N = 15$.

We attribute the poor performance of high $N$ IDTs in higher harmonics to the same effect. By adding more finger pairs the delay line performance becomes more susceptible to fabrication defects, since the FWHM decreases with more finger pairs. Thus, at higher harmonics (larger $Q$ factor) even small lithographical deviations will reduce the overall IDT performance.

### 2.3.4 Finger overlap $O$

Finally, we investigate the influence of the finger overlap $O$ on $|\hat{S}_{21}|$. The results are shown in Fig. 2.12 with $\delta |\hat{S}_{21}^O|$ (dB) = $20\log_{10} |\hat{S}_{21}^O|/|\hat{S}_{21}^{25\mu m}|$. Generally, higher overlaps yield higher signal strengths. At low harmonics the difference in signal strengths is especially high with $\delta |\hat{S}_{21}^O| = 15$ dB. In reference [35] it was found that larger overlap increases signal transmission for the 1st harmonic. Our data confirms this for electron beam lithography. In addition we find that with higher harmonics $\delta |\hat{S}_{21}^O|$ decreases. $\delta |\hat{S}_{21}^{200\mu m}|$ even drops significantly at the 7th harmonic.

**Fig. 2.12:** Influence of IDT finger overlap $O$. Higher maximum magnitudes emerge from higher $O$ in low frequency. With higher frequencies $\delta |\hat{S}_{21}^O|$ decreases. The SAW delay line with $O = 200\mu m$ performs poorer for higher harmonics in respect to smaller overlap delay lines.

IDTs with a higher overlap have a greater capacity, which reduces the impedance mismatch (Eq. (14)). At higher harmonics fabrication defects become more problematic. With increasing lengths of overlaps these defects become more likely as the structure has to be written across more grid elements of the electron beam lithography.
With these results we can design high frequency IDTs as well as optimize them for specific frequencies. In Fig. 2.13 the transmission spectrum of a SAW delay line optimized for high frequency operation is shown. Here the 17th harmonic with a center frequency of approximately 13.78 GHz can still be detected. Design parameters are as follows: \( N = 10, \ O = 50 \ \mu \text{m}, \ g = 1.2 \ \mu \text{m}, \ w = 0.8 \ \mu \text{m}, \ \eta = 0.67, 90^\circ \ \text{LNO.} \)

To reach higher frequencies than shown in Fig. 2.13 we suggest changing to a 0° oriented YZ-Cut.

### 2.4 Field dependent microwave spectroscopy

In this section, we present ADFMR results obtained from field dependent microwave spectroscopy up to 5.95 GHz and compare the data to simulations based on a Landau-Lifshitz-Gilbert approach.

#### 2.4.1 Measurements

Our optimized SAW delay lines allow us to study ADFMR in the gigahertz regime, going beyond the frequency range explored in earlier work at WMI [30–33, 35–38] and also beyond recently published results by other groups [34]. For our studies, we deposit a ferromagnetic thin film between two IDTs. Here we use a 20 nm thick layer of cobalt, and detect \( S_{21} \) transmission spectra using a VNA. In that process, we alter two external parameters, namely strength of a magnetic field \( ||H_{\text{ext}}|| = H_{\text{ext}} \) and its direction \( \phi \) relative to the SAW wave vector \( k_{\text{SAW}} (\phi = \angle (k_{\text{SAW}}, H_{\text{ext}})) \).

\( H_{\text{ext}} \) is applied in the plane of the thin film. All measurements are done at room temperature. The setup is illustrated in Fig. 2.14a) and the Device Under Test (DUT) in Fig. 2.14b). To create an external magnetic field we use a BRUKER Präzisionsmagnet B-E 10 B 8, which we can rotate using a stepper motor Nanotec model ST8918L4508-B. The magnetic field is powered by a KEPCO bipolar power supply and measured by a LAKESHORE 475 DSP Gaussmeter.
2.4 FIELD DEPENDENT MICROWAVE SPECTROSCOPY

When phonons drive an ADFMR in a cobalt patch between the IDTs we expect a change in transmission signal \([30–35, 37, 38]\). Each transmission spectrum is processed as described in section 2.2. For each \(\phi\), we calculate

\[
\Delta \hat{S}^\parallel_{21}(H_{\text{ext}}, \phi) = \frac{1}{F} \sum_{f=\text{ROI}_{\text{start}}}^{\text{ROI}_{\text{end}}} \hat{S}^\parallel_{21}(f, H_{\text{ext}}, \phi) - \hat{S}^\parallel_{21}(f, \phi)
\]

\(19\)

with

\[
\hat{S}^\parallel_{21}(f, \phi) = \frac{1}{2} [\hat{S}^\parallel_{21}(f, +H_{\text{ext}}^{\text{max}}, \phi) + \hat{S}^\parallel_{21}(f, -H_{\text{ext}}^{\text{max}}, \phi)].
\]

\(20\)

The signal at each field value is set in relation to the mean of signal outputs at highest and lowest applied fields (here: \(\pm \mu_0 H_{\text{ext}}^{\text{max}} = \pm 40 \text{ mT}, \mu_0\) being the vacuum permeability). By doing so, the relative change \(\Delta \hat{S}_{21}\) due to magnetic field dependence of the transmission at a specific \(\phi\) becomes evident and we correct for any temporal drift effects. At \(\mu_0 H_{\text{max}}\) we assume to be far away from the ferromagnetic resonance condition. In order to achieve a better signal-to-noise ratio, we define a ROI (approx. the FWHM) in each \(S_{21}(f)\) spectrum centered around the SAW transmission peak, with total number of frequencies \(F\), and average the relative change over \(F\). The resulting plots are shown in Figs. 2.15 and 2.18 with

\[
\Delta \text{Re} \{\Delta \hat{S}_{21}\} = \max \{\text{Re} \{\Delta \hat{S}_{21}\}\} - \min \{\text{Re} \{\Delta \hat{S}_{21}\}\}
\]

\(21\)

and

\[
\Delta \text{Im} \{\Delta \hat{S}_{21}\} = \max \{\text{Im} \{\Delta \hat{S}_{21}\}\} - \min \{\text{Im} \{\Delta \hat{S}_{21}\}\}.
\]

\(22\)

Figure 2.15 shows data obtained using samples on a \(0^\circ\) oriented YZ-Cut LNO substrate.
$0^\circ$ oriented YZ-Cut LiNbO$_3$

Fig. 2.15: Field dependent VNA measurements of SAW delay lines with 500 $\mu$m $\times$ 75 $\mu$m cobalt patch of thickness 20 nm in between two IDTs. The color bar represents data calculated from Eq. (19). The left side shows the field dependence of the real part of the SAW transmission, the right side the imaginary part. The plots display results from measurements of 4 different harmonics of the same sample on a $0^\circ$ oriented YZ-Cut LNO substrate.
In Fig. 2.15 data is shown for ADFMR measured up to the 7th harmonic with fundamental frequency $\tilde{f}_1 = 0.85$ GHz. Each plot shows a four-fold symmetry about the origin, i.e., $H_{\text{ext}} = \phi = 0$. This is characteristic for ADFMR as shown in references [31,34,38]. $\text{Re} \{ \Delta S_{21} \}$ corresponds to SAW absorption, $\text{Im} \{ \Delta S_{21} \}$ corresponds to SAW dispersion. We attribute this behavior to the nature of magnetic susceptibility, which is a complex quantity describing absorption and dispersion in magnetic resonance. For each frequency the FMR is found between $\phi = \pm 15^\circ$ in the real part whereas for the imaginary part it extends beyond $\pm 30^\circ$. As seen from Fig. 2.15 the shape of the ADFMR depends on the frequency. It is interesting to note that the features are stronger at negative products of $\phi$ and $H_{\text{ext}}$ (e.g., $\mu_0 H_{\text{ext}} = -10$ mT, $\phi = +10^\circ$) than they are for positive products. This behavior inverts for measurements of $S_{12}$ (see Fig. 2.16), in agreement with time reversal symmetry [62,63]. Thereby the sample displays characteristics of an acoustic diode with non-reciprocal SAW transmission. As is demonstrated in reference [33], acoustic shear vertical waves in the $xz$-plane of the substrate are responsible for the asymmetry which is found in our measurements. The strength of asymmetry increases with frequency, as shown in Fig. 2.17, where the relation $\Delta S_{21}^{\text{max}} / \Delta S_{12}^{\text{max}}$ is plotted. Here, $\text{max}_{21}$ indicates that both $\Delta S_{21}$ and $\Delta S_{12}$ are taken at maximum ADFMR conditions for $\Delta S_{21}$. The relation represents the mean value of the asymmetry in Real and Imaginary part. We suspect frequency dependent magnetization ellipticity in FMR to be the reason for the increasing asymmetry, which will be further discussed in section 2.4.2.

![Diagram](image)

**Fig. 2.16:** ADFMR at 5.95 GHz. Shown in both plots is the real part of $\Delta S_{ij}$. The left plot shows results for the S-parameter $S_{21}$, i.e., for SAWs that travel from IDT 1 to IDT 2. The right side shows results for $S_{12}$, i.e., the inverse direction. Due to the asymmetric ADFMR profile, for one SAW direction the acoustic signal transmission is higher than for the opposite direction, while keeping the same external magnetic field and angle, e.g., $H_{\text{ext}} = 14$ mT and $\phi = -15^\circ$. Thus, by favoring one SAW direction over the opposite direction, the sample behaves as an acoustic diode.

At approximately 2 mT to 3 mT a horizontal feature is visible in most plots. Since the magnetic field sweeps from negative to positive field, this feature is attributed to the magnetic switching of the cobalt patch magnetization.
ΔRe \{ΔS_{21}\} and ΔIm \{ΔS_{21}\} show a strong SAW frequency dependence: At 850 MHz the real part only changes by 0.5%, the imaginary part by 3% whereas at 5.95 GHz center frequency the change is much stronger with the real and imaginary part showing an FMR dependence of up to 50% change in respect to S_{21}(f, ±H_{\text{ext}}^{\text{max}}, \phi). Therefore also the signal-to-noise ratio improves.

That we observe different ΔRe \{ΔS_{21}\} and ΔIm \{ΔS_{21}\} at small frequencies is likely due to the poor signal-to-noise ratio as well as unsaturated magnetization of Co at low magnetic fields.

Our measurement results for this substrate fit very well in terms of ADFMR shape and frequency dependance to previous work at the Walther-Meißner-Institute where nickel was used as a ferromagnetic thin film at frequencies up to 2.24 GHz [31,33,38]. In reference [32] Co was used in a Co/Pt bilayer for ADFMR spin pumping at 1.55 GHz SAW frequency. Here a four-fold symmetry was observed as well with coercive field of 2 mT.

The results presented here go beyond previously published results by measuring ADFMR at frequencies up to 5.95 GHz. This is an important point, as the qualitative shape of the resonance only becomes apparent at high frequencies, whereas at lower frequencies, the Co magnetization is not fully saturated at the FMR fields.
2.4 FIELD DEPENDENT MICROWAVE SPECTROSCOPY

128° Y-Cut LiNbO$_3$

![Fig. 2.18: Field dependent VNA measurements of SAW delay lines for a sample on a 128° Y-Cut LNO substrate with cobalt thin film. For c) and d) no data is available below $\phi = -41°$. The field sweep direction in e) and f) is reversed.](image)

Figure 2.18 shows measurement results for an acoustic delay line fabricated on a 128° Y-Cut LNO substrate where ADFMR was measured for the 5$^{th}$ harmonic at 5 GHz, shown in a) and b), and the 3$^{rd}$ harmonic at 3 GHz, shown from c) to f). For the 3$^{rd}$ harmonic, results are presented for magnetic field upsweep in c) and d), and downsweep in e) and f).

