Sources of error in a Faraday magnetometer for magnetic microstructure analysis

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Abstract. In this work we examine a Faraday magnetometer built for microstructure analysis. We single out sources of error and quantitatively evaluate their effect on the measurement process. From this we derive a generalised estimation concerning temporal, spatial and amplitude resolution. We point out where the examined setup can be improved, but also where the limits of feasibility of a Faraday magnetometer as a means of measuring magnetic microstructures lie.

1. Introduction
A relatively inexpensive way to encode information on a small area is by using magnetic structures of varying magnetisation. This technique can be found on magnetic stripe cards or banknotes, for example. Depending on the implementation, the structure size can be well below 100 µm. In order to visualise and qualitatively evaluate the magnetic fields caused by these magnetic microstructures, magneto-optical magnetometers based on the Faraday effect have shown good results as they work contactless and can operate at high speeds [1]. In order to find the constraints regarding amplitude and spatial resolution as well as acquisition speed for the usage of a Faraday magnetometer as a means of quantitative high-speed measurement of magnetic microstructures, a thorough calibration of the setup is needed.

2. Theoretical background and overview over setup
The Faraday effect describes the angular change of the polarisation plane of linearly polarised light passing through a magneto-optically active medium when this is subjected to a magnetic field. The angular displacement is proportional to \( H_L \) - the component of the magnetic field parallel or antiparallel to the light propagation direction -\( \), the thickness \( d \) of the medium and its Verdet constant \( V \).

The Faraday effect is the basis of a magneto-optical magnetometer as shown in Figure 1. This setup allows to determine the strength of magnetic fields by measuring changes in light intensity. Light is initially polarised with a polarisation filter. It then travels through a reflective coated Faraday crystal twice thus rotating the polarisation plane by an angle corresponding to double the thickness of the crystal. Before being captured by the camera, it is propagated through an analyser. The two polarisers are installed at a 45° angle in order to maximise the setup’s sensitivity to angular changes.
Our implementation of such a Faraday magnetometer yielded to singling out and quantifying possible sources of error as well as finding its overall limitations as a device for fast, precise and localised magnetisation measurements. The setup is built using a tubular system by Qioptiq as it offers good shielding against potentially interfering ambient light. The utilised light source is a high-power LED with a wavelength of 585-595 nm. We chose this wavelength on account of the crystal’s high sensitivity in this range. The LED is cooled passively to minimise temperature drift of the intensity and the wavelength - however, for precise measurements the temperature should be set to a fixed value using a control system. As magneto-optically active medium we used a Bismuth substituted Yttrium Iron Garnet (Bi:YIG) crystal by Matesy as it has an exceptionally high Verdet constant of $2.5 \times 10^6$ rad/Tm. Its suggested range of usage is within -2 and 2 kA/m. The monochromatic camera by Allied Vision has a 2.2 Megapixel CMOS-Sensor with a 12-Bit-ADC and a maximum framerate of 49.5 fps. Lastly, in order to characterise the setup, we subjected the crystal to a well-defined magnetic