The ADFMR features display a rather different pattern in comparison with the 0° oriented YZ-Cut LNO substrate. Here the plots are nearly mirror symmetric along the $H_{ext} = 0$ axis, but show a strong asymmetry along the $\phi = 0$ axis. The ADFMR is similar to the ADFMR measured in the YZ-Cut substrate only at positive angles. As shown later in section 2.4.2, shear horizontal compo-
components $\varepsilon_{xy}$ and in plane magnetization components perpendicular to $k_{\text{SAW}}$ in the cobalt film, due to anisotropy effects, are a possible reason for this behavior. As shown in Fig. 2.18, the ADFMR is slightly stronger at a negative product of $H_{\text{ex}}$ and $\phi$ here as well, suggesting shear vertical waves in the $xz$-plane.

The sweep direction was reversed in Fig. 2.18(e) and f) to verify that the horizontal features at 2-3 mT depend on sweep direction. In fact the horizontal features now appear at approximately $-2$ mT to $-3$ mT. Both the amplitudes of $\Delta \text{Re} \{\Delta \hat{S}_{21}\}$ and $\Delta \text{Im} \{\Delta \hat{S}_{21}\}$, and the frequency dependence of the ADFMR shape fit to the previous observations for the YZ-Cut substrate.

To our knowledge, these are the first measurements of ADFMR on $128^\circ$ LNO with angular resolution. The different crystalline structure of the Y-Cut LNO allows us to investigate the influence of additional shear components as well as anisotropic components and verify the theoretic model of our simulations.

### 2.4.2 Simulation

In this section, we present simulations based on Dreher et al. [33] and compare these to our results from section 2.4.1.

The algorithm given in reference [33] is obtained by solving the Landau-Lifshitz-Gilbert (LLG) equation (see Eq. (1)) and the elastic wave equation. To do so, a coordinate transformation from the laboratory frame $\{x, y, z\}$ to a $\{1, 2, 3\}$ coordinate system is chosen, in which the magnetization precession about the magnetization equilibrium direction $m_0$ is described in a two-dimensional plane, with $m_0$ pointing along the 3 direction. Finding $m_0$ is a matter of minimizing the static free-enthalpy density $G$ with respect to the magnetization direction $m = M/M_s$, normalized to the saturation magnetization $M_s$:

$$G = -\mu_0 H \cdot m + B_d m_z^2 + B_u (m \cdot u)^2 - \mu_0 H_{\text{ex}} \cdot m. \quad (23)$$

The meaning of each term is as follows:

- $-\mu_0 H \cdot m$: Zeeman term with externally applied magnetic field $H$.
- $B_d m_z^2$: Shape anisotropy with $B_d = \mu_0 M_s/2$ and $z$-component $m_z$ of $m$.
- $B_u (m \cdot u)^2$: Uniaxial in-plane anisotropy with parameter $B_u$ along unit vector $u$.
- $-\mu_0 H_{\text{ex}} \cdot m$: Exchange field $H_{\text{ex}}$.

In contrast to reference [33], we do not include the exchange field in our calculations as to keep the simulation simple. The difference in results is expected to be small, because the wavelengths of the SAW are still large compared to those relevant for exchange interaction [38]. The magnetoelastic interaction of SAW and magnetization causes a contribution to the dynamic, magnetoel-
2.4 FIELD DEPENDENT MICROWAVE SPECTROSCOPY

Elastic free-enthalpy density $G^d$ given by

$$G^d = b_1 \left[ \epsilon_{xx}(x, t)m_x^2 + \epsilon_{yy}(x, t)m_y^2 + \epsilon_{zz}(x, t)m_z^2 \right] + b_2 \left[ \epsilon_{xy}(x, t)m_x m_y + \epsilon_{xz}(x, t)m_x m_z + \epsilon_{yz}(x, t)m_y m_z \right].$$

Here $b_{1,2}$ are magnetoelastic coupling constants and $\epsilon_{ij} = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)/2$ with $i, j \in \{x, y, z\}$ are strain tensor components where $u_i$ are components of the mechanical displacement field. For polycrystalline films, e.g., our Co films, $b_1 = b_2$ applies. As stated earlier in chapter 1, an ideal surface acoustic Rayleigh wave has non-zero components in $\epsilon_{xx}, \epsilon_{zz}$ and $\epsilon_{xz}$.

With this, the solution for the magnetizations $M_1$ and $M_2$ is

$$\begin{pmatrix} M_1 \\ M_2 \end{pmatrix} = \bar{x} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$= \frac{\mu_0 M}{D} \begin{pmatrix} G_{22} - G_3 - i\omega \alpha/\gamma & -G_{12} - i\omega/\gamma \\ -G_{12} - i\omega/\gamma & G_{11} - G_3 - i\omega \alpha/\gamma \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

with

$$D = (G_{11} - G_3 - i\omega \alpha/\gamma)(G_{22} - G_3 - i\omega \alpha/\gamma) - G_{12}^2 - (\omega/\gamma)^2.$$

$\mu_0 h_{1,2}$ denote the effective driving fields, $\omega$ is the angular SAW frequency, $\gamma$ represents the gyromagnetic ratio and $\alpha$ is a phenomenological damping parameter from the LLG equation. $G_i$ and $G_{ij}$ are partial differentiations with $G_i = \partial_{m_i} G|_{m=m_0}$ and $G_{ij} = \partial_{m_i} \partial_{m_j} G|_{m=m_0}$. Consistent with reference [33], we calculate $\Delta \hat{S}_{21}$ as

$$\Delta \hat{S}_{21} \propto -\frac{\omega \mu_0}{2} V (M_1 h_1 + M_2 h_2),$$

where $V$ is the volume of the Co thin film. Our simulation results for $0^\circ$ LNO are shown in Fig. 2.19, followed by plots of the parameters used in the calculations (see Figs. 2.20 and 2.21). The results for $128^\circ$ LNO are shown in Fig. 2.23.

Our ADFMR simulations for Co on a $0^\circ$ LNO substrate reproduce our measurement results in Fig. 2.15 very well. By choosing the shear vertical strain component $\epsilon_{xz} \neq 0$ the asymmetry observed in experiments is introduced in the simulations as well. It is to be noted that the choice of parameters for these simulations are within order of expected values, but had to be changed for each frequency to reproduce the respective plot.
Fig. 2.19: Simulation of ADFMR using a LLG approach. The simulation matches the measurements in Fig. 2.15 very well.
In Fig. 2.20 the values for parameters a) $B_u$, b) $M_s$, and c) $\alpha$ are plotted over frequency. Both uniaxial in-plane anisotropy $B_u$ and saturation magnetization $M_s$, and thereby shape anisotropy $B_d$ (see Eq. (24)), have to be increased with frequency, although both parameters are expected to stay constant. One possible reason for this is that the simulation calculates magnetic saturated FMR. At lower frequencies the observed magnetic field conditions for ADFMR are too low for the Co film to be saturated, which brings a discrepancy to the comparison of experiment and simulation. Another possible reason is that the simulation ignores the effects of dipolar interactions [34]. The decrease of the damping parameter $\alpha$ in Fig. 2.20c) is to be expected due to the definition of the damping factor in the framework of the Landau-Lifshitz model, which we denote here as $\alpha_{\text{LLG}}$. $\alpha_{\text{LLG}}$ is the slope by which the FWHM $\Delta H$ of FMR increases with frequency $f$. $\Delta H$ is then given by [64]

$$\Delta H = \frac{4\pi \alpha_{\text{LLG}} f}{|\gamma| \mu_0} + \Delta H_0,$$  \hspace{1cm} (28)

where $\Delta H_0$ is a nonzero intercept, attributed to an imhomogeneity of the local resonance field [64]. In the model of Dreher et al. [33], $\Delta H_0$ is not explicitly included, so that instead an effective damping factor $\alpha$ with

$$\Delta H = \frac{4\pi \alpha f}{|\gamma| \mu_0},$$  \hspace{1cm} (29)

is used in the calculations, where

$$\alpha = \alpha_{\text{LLG}} + \frac{|\gamma| \mu_0}{4\pi f} \Delta H_0.$$  \hspace{1cm} (30)

Consequentially, the fit parameter for damping decreases for increasing frequencies.

**Fig. 2.20:** Simulation parameters used for Fig. 2.19 over frequency.
Figure 2.21 shows a significant decrease of the simulated compressional component $\varepsilon_{xx}$ in relation to the shear vertical component $\varepsilon_{xz}$ over frequency. The need to decrease this relation in order to reproduce the experimental data is unexpected. One reason might be a direct frequency dependence of the Rayleigh wave strain components. Another reason could be a frequency dependent asymmetry of the backaction of virtual fields on the strain components. However, in both cases, no frequency dependence is stated in either of the current theoretical models [33, 40].

We therefore attribute this behavior to frequency dependent magnon-phonon coupling due to the ellipticity and chirality of the SAW in combination with the geometry of our samples. One refers to the ratio $|m_x/m_z|$ at FMR ($H_{ext} = H_{res}$) as the ellipticity of the precession, which is equivalent to the relation of susceptibilities $|\chi_{xx}|/|\chi_{xz}|$ at FMR [65]. This can be approximated with

$$|\chi_{xx}|/|\chi_{xz}| \approx \sqrt{1 + M_s/H_{res}}. \quad (31)$$

The resonant field $H_{res}$ increases with frequency (see Eq. (2)). Therefore, according to Eq. (31), the ellipticity of the total magnetization decreases with frequency. When ellipticity of magnetization and ellipticity of the displacement motion, which a lattice element undertakes in the SAW, match one another, we expect maximum magnon-phonon coupling. However, the phonon and magnon chirality have to match as well. Because the phonon chirality is inverted under inversion of phonon propagation direction, this leads to the asymmetry visible in Fig. 2.16.

Figure 2.22: Figure a) shows qualitatively the variation of particle displacements with depth, adapted from S. Datta [40]. Figure b) illustrates the corresponding propagation direction of a particle. The detailed nature of the displacement behavior depends on substrate material and orientation.
On the other hand, if magnon and phonon ellipticities do not match well to begin with, chirality would not have as strong an influence on the coupling, which is why at lower frequencies, smaller asymmetry is detected (see Fig. 2.17). In the mathematical model for the simulations the frequency dependent magnon ellipticity is included. Therefore we’d normally expect a constant relation between compressional and shear vertical wave component. However, this relation decreases over frequency (see Fig. 2.21). We attribute this to geometrical factors: With higher frequencies, the SAW wavelength decreases, which also decreases the difference between SAW wavelength and Co film thickness (20 nm). Even below the depth of one wavelength into the Co bulk, the particle displacement motion of the SAW exhibits a sign reversal, i.e., changing chirality [40]. The exact nature of particle displacement with depth depends on substrate material and orientation, but the qualitative nature, illustrated in Fig. 2.22, is the same. As the relation of displacement ellipticity $u_x/u_z$ and depth (in wavelengths) is approximately exponential, the corresponding relation between compressional and shear wave simulation parameter would need exponential adjustment as well, which is what we observe in our results. Further investigation, including the dependence on Co film thickness will be needed.

In Fig. 2.23 the simulation results for a 128° LNO are shown. Reproduction of ADFMR features as seen in measurement results (see Fig. 2.18) are not as successful as for 0° LNO. However, main characteristics can be explained with the simulation.

![Fig. 2.23: Simulation of ADFMR for 128° LNO substrate. The simulation reproduces the main features of the corresponding experimental results in Fig. 2.18.](image-url)
Mirror symmetric features are introduced in the simulation by setting the angle between SAW k-vector and the uniaxial in-plane anisotropy field to be $\phi_u = \pi/40$ instead of zero and adding a non-zero shear horizontal component $\varepsilon_{xy}$, in agreement with literature [40]. We observe that both changes lead to the desired mirror symmetry. However, additional sample measurements and simulation calibration are needed to clarify the underlying strain and anisotropy components present in ADFMR with 128° LNO.

2.5 Summary

In section 2.1, the setup of microwave spectroscopy was presented. The VNA as measurement instrument and the transmission signal $S_{21}$ for SAW delay lines was introduced.

In section 2.2, the data processing using a time gating algorithm was explained. Measurements with the VNA contain many spurious signals, masking the SAW. Inverse Fourier transformation of the frequency spectrum into the time domain allows separating signals with respect to the transit time from port 1 to port 2 of the VNA. By applying a window over the time span in which SAWs arrive at port 2, SAW signals become well visible in the subsequent Fourier transform.

In section 2.3, we have investigated the influence of the crystalline structure of LNO (incl. IDT orientation), IDT metallization ratio $\eta$, number of finger pairs $N$, and finger pair overlap $O$ on delay line performance. We have found that for SAW propagation along the z-direction of the crystalline structure a 0° oriented YZ-Cut yields higher SAW signals than a 90° orientation. The 128° Y-Cut gives similar results to the 0° YZ-Cut. Signal strength decays exponentially with frequency due to thermal losses and air loading. This decay is independent of index of harmonic. Therefore using a high fundamental frequency to reach high SAW frequencies is interchangeable with using higher harmonics instead. However, resonators work best for their fundamental frequency while providing only poor support for higher harmonics due to the reflector’s design with a spacing of half the fundamental wavelength between reflecting elements [40]. Since one of the goals of this thesis is to set the path for high frequency acoustic resonators we concentrate on IDTs with fundamental frequencies of at least 850 MHz. The metallization ratio dictates the suppression of higher harmonics. Calculations fit to our measurements very well. For optimum performance of 1st or 5th harmonic a metallization ratio of $\eta = 1$ is most suitable, but at the same time, every second odd harmonic does not perform well using this ratio. For other metallization ratios more complicated suppression patterns appear. We expect very small metallization ratios ($0 \leq \eta \leq 0.01$) to work particularly well. However, the necessary small finger widths might prove to be challenging in fabrication. Furthermore, calculations have shown that smaller metallization ratios also increase the IDTs impedance, which is unfavorable in regard to impedance matching and insertion loss.

Number of finger pairs should also be chosen depending on the harmonic of interest. For a low index of harmonic (i.e. 1st or 3rd) a higher number of finger pairs yields higher maximum signal magnitudes, whereas higher indices perform better with less finger pairs. The FWHM decreases with an increase of finger pairs regardless of harmonic. Accordingly, the $Q$ factor increases with
harmonic index. At small harmonics we find an overlap of 100 µm or higher to be preferable. In our study an overlap of 200 µm shows a poor performance for higher harmonics. The other samples with \( O = 100 \mu m, O = 50 \mu m, O = 25 \mu m \) approach each other in terms of signal strength for higher harmonics.

Besides pointing out influence of different design parameters on specific harmonics, we have also shown that our IDTs reach frequencies up to 13.78 GHz. Only a few groups have worked with IDTs in this frequency regime, e.g., Chen et al. (12 GHz) [41]. With a distance between two IDTs of approx. 1 mm that is available for additional thin films, our SAW delay lines can also be used for ADFMR measurements.

In section 2.4, the setup and results for ADFMR measurements were presented and compared to simulations based on Dreher et al. [33]. SAW frequencies in these measurements range from 0.85 GHz to 5.95 GHz, which goes beyond current ADFMR publications. At high frequencies a strong asymmetry in ADFMR features is observed, which can be explained by SAW shear vertical components. The sample displays characteristics of an acoustic diode with non-reciprocal SAW transmission. Measurements on 128° LNO have also shown a mirror symmetry instead of the usual four-fold symmetry of AFDMR. In-plane anisotropy magnetization components perpendicular to \( k_{\text{SAW}} \) and shear horizontal wave components are possible reasons for this behavior. As this is the first time 128° LNO was used for ADFMR with angular resolution, further studies may yield additional interesting observations.

The simulations for 0° LNO match measurement results very well. At higher frequencies the parameter for the shear vertical wave component \( \epsilon_{xz} \) has to be increased to reproduce measurement results appropriately. We attribute this to the fact that the strain components are depth-dependent, which is not contained in the current model.

128° LNO results were reproduced in the simulations by introducing uniaxial anisotropy field components perpendicular to the SAW propagation direction and shear horizontal strain components.
3 Brillouin light scattering

In this chapter, we will explain the basic physics of Brillouin Light Scattering (BLS). Thereafter we describe the technique of measuring BLS, beginning with the working principle of a Fabry-Pérot interferometer and its expansion to a Tandem-Fabry-Pérot interferometer. Then we will present the micro BLS setup that we use in this thesis to optically measure SAWs (phonons) and ADFMR (magnons). Finally, we show and discuss our measurement results obtained by BLS.

3.1 Fundamentals of Brillouin light scattering

As the name suggests, Brillouin Light Scattering is an optical scattering effect. BLS can be understood very well non-classically as an inelastic scattering event of an incident photon with a quasi-particle, i.e., a phonon or a magnon [66]. Let \( f \) and \( k \) be the frequency and wave number of a (quasi-)particle with the indices ‘\( i \)’ for ‘incident photon’, ‘\( q \)’ for ‘quasi-particle’, and ‘\( s \)’ for ‘scattered photon’. Then conservation of energy and momentum require

\[
hf_s = hf_i \mp hf_q
\]

and

\[
hk_s = hk_i \mp hk_q,
\]

where \( h \) is the Planck constant and \( \hbar \) the reduced Planck constant. As shown in Eqs. (32) and (33) the incident photon can either lose energy and momentum by creation of a quasi-particle (Stokes scattering) or absorb energy and momentum from an existing quasi-particle (Anti-Stokes scattering). An illustration of the Stokes and Anti-Stokes processes is shown in Fig. 3.1. We note that photon-magnon scattering leads to a 90° shift in photon polarization due to the conservation of angular momentum [66], while photon-phonon scattering conserves the incident photon polarization. Scattering of optical photons with SAWs and SAW induced magnons will result in the frequency shift explained above. Measuring this frequency shift requires a suitable detection method. In this thesis we make use of a Tandem Fabry-Pérot Interferometer (TFPI).

\[ f_s = f_i - f_q \]
\[ k_s = k_i - k_q \]
\[ f_s = f_i + f_q \]
\[ k_s = k_i + k_q \]

Fig. 3.1: Illustration of Brillouin Light Scattering. Quasi-particles can be created in a Stokes scattering as shown in a), or they can be annihilated in an Anti-Stokes scattering as shown in b). Figure adapted from [67].
3.2 Fabry-Pérot interferometer

A Fabry-Pérot Interferometer (FPI) consists of semi-transparent, high finesse mirrors, creating an optical resonator. Light that has been introduced at an angle $\psi$ (see Fig. 3.2) into the FPI will be reflected back and forth between the two mirrors. With every transit $l$, part of the light is transmitted through the partially reflecting mirrors. Therefore the transmitted light will have a phase shift

$$\Delta \varphi = 2\pi \frac{\Delta s}{\lambda}$$

with

$$\Delta s = 2d \sqrt{n^2 - \sin^2 \psi} \equiv 2dn^*, \quad \text{(35)}$$

where $\lambda$ is the laser wavelength, $n$ the refractive index of the mirrors, and $d$ the distance between mirrors. An illustration is shown in Fig. 3.2a). Behind the optical resonator a number of $F^*$ offset beams will interfere with one another. $F^*$ is called the finesse of the interferometer [68], which is related to the reflectivity $R$ of the mirrors with

$$F^* = \frac{\pi \sqrt{R}}{1-R} = \frac{\delta \nu}{\Delta \nu'}, \quad \text{(36)}$$

where $\delta \nu$ and $\Delta \nu$ are defined in Fig. 3.2b).

![Fig. 3.2: Principle of a Fabry-Pérot interferometer. Figure a) illustrates the optical path of a laser beam, adapted from [68]. Figure b) shows the normalized transmission amplitude from Eq. (40) for different values of $F^*$.](image)

The transmission is highest for constructive interference, i.e., when the optical path difference is $\Delta s = m\lambda$ with $m \in \mathbb{N}$. Therefore

$$\lambda_m = \Delta s/m.$$  \hspace{1cm} \text{(37)}
The periodicity between two adjacent $\lambda_m$ is called Free Spectral Range (FSR) [68]:

$$\delta \lambda = \lambda_m - \lambda_{m+1} = \frac{2dn^*}{m} - \frac{2dn^*}{m+1} = \frac{2dn^*}{m(m+1)} = \frac{\lambda_m}{m+1}. \tag{38}$$

For the laser frequency $\nu = c/\lambda$ this yields the FSR

$$\delta \nu = \nu_{m+1} - \nu_m = \frac{c}{2dn^*}. \tag{39}$$

From Eq. (36), $F^*$ also gives the relation between $\delta \nu$ to the FWHM $\Delta \nu$ of the transmission curve. This is important because by changing $d$, the FSR can be adjusted, but doing so will also have a proportional effect on $\Delta \nu$ since $F^*$ is a constant. Choosing $d$ is therefore a tradeoff between spectral range and resolution. In Fig. 3.2b) transmission curves are plotted for different values of $F^*$, normalized to the incident beam. Transmission amplitudes $I_T$ are calculated using the Airy function [69]:

$$I_T = \frac{I_0}{1 + F^* \sin^2(\Delta \varphi/2)}. \tag{40}$$

### 3.3 Tandem-Fabry-Pérot interferometer

The condition for constructive interference, given in Eq. (37), can be satisfied by multiple wavelengths at the same time. Thereby the spectrum of a single FPI does not tell the user the intensity of the light with a specific wavelength, but rather the intensity from all possible wavelengths that satisfy Eq. (37). However, this shortcoming can be overcome by installing two consecutive FPIs, in an arrangement called a Tandem-Fabry-Pérot Interferometer (TFPI). The basic idea is that by using two FPIs, FPI1 and FPI2, with slightly different mirror spacing $d_1 \neq d_2$, a second condition applies for transmission. Let $\lambda_\xi$ be all transmitting wavelengths for FPI1 and $\lambda_\zeta$ for FPI2 with $\xi, \zeta \in \mathbb{N}$, then to pass through both FPIs it is necessary that

$$\frac{2d_1n^*}{\xi} = \frac{2d_2n^*}{\zeta} \Leftrightarrow \frac{d_1}{d_2} = \frac{\xi}{\zeta}. \tag{41}$$

Any neighboring interferences by one FPI, e.g., $\xi \pm 1, 2, 3,...$, will be suppressed by the other. An illustration is shown in Fig. 3.3a). With the need to satisfy Eq. (41), measurement sweeps through wavelengths by varying the mirror distance become problematic, since it requires that $\frac{d_1}{d_2}$ is constant. To ensure this, in the Sandercock-type TFPI the FPIs each have one static mirror and one movable mirror on a translation stage that connects the moveable mirrors with an angle $\sigma$ as shown in Fig. 3.3b). This way, $\frac{d_1}{d_2} = \frac{1}{\cos \sigma}$ during the entire scan [70].
3.4 Micro focused Brillouin light scattering spectrometer

In this section we will present the micro BLS setup used for our experiments. The setup is illustrated in Fig. 3.4. The photon source is a 532 nm single frequency laser with a linewidth $< 10$ MHz. At the beginning of the optical path, a beam splitter (BS) directs part of the laser beam to the TFPI. This laser beam is used as an undisturbed reference peak to stabilize the interferometer. The TFPI is of Sandercock-type with a finesse between $F^* = 80$ and $F^* = 120$. White light from an LED is added into the optical path of the probe laser beam by a second BS. A polarizing beam splitter (PBS) linearly polarizes the beam before it enters a microscope objective (MO), which focuses the beam on the sample surface. After reflection/scattering at the sample the beam passes the PBS once more, where a part of the beam is directed towards the TFPI and thereafter to a photon counter.
counter and computer. Another part of the beam is directed to a CCD camera that provides an image of the sample and laser spot, so that the laser spot can be positioned and focused on the sample surface.

Due to the polarization at the PBS, reflected photons that did not experience a change in polarization from a scattering event (e.g., photon-phonon-scattering), will be strongly suppressed before entering the TFPI. Optionally, a $\lambda/2$ plate can be inserted between PBS and MO to adjust the setup sensitivity for scatter events that do not change the photon polarization. The polarization of the laser beam with incident electric field $E_i$ is rotated by twice the $\lambda/2$ plate polarization angle $\theta$ to a rotated electric field $E_r$ (see Fig. 3.4). After reflection/scattering at the sample, the laser beam polarization is rotated once more by $2\theta$ at the $\lambda/2$ plate, which accumulates to a total rotation by $4\theta$. The sample is mounted on a moveable stage with piezoelectric controls. The range of movement is $100 \mu m \times 100 \mu m$ in the $xy$-plane. Furthermore, two permanent magnets create an in-plane magnetic field $H_{ext}$ at the position of the sample. The field strength can be changed by changing the distance between the magnets. For magnetic field sweeps one can also control the field strength by using two stepper motors that move the permanent magnets. The adjustment range is approximately $10$ cm and the magnetic field sweep range depends on the initial position and strength of the permanent magnets. A Hall probe is used for magnetic field calibration. An IDT is connected to a radio frequency source for the excitation of SAWs.

The spatial resolution $D$ achieved with a micro BLS depends on the laser’s wavelength and the numerical aperture ($NA$) of the microscope objective [68]

$$D = \frac{0.61\lambda}{NA}.$$  \hfill (42)

With $\lambda = 532$ nm and $NA = 0.75$ our micro BLS achieves a resolution of $D = 433$ nm. The micro BLS is not phase sensitive so that it measures only intensities. That means that the wavefronts of propagating waves cannot be spatially resolved, but standing waves can, up to the limit given by $D$.

Conservation of momentum (Eq. (33)) puts an upper limit to the wave number of quasi-particles that can be detected generally (even above spatial resolution). Momentum is conserved, where translation invariance is fulfilled [71], which is the case for momentum components parallel to the reflecting surface. For an incident photon to be collected by the MO after a scattering event, the maximal transition of momentum $\Delta k$ is two times its maximum incident momentum $k_{i,max}$ and therefore $k_s = -k_{i,max} = k_{s,max} - 2k_{i,max}$. That means a detectable quasi-particle can have maximum wave number $|k_{q,max}| = 2k_{i,max}$. The magnitude of the $k_{i,max}$ depends on the $NA$ of the MO [68] with

$$k_{i,max} = \frac{2\pi NA}{\lambda \tilde{n}_{env}},$$  \hfill (43)

where $\tilde{n}_{env}$ is the refractive index of the environment the MO is operating in. With $\tilde{n}_{env} = \tilde{n}_{air} \approx 1$ this leads to a maximal quasi-particle wave number

$$k_{q,max} = 2 \times \frac{2\pi}{\lambda} NA = 2 \times \frac{2\pi}{532 \text{ nm}} = 17.7 \mu m^{-1}.$$  \hfill (44)
For SAWs on $0^\circ$ LNO this means $f_{\text{SAW, max}} = v_{\text{SAW}} k_{q, \text{max}}/2\pi = 9.8$ GHz.

For each measurement, the TFPI detects the photon frequency shift by changing the mirror distance. The sweep speed can be separated into intervals to get higher measurement sensitivity in Region Of Interests (ROIs). Since the amplitudes of Stokes and Anti-Stokes peak are the same, it is sufficient to measure only one of the two. In our measurements, we keep the sweep area mainly in positive frequency shifts (Anti-Stokes), except for parts of the reference peak, which extends into the negative regime. A typical BLS spectrum acquired during our measurements with reference peak and Anti-Stokes peak is shown in Fig. 3.5. Here, a SAW with frequency of 4.25 GHz was excited by applying a microwave power of 13 dBm to the IDT. The laser spot was put in the propagation region of the SAW and the $\lambda/2$ plate was set to $\theta = 22.5^\circ$.

Figure 3.6 shows an illustration of the sample. The SAW that is created at the IDT connected to the rf source travels along the delay line to a second IDT, where it gets partially reflected. Therefore the SAW delay line forms an acoustic cavity. A Co thin film is placed in between IDTs. The green laser spot is positioned at the beginning of the Co film. This laser position is used for all measurements if not stated otherwise.
3.5 Brillouin light scattering of phonons and magnons

In this section, measurement results and discussion are presented. First, we optically measure SAWs generated by the IDT. Adjusting the $\lambda/2$ plate, shown in Fig. 3.7a), enables us to make the setup sensitive to photon-phonon scattering and measure SAW dispersion across the sample. This also allows us to verify the spatial resolution of the instrument. An external magnetic field is added to study SAW induced magnons. Our measurements represent the first optical spectroscopy of ADFMR. With our measurements, we study magnon-phonon coupling as a function of frequency, external magnetic field and laser spot position.

All following data has been obtained by fitting the Anti-Stokes BLS peaks with a Lorentz function and normalizing the fitted peak area to the reference peak area, so that laser instabilities are corrected. The resulting quantity $A_{\text{norm}}$ is a measure of counts per arbitrary time frame, i.e., an intensity.

Figure 3.7 shows the polarization dependence for the detection of photon-phonon-scattering in the micro BLS setup. The IDT generates SAWs at 4.25 GHz outside of ADFMR conditions. polarization sensitivity is adjusted by rotating the $\lambda/2$ plate in Fig. 3.4. Maxima are found at $\lambda/2$ plate orientation of $\theta = 22.5^\circ$ and $\theta = 67.5^\circ$, which corresponds to a total polarization shift of $90^\circ$ ($\pi/2$) and $270^\circ$ ($3\pi/2$). We attribute this to the PBS. The signal does not fall to zero at $0^\circ$. This means even without polarization shift part of the photons pass the PBS and reach the TFPI. We attribute this to a finite efficiency of the PBS. This makes measurements more difficult, because even for a magnon-sensitive setup a frequency shifted BLS peak thus does not guarantee the detection of magnons. Since a BLS peak can also emerge from unfiltered photon-phonon scattering, magnon-sensitive measurements must be more sophisticated, e.g., including field sweeps.
or comparisons with phonon-sensitive measurements.

In Fig. 3.8 on the left side we plot the area of the Anti-Stokes peak as a function of $x$ and $y$ position of the laser spot on the sample (see Fig. 3.9) for SAWs at 4.25 GHz. The right side shows an intensity profile across position $y$ ($\Delta k_{\text{SAW}}$) averaged over position $x$. There are three interesting observations from Fig. 3.8:

Firstly, the SAW path has a width of approximately 50 µm. This corresponds to the IDT design with $O = 50$ µm. Given that the measurement is taken in the middle of the SAW delay line, this means the SAW does not show strong dispersion. Secondly, the plot shows a varying intensity in the direction orthogonal to the SAW propagation. These are possibly stemming from quantization of phonon modes to the width of the SAW beam. Finally, there are no visible wavefronts across the $x$ position ($\parallel k_{\text{SAW}}$). We confirmed this with line scans of higher resolution where also no wavefronts appeared. As BLS is not phase-sensitive, wavefronts of propagating waves cannot be resolved. Furthermore, with a corresponding standing wave periodicity of 410 nm the spatial resolution of the setup is insufficient according to Eq. (42).

![Fig. 3.9: Laser spot position for 2D sweep, shown in Fig. 3.8.](image)

A small area sweep for a sample with $f_{\text{SAW}} = 2.55$ GHz is shown in Fig. 3.10a). This time standing waves along the SAW propagation are visible. In Fig. 3.10b) a Fourier analysis is shown along the $x$ direction, taking the averaged $y$-intensity for every $x$. The peak at $1.47 \mu m^{-1}$ corresponds to $\lambda_{\text{SAW}} = 2 \times (1.47 \mu m^{-1})^{-1} = 1.361 \mu m$, where the factor of 2 takes into account that the standing wave has half the periodicity of the originating propagating waves. This is a deviation from the designed wavelength of only $\Delta \lambda = 0.5\%$. Although 2.55 GHz IDTs would allow, in principle, for sufficient spatial resolution to image standing waves with BLS, for magnon detection they proved
to be unfavorable. We know from Fig. 2.15 that the ADFMR effect depends on frequency. In our measurements with the 2.55 GHz sample, which are not shown in this thesis, ADFMR effects were too small to be observed by BLS.

As the upper limit for general phonon and magnon detection in the BLS setup is around 9.8 GHz (see section 3.4), we instead measure external magnetic field dependence of $A_{\text{norm}}$ for a 5.95 GHz sample. Although spatial resolution of standing waves will not be possible, the effects of ADFMR on the BLS intensity peaks should be well visible since the strong ADFMR features of this sample are known from VNA measurements shown in Fig. 2.15. Accordingly, the sample is positioned in such a way that $H_{\text{ext}}$ is in a $12^\circ$ angle to $k_{\text{SAW}}$.

![Figure 3.11](image)

**Figure 3.11:** a) $f_{\text{rf}}$ sweeps for different external magnetic fields in a magnon-sensitive measurement setup. b) $\Delta \Sigma [A_{\text{norm}}]$ at 5.95 GHz over external magnetic field.

Figure 3.11a) shows $A_{\text{norm}}$ vs. rf source frequency $f_{\text{rf}}$ for $5.1 \text{ mT} < \mu_0 H_{\text{ext}} < 15.1 \text{ mT}$. All plots have a maximum at 5.95 GHz, which is the IDTs central frequency. With increasing magnetic field strength, the peak area also increases, until it suddenly drops at 15.1 mT. The difference in sum of each sweep $\Delta \Sigma [A_{\text{norm}}] = \Sigma [A_{\text{norm}}\mu_0 H_{\text{ext}}] - \Sigma [A_{\text{norm}}^{5.1 \text{ mT}}]$ is shown in Fig. 3.11b), where the maximum is found at 12.6 mT, similar to our VNA results in chapter 2.4. By subtracting the signal of phonon scattered photons $A_{\text{norm}}^{5.1 \text{ mT}}$, which were not completely filtered out by the PBS, the increase in photon counts due to photon-magnon scattering becomes evident. This is an important difference to the measurement method of chapter 2.4, where the VNA measurements are indirect, detecting SAW signals, not magnons.
Furthermore, the VNA measurement does not provide spatial resolution. Figure 3.12 shows a line scan for $\mu_0 H_{\text{ext}} = 4 \text{ mT}$ and $\mu_0 H_{\text{ext}} = 12 \text{ mT}$, which extends from LNO 10 $\mu\text{m}$ into the cobalt patch (see Fig. 3.13). $A^{\text{norm}}$ is higher on Co due to a higher reflectivity. On Co, the 12 mT measurement generally shows a much stronger signal. However, the difference in signal strength between 12 mT and 4 mT strongly depends on laser spot position. This might be due to a complicated pattern of standing waves that cannot be spatially resolved for this sample.

For further investigation, it is therefore necessary to use a sample which provides both spatial resolution in the BLS as well as measurable ADFMR. We found this to be the case for a 3.21 GHz sample. Spatial resolution of standing waves with periodicity of $\lambda = 0.555 \mu\text{m}$ is shown in Fig. 3.14a) for a phonon-sensitive $\theta = 22.5^\circ$ line scan (black line). We find that the deviation of $\lambda_{\text{SAW}}$ from the design wavelength is $\Delta \lambda = 2\%$. The plot gives values for $A^{\text{norm}}$ to point out that $A^{\text{norm}}$ does not drop to 0 at any position. Even at valley points of the standing SAW there are still phonons detected. This is expected for a propagating wave. Indeed, the strong variation of $A^{\text{norm}}$ with position is rather surprising and indicates either the presence of strong standing wave patterns or enhanced scattering cross section of the standing waves. After application of rubber cement (Marabu Fixogum) before the output IDT and behind the Co thin film, to suppress SAW reflections, the standing wave profile is, in fact, highly reduced, illustrated in Fig. 3.14a) in red. However, SAW reflections could not be entirely annihilated, which we attribute to insufficient suppression of reflections at the Co edges.

**Fig. 3.12:** Magnon-sensitive line scan for a 5.95 GHz sample before and on Co.

**Fig. 3.13:** BLS laser spot position for line scan in Fig. 3.12.
Fig. 3.14: Line scans of a 3.21 GHz sample. a) shows a phonon-sensitive measurement to ensure spatial resolution. The original SAW delay line is shown in black, whereas the red line shows a delay line with rubber cement for suppression of SAW reflection before output IDT and behind the Co thin film. Fig. b) and c) present magnon-sensitive measurements for two different fields at the beginning of the Co patch and the end, respectively. Throughout the sample a beating is detected. Applying an external field inside ADFMR (6.5 mT, green line) leads to a strong increase in intensity at beating peak positions.

In Fig. 3.14b) a 100 µm line scan is shown, starting before the Co patch, using magnon-sensitive settings $\theta = 0°$. Once the measurement is done outside of ADFMR (black line with 11.40 mT) and once well within ADFMR conditions (green line with 6.50 mT), based on VNA pre-characterizations. Out of ADFMR a beating with 12.1 µm wavelength becomes visible. At the cobalt edge a particularly strong signal is detected, for which interferences from reflected phonons at the Co edge are a possible reason. For the condition of ADFMR, intensities strongly increase near peak positions of the beating with a small shift of maxima in $x$. Near the beginning of Co an increase of up to 40 normalized counts can be seen. Further away from the edge the peak height of $A_{\text{norm}}$ decreases. At valley points $A_{\text{norm}}$ does not increase at all. We attribute the strong increase in $A_{\text{norm}}$ to magnons generated in ADFMR. Figure 3.14c) shows the same measurement at the end of the Co patch. The beating and magnon contribution are still present, although in smaller amplitude than at the beginning of the Co patch.

The occurrence of a beating profile identifies the presence of at least 2 different k-vectors that interfere with each other, in contrast to the standing wave profile on LNO, shown in Fig. 3.14a). One reason might be the acoustic impedance mismatch presented for the traveling SAW by the Co. In the sample under test, the speed of a SAW on LNO is 3488 m/s, whilst in Co sound travels with a velocity of 4720 m/s [72]. Another reason may be simultaneous detection of a SAW k-vector and a spin wave k-vector, differing from the SAW due to the non-linear magnon dispersion relation [73]. In that context the more complicated profile in ADFMR conditions might stem from the excitation of a multitude of magnon modes at the SAW frequency, and thereby increasing the number of k-vectors that form the detected interference pattern. The shift of the peak position in ADFMR conditions is attributed to changes in Co crystal anisotropy in FMR, which influences the speed of sound and thus the interference pattern (FMR backaction [33, 38]). As for the strong
increase in magnon count near peak positions in contrast to no increase at all near valley points, we suspect the reason to be in different ellipticities along positions of the beating profile, similar to our observations in chapter 2.4.

It was expected to find magnon formation throughout the Co patch, gradually decreasing towards the end of the patch as the SAW loses energy to magnons, thermal excitations and air loading. Standing waves and beating were thought to only add a small contribution. Therefore, the large contribution of standing waves to the signal is an interesting discovery and indicates the rich physics involved.

A series of 16 similar line scans are summarized in Fig. 3.15, forming a heat map over external magnetic field and laser spot position along SAW propagation path. At each magnetic field, the Co edge is visible at $x = 2 \mu m$ by an increase in BLS count. Again, a beating profile with a periodicity of 12 $\mu m$ is observed with an increase in magnon count only at peak positions and not at valley points. The peak position continuously shifts with magnetic field strength in $x$, moving by approximately a total of 3 $\mu m$ from its position at $\mu_0 H_{ext} = 6$ mT to its position at $\mu_0 H_{ext} = 11.4$ mT. We attribute this to FMR backaction, further complicating the interference pattern. Figure 3.15b) shows the sum of normalized counts for every field subtracted by the sum at 11.4 mT with $\Delta \Sigma[A_{norm}^x] = \Sigma[A_{norm}^{11.4 \text{ mT}}] - \Sigma[A_{norm}^{\mu_0 H_{ext}}]$. The peak of magnon count lies in between 5.0 mT and 6.5 mT, which fits to results from chapter 2.4. To extend the field range, so that magnetic fields below and above ADFMR conditions can be measured, modifications of the BLS setup are required.

Fig. 3.15: a) Heat map of magnon-sensitive line scans for 16 external magnetic fields. Position of maximum shifts continuously with external magnetic field strength. b) Difference of summed signal over all positions $\Delta \Sigma[A_{norm}]$ vs. external magnetic field.

A series of 16 similar line scans are summarized in Fig. 3.15, forming a heat map over external magnetic field and laser spot position along SAW propagation path. At each magnetic field, the Co edge is visible at $x = 2 \mu m$ by an increase in BLS count. Again, a beating profile with a periodicity of 12 $\mu m$ is observed with an increase in magnon count only at peak positions and not at valley points. The peak position continuously shifts with magnetic field strength in $x$, moving by approximately a total of 3 $\mu m$ from its position at $\mu_0 H_{ext} = 6$ mT to its position at $\mu_0 H_{ext} = 11.4$ mT. We attribute this to FMR backaction, further complicating the interference pattern. Figure 3.15b) shows the sum of normalized counts for every field subtracted by the sum at 11.4 mT with $\Delta \Sigma[A_{norm}^x] = \Sigma[A_{norm}^{11.4 \text{ mT}}] - \Sigma[A_{norm}^{\mu_0 H_{ext}}]$. The peak of magnon count lies in between 5.0 mT and 6.5 mT, which fits to results from chapter 2.4. To extend the field range, so that magnetic fields below and above ADFMR conditions can be measured, modifications of the BLS setup are required.
3.5 BRILLOUIN LIGHT SCATTERING OF PHONONS AND MAGNONS

Fig. 3.16: a) $A_{\text{norm}}$ over $f_{rf}$ for two magnetic fields. Two measurements for each field monitors repeatability of the measurement. b) $\Delta A_{\text{norm}}$ vs. frequency, taken from the average values in figure a). At a constant laser position, signal increase for ADFMR measurement can change by $\Delta A_{\text{norm}} = 50$ depending on $f_{rf}$.

After using a line scan to find a position of high magnon formation (at $f_{rf} = 3.21 \text{ GHz}$), $f_{rf}$ can be varied at that position as seen in Fig. 3.16. Figure a) shows $A_{\text{norm}}$ for 6.5 mT and 11.4 mT, measured twice to monitor repeatability. Figure b) shows $\Delta A_{\text{norm}} = A_{\text{norm}}^{6.5 \text{ mT}} - A_{\text{norm}}^{11.4 \text{ mT}}$ over frequency $f_{rf}$. The plots reveal that signal increase in ADFMR is strongly dependent on $f_{rf}$ and can change drastically over 100 MHz. With the previous measurements this can be understood with the positions of beating peaks, which would change for even small differences of $f_{rf}$, and thus SAW frequencies, as constructive and destructive interference positions change. Repetition of the measurement shows near perfectly matching results.

Fig. 3.17: BLS laser spot positions for field sweep and line scan.

Field sweeps with $f_{rf} = 3.21 \text{ GHz}$ and with the laser spot positioned on a beating peak at the end of the Co film (see Fig. 3.17) show an intensity peak $\Delta A_{\text{norm}} = A_{\text{norm}}^{\mu_0 H_{\text{ext}} = 6.5 \text{ mT}} - A_{\text{norm}}^{11.4 \text{ mT}}$ around the expected $H_{\text{ext}} = 6.5 \text{ mT}$ for magnon-sensitive measurements, as seen in Fig. 3.18.
The reference value $A_{\text{norm}}^{11.4\,\text{mT}}$ is taken as the average from up and down sweep. For magnon-sensitive measurements a normalized magnon count of approx. $\Delta A_{\text{norm}} = 35$ is reached, whereas in phonon-sensitive measurements the normalized phonon count increases by 90 at 6 mT and drops to -55 at 7.5 mT. The stronger change in the count of phonons in comparison to magnons is expected, since phonon count is generally higher and the laser spot is positioned at the end of the Co film, where arriving phonons have already interacted with the Co film on the way, whereas magnons are created locally.

The increase of phonon count at 6 mT, however, is unexpected. We suspect the FMR backaction to be responsible. For a more distinct result, a comparison between magnon and phonon count over several laser positions is therefore more suitable.

![Fig. 3.18: Field up and down sweep for a phonon- and magnon-sensitive setup.](image1)

![Fig. 3.19: a) Line scans for two fields in a phonon- and magnon-sensitive measurement. b) $\Delta A_{\text{norm}}$ for the measurement results shown in a) with phonons represented by the red line and magnons by the black line.](image2)

Shown in Fig. 3.19a) is a line scan for phonon- and magnon-sensitive measurements at a laser position indicated in Fig. 3.17. Each scan is done for an external magnetic field inside and outside ADFMR condition. As expected, the phonon count is much higher (about a factor of 10) than the magnon count. Standing wavefronts are well visible, especially outside the ADFMR. Inside ADFMR, phonon intensity gets distorted and generally decreases. This is also visible in Fig. 3.19b), where the change of intensity $\Delta A_{\text{norm}}$ is plotted over position $x$ in the line scan. For phonons (red line) the signal decreases in ADFMR by an average of about -19.05. This amounts up to a relative change of phonon intensity of approx. $-14\%$, which fits well with our results in chapter 2.4, where a Co patch of the same length (500 µm) was used. Magnon count (black line) generally
increases in ADFMR with +3.56 magnon count on average. It is interesting to note that positions, where magnon count strongly increases also show a strong decrease in phonon count. This shows that the FMR is in fact acoustically driven, which was optically measured the very first time in this thesis.

3.6 Summary

In this chapter, the physics of Brillouin Light Scattering in section 3.1 and the measuring techniques were presented, including the working principles of a Fabry-Pérot interferometer (section 3.2), the expansion to a Tandem-Fabry-Pérot interferometer (section 3.3) and the description of the general micro focused BLS setup (section 3.4).

In section 3.5, we optically investigated SAWs for several samples in the gigahertz regime. In doing so, we confirmed the spatial resolution of the BLS setup and simultaneously found acoustic orthogonal modes in the SAW path. By using BLS area sweeps, we have shown that the SAWs of our IDTs are well confined. Adding an external magnetic field, we have optically found ADFMR with BLS at the pre-characterized field parameters. Furthermore, we discovered that magnon-phonon coupling in our SAW delay lines is extremely position dependent, with magnon formation not throughout the Co thin film but only at peak positions of a detected beating profile. Measurements showed that the position of maximum magnon intensity is dependent on the external magnetic field. We believe this to be due to FMR backaction and the excitation of several spin wave modes. Finally, we have shown that magnon detection increases where phonon intensity decreases, identifying the magnons as a result of ADFMR.

Our results represent the first optical measurement of ADFMR. The results reveal rich physics involved, which motivates further investigation of the subject.
4 Birefringence and magneto-optic Kerr effect

In this chapter, SAW delay lines with a Co thin film are measured using a Frequency Resolved Magneto-Optic Kerr Effect (FRMOKE) setup. The setup is capable of measuring SAWs via birefringence detection and FMR via the Magneto-Optic Kerr Effect (MOKE). First, we will explain the fundamentals of birefringence detection and MOKE, which will be followed by a presentation of the FRMOKE setup. Then, optical SAW measurements are shown. Finally, we investigate the influence of external magnetic fields on the optical signal.

While a distinction between phonon and magnon is not possible as it is in the BLS setup, the FRMOKE setup is phase-sensitive, which enables the detection of propagating wavefronts.

4.1 Birefringence

Birefringence is an optical property of a material for which the refraction of light depends on the light’s polarization and propagation direction [68]. While some materials, like calcite, are inherently birefringent due to their anisotropic crystalline structure, isotropic materials become birefringent as a result of physical stress. The source of that stress can be for instance a surface acoustic wave. Generally optical properties of a dielectric medium can be described with the relative permittivity (or dielectric constant) \( \varepsilon \). In non-magnetic materials, the connection between refractive index \( \tilde{n} \) and permittivity is given by [68]

\[
\tilde{n}^2 = \varepsilon = 1 + N \alpha \varepsilon_0. \tag{45}
\]

As given in Eq. (45), \( \varepsilon \) can also be understood as a measure of the number of induced dipoles per volume in the medium, denoted by \( N \), and their polarizability \( \alpha \). \( \varepsilon_0 \) is the vacuum permittivity. This shows the close relation between crystalline structure and optical properties of a material. In an isotropic medium the permittivity is a scalar, being the same for every spatial direction. In general, however, \( \varepsilon \) is a tensor

\[
\tilde{\varepsilon} = \begin{pmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\
\varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\
\varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz}
\end{pmatrix}. \tag{46}
\]

For simplification one can assume the medium to be non-absorbing (\( \varepsilon_{ij} \) real) and optically inactive (\( \tilde{\varepsilon} \) symmetric). Then the permittivity can be written in form of its principle axes, which leaves a diagonal

\[
\tilde{\varepsilon}_{PA} = \begin{pmatrix}
\varepsilon_1 & 0 & 0 \\
0 & \varepsilon_2 & 0 \\
0 & 0 & \varepsilon_3
\end{pmatrix}. \tag{47}
\]

With Eq. (45) this means \( \tilde{n}_1 = \sqrt{\varepsilon_1}, \tilde{n}_2 = \sqrt{\varepsilon_2}, \) and \( \tilde{n}_3 = \sqrt{\varepsilon_3} \). For isotropic materials \( \tilde{n}_1 = \tilde{n}_2 = \tilde{n}_3 \). In birefringent materials either one of the diagonal components is unique (\( \tilde{n}_1 = \tilde{n}_2 \neq \tilde{n}_3, \text{uniaxial} \)) or all three components are different (\( \tilde{n}_1 \neq \tilde{n}_2 \neq \tilde{n}_3 \neq \tilde{n}_1, \text{biaxial} \)).
In the example of a uniaxial crystal, we define an optic axis. Light with polarization perpendicular to the optic axis is governed by an ordinary refractive index \( \tilde{n}_o = \tilde{n}_1 = \tilde{n}_2 \), whereas light with polarization parallel to the optic axis will experience an extraordinary refractive index \( \tilde{n}_e \), which lies in between \( \tilde{n}_o \) and \( \tilde{n}_3 \) depending on the wave vector direction of light. This can be understood with the index ellipsoid: Drawing a vector \( \tilde{n} = \{ \tilde{n}_x, \tilde{n}_y, \tilde{n}_z \} \) into the principal axis coordinate system will form an ellipsoid

\[
\frac{\tilde{n}_x^2}{\tilde{n}_1^2} + \frac{\tilde{n}_y^2}{\tilde{n}_2^2} + \frac{\tilde{n}_z^2}{\tilde{n}_3^2} = 1, \tag{48}
\]

as illustrated in Fig. 4.1.

The magnitude of \( \tilde{n}_e \) depends on the wave vector’s angle to the optic axis \( \tau \) with \( \tilde{n}_o (\tau = 0^\circ) = \tilde{n}_o \) and \( \tilde{n}_e (\tau = 90^\circ) = \tilde{n}_3 \). A light ray that contains polarizations parallel and orthogonal to the optic axis will therefore split into two rays when entering a uniaxial crystal (double refraction): an ordinary ray governed by \( \tilde{n}_o \) that follows Snell’s law of refraction, and an extraordinary ray governed by \( \tilde{n}_e \) that additionally will experience a change of direction even if the angle of incidence to the surface normal is \( \psi = 0^\circ \). This is because, due to the relative permittivity being directional dependent, the direction of propagation ( = direction of the Poynting vector) is no longer the same as the direction of the wave vector if \( \tau \neq 0^\circ \). As each ray is governed by a different refractive index while passing through the material of thickness \( d \), behind it a phase shift \( \Delta \varphi \) will establish with

\[
\Delta \varphi = 2\pi \frac{d \Delta \tilde{n}}{\lambda}, \tag{49}
\]

where \( \Delta \tilde{n} = |\tilde{n}_o - \tilde{n}_e| \). Detection of the strength of birefringence, namely \( \Delta \tilde{n} \), lies therefore in measuring \( \Delta \varphi \) and the accompanying shift in polarization, which will be part of section 4.3.

### 4.2 Magneto-optic Kerr effect

The Magneto-Optic Kerr effect [74] is responsible for a polarization rotation of light that has been reflected from a surface with magnetic moment \( m \) [75]. It is closely related to the Faraday effect, in which the same rotation takes place but for light that travels through a medium while a magnetic field is applied. The Faraday effect was found by Michael Faraday in 1845. In 1877 John Kerr found the magneto-optic Kerr effect while he studied the polarization of light reflected from a polished electromagnet pole [74].

MOKE can be explained microscopically and macroscopically [75, 76]. Microscopically, the electric field of a light ray generates the motions of electrons in a medium that the light passes through. Circularly polarized electric fields drive electrons in the same circularly motion as that of the electric field. In the absence of a magnetic field the radius of the electron orbit is the same for right-circularly polarized light as it is for left-circularly polarized light. The presence of a mag-
netic field adds a Lorentz force that disrupts this symmetry. Is the direction of field parallel to the propagation direction of the light, the radius of the electron orbit increases for right-circularly polarization and decreases for left-circularly polarization. Thereby the Lorentz force changes the motion of electrons and with it the optical properties of the material. The source of the magnetic field does not need to be an applied external field, but can also be ferromagnetism of the material itself. Spin-orbit coupling then connects the magnetic and optical properties of the material.

Macroscopically, the magneto-optic effects stem from off-diagonal components of the permittivity tensor. Maxwell explains the rotation of polarization by different propagation velocities of the respective circularly polarization [77]. This leads to a phase shift that results in a rotated net polarization. The magnitude of polarization rotation is proportional to the magnetization of the material. Changes in the magnetization of the material, e.g., because of FMR, will result in different polarization rotations. FMR is therefore detectable by measuring variations in the polarization.

4.3 Experimental setup

![FRMOKE Setup](image)

**Fig. 4.2:** FRMOKE Setup. The setup is sensitive to both birefringence and magneto-optic Kerr effect.

In the following the FRMOKE setup, shown in Fig. 4.2, is presented. Similar to the BLS setup from chapter 3.4, LED light is added to a monochromatic laser beam (\(\lambda = 650\) nm) to create an image of the sample, detected by a CCD camera. The laser beam then passes through a polarizer \(P\) before it gets focused onto the surface of the sample. From the reflection the polarized laser beam splits into an ordinary and extraordinary beam with a phase shift \(\Delta \varphi\) as described in section 4.1. Additionally, a local magnetization rotates the polarization as described in section 4.2. The reflected beam gets then redirected by a beam splitter and passes through an analyzing polarizer \(A\). The polarization axis of the analyzer is rotated by 45° to the polarization axis of polarizer \(P\). That way the setup is at its maximum sensitivity towards changes of the polarization of the laser beam. Thereafter the laser light impinges on a photo detector with bandwidth of 30 GHz that connects...
to a VNA port. The other port of the VNA works as microwave output and is connected to one of
the sample’s IDTs. By using the VNA, the measurement setup has a frequency resolution of 1 Hz
and furthermore allows phase resolution. The sample is mounted on a stage with piezoelectric
motor control in all three spatial dimensions. An external magnetic field can be generated by an
electromagnet with a range of ±150 mT.

4.4 Optical detection of traveling magnetoacoustic waves

In this section, birefringence and magneto-optical effects are measured with the FRMOKE setup.
Results are presented for measurements of SAWs in form of 2D scans, frequency sweeps and line
scans. Finally, we show frequency sweeps for different external magnetic fields.

Figure 4.3 shows a 2D scan of a SAW passing through a 75 µm × 75 µm Co thin film, placed
approximately 500 µm behind the IDT. The color code indicates the real part of $S_{21}$ with maxima shown in red and minima in blue. The IDT creates an SAW of fundamental frequency $f = 0.85$ GHz and has a finger overlap $O = 50$ µm.

When the FRMOKE setup is used together with a VNA frequency sweep, the time gating algo-
rithm of section 2.2 can be applied. Shown in Fig. 4.4 are two frequency sweeps of the same
sample. For one sweep the VNA has been used for a SAW delay line as described in chapter 2
(black line) with VNA port 2 connected to a second IDT. The other sweep (red line) uses the
FRMOKE setup with the VNA port 2 connected to a photo detector. The laser spot is positioned
on the Co film in between the IDTs. Both measurements reveal the fundamental SAW and its higher harmonics. The highest frequency that the FRMOKE setup can display of this sample is approximately 2.56 GHz. Higher than that only spurious noise is recorded. We attribute this to the setup’s spatial resolution. In contrast to BLS spectroscopy, the spatial resolution limits the highest detectable SAW frequency (smallest SAW wavelength). Therefore in further investigation no frequencies higher than 2.56 GHz are used.

![Frequency sweep](image1)

**Fig. 4.4:** Frequency sweep of the same sample measured with a VNA as SAW delay line (black) and in the FRMOKE setup (red). Both plots show $|S_{21}|$. The maximum frequency detectable for this sample with FRMOKE is 2.56 GHz.

![Line scan](image2)

**Fig. 4.5:** Line scan across a Co film. The signal is plotted in $\text{Re}\{S_{21}\}$. Towards the SAW source the signal increases in an exponential fashion, but with distorting beating and stronger signal detection at the cobalt edges.

In a line scan across a 500 µm long Co film, we study the SAW decay with the FRMOKE setup. The VNA generates a continuous wave with $f = 1.94$ GHz matching the IDT design of this sample. The result is shown in Fig. 4.5 with the SAW signal plotted as real part of $S_{21}$. Generally, the signal increases in an exponential fashion towards the SAW source. However, features resembling acoustic beating distort a clean exponential decay of the SAW with propagation distance. Furthermore, at the beginning of the Co patch a stronger signal is recorded. We suspect both observations to originate from interference effects, as discussed in chapter 3.5.
Finally, we want to investigate the influence of an external magnetic field $H_{\text{ext}}$. The sample is positioned such that the SAW propagation direction lies at a $15^\circ$ angle to the external magnetic field $H_{\text{ext}}$ ($\phi = \angle (k_{\text{SAW}}, H_{\text{ext}}) = 15^\circ$).

Then a VNA pre-characterization at center frequency $f = 1.9$ GHz is performed as described in chapter 2.4, with the difference that here the second SAW transit with reflection parameter $S_{11}$ is used. In that way, simultaneous ADFMR detection by microwave and optical spectroscopy is possible. The results of the microwave spectroscopy are shown in Fig. 4.6.

At small magnetic fields ($|\mu_0 H_{\text{ext}}| < 10$ mT) resonance-like features are observed and attributed to ADFMR.

Frequency sweeps obtained using the same sample are shown in Fig. 4.7. The plot in Fig. 4.7a) shows microwave spectroscopy results obtained by connecting the two IDTs to the two ports of a VNA. The central frequency is at approximately 1.9 GHz. FRMOKE measurements with two different magnetic fields are shown in Fig. 4.7b). At $\mu_0 H_{\text{ext}} = 8$ mT, which lies in the expected FMR region from Fig. 4.6, the measured magnitude is more than 3 dB stronger than at a field far out of FMR conditions at $\mu_0 H_{\text{ext}} = 50$ mT.

Additionally, we observe a shift in center frequency of the FRMOKE measurements if compared
to the VNA measurements. For both values of the external magnetic field the center frequency decreased. For the 50 mT measurement the center frequency shifts by approximately 25 MHz, for the 8 mT measurement by 50 MHz. These shifts were not observed in VNA measurements without FRMOKE. At this point not enough data has been collected to draw conclusions of the physics involved. We suspect that besides magneto-optic effects also FMR backaction and magnetostriction induced by the external field may affect the measurement results. Furthermore, local heating due to the laser beam cannot be ruled out either. Further investigation is necessary to fully characterize the influence of external magnetic field and verify the possible optical detection of ADFMR.

4.5 Summary

In sections 4.1 and 4.2, the fundamentals of birefringence and the magneto-optic Kerr effect were laid out respectively. In section 4.3, the FRMOKE setup and its working principles were presented. Our measurement results are given in section 4.4. Spatial scans show propagating SAWs with small dispersion at 0.85 GHz SAW frequency. At 2.9 GHz no SAW signal could be detected anymore. Line scans across a 500 µm Co thin film reveal an exponential decay of the SAW signal with additional beating. A first magnetic field dependent frequency sweep shows a higher FRMOKE signal at the pre-characterized ADFMR conditions than outside of ADFMR conditions. Further investigation is necessary to constitute detection of magnon-phonon coupling with FRMOKE, including thorough position dependent measurements as its importance has been shown in chapter 3.
Summary and conclusion

In this thesis, Acoustically Driven FerroMagnetic Resonance (ADFMR) measurements were conducted with self-fabricated high frequency Surface Acoustic Wave (SAW) delay lines loaded with a cobalt thin film. Three different measurement setups were used to characterize magnon-phonon coupling. In this chapter, we briefly summarize the measurements of each setup, followed by a conclusion of our results.

In chapter 2, we used a Vector Network Analyzer (VNA) for microwave spectroscopy measurements of SAW delay lines. First, we optimized our InterDigital Transducers (IDT) with respect to substrate, delay line alignment, metallization ratio, number of IDT finger pairs, and finger overlap. Calculations for transconductance transfer and insertion loss were performed for interpretation of the measurement data. We then expanded the setup for field dependent measurements with angular resolution. We presented results for Co on a 0° oriented YZ-Cut LiNbO₃ (LNO) substrate and a 128° Y-Cut LNO, where the different crystalline structures of the two substrates provide different SAW shear strain components. For both substrates multiple phonon frequencies were measured with up to 5.95 GHz for 0° LNO. Results were compared to simulations based on a model using a Landau-Lifshitz-Gilbert (LLG) approach.

In chapter 3, we optically measured phonons and ADFMR generated magnons with spatial resolution, using Brillouin Light Scattering (BLS). By adjusting a λ/2 plate, phonon-photon and magnon-photon scattering processes can be distinguished. Spatial resolution limits of the setup were confirmed with 2D sweeps and line scans. We then measured magnon intensity with respect to rf source frequency, external magnetic field and measurement position, and compared these results to phonon intensity.

In chapter 4, SAWs were detected with spatial and phase resolution in a Frequency Resolved Magneto-Optic Kerr Effect (FRMOKE) setup. We performed 2D sweeps, frequency sweeps and line scans. Finally, frequency sweeps were conducted inside and outside of ADFMR conditions.

The goal of this thesis was to characterize magnon-phonon coupling using frequencies that go beyond previous work on ADFMR and utilizing optical measurement setups to obtain spatial resolution. By achieving this, we discovered intricate interactions between traveling phonons and magnons that have not been studied before. In this regard we want to emphasize three major achievements of this thesis:

Characterization of IDT design
As SAWs represent the fundamental ingredient of ADFMR, control over their generation is of utmost importance. In the process of IDT optimization, we were able to establish a detailed characterization of IDT design parameters and their influence on SAW signal magnitude. Our measurement results confirm calculations on impedance matching and transconductance transfer. Besides reaching SAW frequencies above 13 GHz, this also enables us to design optimized IDTs for specific SAW frequencies. We believe this new level of control on IDT design will benefit future investigations of ADFMR.
Influence of SAW shear strain components

In expanding the range of SAW frequency for ADFMR, we were able to study the effect of shear strain components on ADFMR. We found that shear vertical strain components break the conventional four-fold symmetry of ADFMR, reducing it to point symmetry. Thereby, our samples gain characteristics of acoustic diodes, attenuating SAWs traveling in a specific direction stronger than those traveling in the opposite direction. This establishes non-reciprocal magnon-phonon coupling due to magnon and phonon ellipticity and chirality.

Additionally, in performing the first ADFMR measurements on 128° Y-Cut LNO with angular resolution, we observed that further symmetry breaking occurs in the presence of shear horizontal strain components and uniaxial in-plane anisotropy field components perpendicular to the SAW propagation direction. Simulations based on a LLG approach \[33\] reproduce experimental data for 0° LNO very well and can explain the main characteristics for 128° LNO. Our results increase our understanding of magnon-phonon coupling and open exciting perspectives for the technological implementation of acoustic diodes in the gigahertz frequency range.

Spatially resolved magnon detection in optical measurements

Our results represent the first optical measurements of ADFMR and allow us to characterize magnon-phonon coupling with spatial resolution. The optically detected ADFMR is compatible with our microwave spectroscopy results, but reveals an unexpectedly complex spatial dependence of the magnon-phonon interaction. This is attributed to the formation of standing acoustic waves and acoustical excitation of propagating magnons with a range of wave vectors.

Furthermore, the optical measurement setup allowed us to independently detect phonons and magnons, whereas previous work on ADFMR was only sensitive to phonons launched and detected by IDTs. We have shown that local magnon creation is accompanied with a reduction of phonon number, demonstrating that the FMR is indeed acoustically driven. Our results inspire future research on ADFMR in spatially confined magnonic waveguides.
Outlook

The results of this thesis motivate further research in the field of ADFMR on several different levels. In the following, we give an outlook on possible future directions for measurements on magnon-phonon coupling.

IDT optimization

One way to expand our measurements on ADFMR is by generating stronger signals and higher SAW frequencies. For this, multiple possibilities exist, ranging from environmental to design changes.

In chapter 2.3, we have discussed exponential decay of SAW signal magnitudes over frequency, due to interaction with thermally excited elastic waves and losses to air adjacent to the surface (air loading) [57]. Measurements conducted at low temperature and low pressure are therefore expected to yield stronger signals and thereby higher frequencies. At low temperature, superconducting IDTs (made from aluminum or niobium) can be used, which removes the contribution of ohmic losses to the total IDT insertion loss and might also allow for the generation of more homogeneous SAW wavefronts. With an optical cryostat, these properties are also available for FRMOKE and BLS measurements.

Another approach for signal maximization is the exploitation of constructive interferences with SAW resonators [41], which might allow us to study magnon-phonon coupling in the strong coupling regime. First SAW resonator designs have already produced promising results, as seen in Fig. 4.8. 132 Al stripes were placed directly behind the IDT as well as in 1 mm distance to reflect the SAW. The IDT has not been fully optimized in regard to impedance matching and the resonator has not been adjusted for maximum constructive interference. Still, multiple transits of the SAW are visible in Fig. 4.8. The 16th transit of the fundamental 1.83 GHz signal is well visible without decline in signal-to-noise ratio. Using Eq. (18), the quality factor of this acoustic resonator is approximately $Q = 200$. With high amplitude standing waves, resonator designs are especially useful for intensity based measurements setups, e.g., BLS. However, since acoustic
resonators do not perform well for higher harmonics, the necessary fabrication of IDTs with high fundamental frequencies may prove to be challenging.

Finally, altering the IDT concept might be beneficial. Several designs for IDT finger arrangement are possible, e.g., using double- [40] or triple-split [78] IDTs. In a first investigation we have fabricated double-split and split-52 [79] IDTs, as seen in Fig. 4.9. Signals for the double-split IDTs reach above 10 GHz in our first attempted design, while the signals of split-52 IDTs generate SAWs with relatively low FWHM, fulfilling their design purpose [79]. We therefore see potential in both IDT concepts. Due to the bidirectional behavior of IDTs, an insertion loss of 6 dB is inevitable in standard SAW delay lines. Implementing the design of unidirectional transducers from recent publications [80] can reduce these losses.

![Double-split and Split-52 IDTs](image)

**Fig. 4.9:** Signal magnitudes and concepts for double-split and split-52 IDTs.

In recent publications, circular IDT finger designs have been used to create a SAW focal point [81, 82]. Combining this SAW channeling with optical measurements and a ferromagnetic thin film at the focal point may open a pathway for the detection of nonlinear magnon-phonon coupling.

**Microwave spectroscopy**

Compared to optical measurement setups, microwave spectroscopy remains a convenient and powerful measurement method, which has produced important results on magnon-phonon coupling in earlier research on ADFMR as well as in this thesis.

As demonstrated in chapter 2, the expansion to higher frequency ADFMR with microwave spectroscopy still uncovers novel aspects of the rich physics involved. In this context, the capabilities of our IDT designs to generate SAWs near 14 GHz (see Fig. 2.13), have not yet been taken full advantage of. ADFMR measurements at 10 GHz and above should be easily accessible if the dynamic range of the measurement can be increased by use of suitable microwave amplifiers.
In chapter 2.4, it was shown that SAW shear strain components introduce a breaking of the conventional four-fold symmetry of ADFMR. This effect increases with frequency. To further investigate and have control over this phenomenon, future research needs to systematically study the influence of different shear components, so that eventually an acoustic diode can be fabricated in a simple on-chip design. As mentioned earlier, we recommend an investigation concerning the components’ dependence on ferromagnetic thin film thickness. Besides working with the piezoelectric substrates used in this thesis and various SAW delay line alignments, e.g., ADFMR in 90° YZ-Cut LNO, also other substrates should be taken into consideration that yield different shear strain components. Examples include the materials LiTaO$_3$ and especially quartz, with high shear horizontal strain components for the generation of Love waves. Both materials are often utilized in the field of biosensors [83–85].

Fig. 4.10 shows a simulation of a 10 GHz ADFMR, based on our results in section 2.4. The ratio between compressional wave and shear vertical wave has been selected to simulate optimum acoustic diode behavior, with $|\varepsilon_{xx}/\varepsilon_{xz}| = 20$. The magnitude of SAW attenuation is easily scalable by the length of the ferromagnetic thin film (see Eq. (27)). Deposition of an additional antiferromagnetic material as pinning layer on top of the ferromagnetic thin film could further simplify the application of the acoustic diode by providing an exchange bias that substitutes external magnetic fields.
Optical Measurements

The spatial resolution in optical measurements allow for a variety of further investigation, concerning magnon-phonon coupling.

Subsequent to our measurements, in both BLS and FRMOKE setups, we suggest conducting similar experiments to gain a broader data set that helps drawing a clearer picture of the involved interactions. Specifically, this means to extend the number of ADFMR frequencies, substrates, magnetic field range, etc. While the FRMOKE uses an electromagnet for field generation, the current BLS setup works with permanent magnets. Replacing the permanent magnets with a 2D electromagnet would allow for angular resolved ADFMR measurements, covering the full range of ADFMR conditions. Furthermore, by changing the polarity of the external magnetic field, asymmetries in ADFMR features could be investigated.

In regard to ADFMR frequency, the issue of limitations in detection due to the laser wavelength remains. Using lasers of smaller wavelength increases the available frequency range accordingly. Additionally, using materials with smaller saturation magnetization as Co, e.g., nickel \[31,33,38\], ADFMR measurements at lower frequencies are likely to improve in regard to FMR signals. A similar approach can be done by changing the external magnetic field direction from an in-plane alignment to out-of-plane (OOP), as OOP FMR features occur at higher field values, thereby saturating the magnetization of the thin film at lower frequencies [38].

In chapter 3.5, the distortion of the beating profile inside ADFMR conditions was attributed to excitation of multiple magnon modes at the SAW frequency. Designing nanoscale patterns for the ferromagnetic thin film counteracts the broadened excitation spectrum by spatially limiting the allowed magnon modes. Furthermore, by choosing more sophisticated patterns for the ferromagnetic thin film, spatially dependent interactions can be investigated. One example is the deposition of periodically patterned ferromagnetic films to study effects of longer range, as e.g., dipole-dipole interactions. As the magnetization in an arrangement of ferromagnetic stripes can favor antiferromagnetic ordering, ADFMR in antiferromagnetic systems would be approached.

Finally, interesting experiments can be conducted with time resolved optical measurement setups. In that context, different rf pulses and their effects on ADFMR profiles represent a promising research direction. One possible phenomenon that can be thereby detected, is the spin-Cherenkov effect, which so far only exists in theory [86]. Similar to the Cherenkov effect in particle physics, it describes the spontaneous emission of radiation (i.e. magnons) from a source (i.e. phonons) that travels faster through a medium than the propagation speed of the fundamental wave excitation of this medium [86]. First initiatives have already been made to collaborate with research groups for Time Resolved FerroMagnetic Kerr Effect (TR-MOKE) measurements.
Appendix

A) Fabrication details
Further details on the sample fabrication are as follows:

Substrate:
- Black LiNbO$_3$ by Roditi International Corporation
- Single side polished
- Dimensions: 10 mm × 6 mm × 0.5 mm

Spin coating
1. Applying PMMA/MA 33% resist layer ‘AR-P 617.08’ by Allresist GmbH, spin coated at 8000 rpm for 1:10 min.
2. Removing surplus PMMA on LNO backside with acetone.
3. Baking on hot plate at 170°C for 2:00 min.
4. Applying conductive resist (CR) layer ‘SX AR-PC 5000/90.2’ by Allresist GmbH, spin coated at 4000 rpm for 2:00 min.
5. Removing surplus CR on LNO backside with water.
6. Baking on hot plate at 90°C for 2:00 min.
7. Applying gold nanoparticles along 6 mm substrate edge for focusing.

Electron beam
- Beam current: 2.5 - 2.7 nA
- Beam voltage: 80 kV
- Datum step: 7
- Beam landing: vertical
- Dose = 2.2 C/m$^2$ (patches) and 2.75 C/m$^2$ (fingers), step 5 nm

Development
1. Removing CR with water.
2. Development of PMMA/MA 33% with developer ‘AR 600-56’: Holding sample for 2:00 min in developer with magnetic stir bar causing flow at 500 rpm.
3. Removing developer by washing off with IPA for 10 s.
4. Drying with N$_2$ jet.
Deposition

1. Depositing 70 nm thick aluminum layer in EBPVD.
2. Depositing 5 nm thick titanium layer in sputter chamber.
3. Removing rest of resist in 70°C acetone. Support is given by ultrasound bath on the lowest level.
4. Removing acetone with IPA. Dry with $\text{N}_2$.
5. For additional cobalt thin film (thickness: 20 nm), all steps are repeated. For design alignment, marking the substrate edges in the e-beam at the exact same position is sufficient (comparison is provided by previously taken screenshots).

B) Sample list

The following table shows the complete sample list of this thesis. Every sample is self-fabricated.

Abbreviations for sample list:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT</td>
<td>Dose Test</td>
</tr>
<tr>
<td>DL</td>
<td>SAW delay line</td>
</tr>
<tr>
<td>R</td>
<td>Resonator</td>
</tr>
<tr>
<td>R+DL</td>
<td>SAW delay line with additional acoustic reflectors</td>
</tr>
<tr>
<td>$f_1$</td>
<td>fundamental frequency (in GHz)</td>
</tr>
<tr>
<td>Name</td>
<td>Substrate</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>CM191016_1</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM191016_2</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM191016_3</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM191016_4</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM211016_1</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM211016_2</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM211016_3</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM081116_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM091116_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM091116_2</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM111116_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM221116_1</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM221116_2</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM281116_1</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM281116_2</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM281116_3</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM301116_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM081216_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM081216_2</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM081216_3</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM081216_4</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM081216_5</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM191216_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM191216_2</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>Name</td>
<td>Substrate</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>CM050117_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM050117_2</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM050117_3</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM050117_4</td>
<td>YZ-LNO, 0° &amp; 90°</td>
</tr>
<tr>
<td>CM170117_1</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM170117_2</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM170117_3</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM_Co260117</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM300117_1</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM300117_2</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM300117_3</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM300117_4</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM300117_5</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td></td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM060217_1</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM060217_2</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM020517_1</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM020517_2</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM020517_3</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM020517_4</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>Name</td>
<td>Substrate</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------</td>
</tr>
<tr>
<td>CM110517_1</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM110517_2</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM110517_3</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM110517_4</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM230517_1</td>
<td>YZ-LNO</td>
</tr>
<tr>
<td>CM230517_2</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM230517_3</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CM230517_4</td>
<td>LNO, 128°</td>
</tr>
<tr>
<td>CS210617_1</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CS210617_2</td>
<td>YZ-LNO, 90°</td>
</tr>
<tr>
<td>CM290717_1</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM290717_2</td>
<td>YZ-LNO, 0°</td>
</tr>
<tr>
<td>CM290717_3</td>
<td>YZ-LNO</td>
</tr>
</tbody>
</table>
References


Acknowledgment

At this point, I would like to thank several people, who contributed directly or indirectly to this Master's thesis.

Prof. Dr. Rudolf Gross, for giving me the opportunity to conduct research at the Walther-Meißner-Institute. I have enjoyed the provided support ranging from access to sample fabrication facilities over various measurement setups and his great pool of knowledge. I'd also like to mention that his well-written scripts have fueled my interest in condensed matter physics and spin dynamics.

Dr. Mathias Weiler, for his general guidance throughout this thesis. After each discussion, measurement results were better understood, future steps were clearer and I myself was freshly motivated. His university lectures strengthened my interest in magnetism and spin dynamics, which has only increased over this past year.

Stefan Klingler, for his introduction to sample fabrication and VNA measurements, but especially his support concerning the BLS setup.

Dr. Hans Hübl, for his experienced input in weekly meetings and his general organization around the institute, including measurement instruments and the Walt(h)er seminar.

Daniel Schwienbacher, for his help around the e-Beam and the field dependent VNA setup.

Stefan Mändl, for the introduction and general administration of the BLS setup.

Dr. Matthias Pernpeintner, for his patient explanations of lithography steps and structure design.

All the people of the Walther-Meißner-Institute, for providing mutual help and a light and friendly atmosphere. This especially applies to Petio Natzkin and Sarah Gelder, with whom I've always enjoyed our coffee breaks and the casual chit-chat.

My girlfriend Birte, for her support not only during the period of my Master's thesis but throughout all of our time in university.

My special thanks to my parents, for support throughout my whole life, providing me with everything I've ever needed. I greatly appreciate what they have done for me. I also acknowledge their patience while listening to me when I forgot myself and talked about physics.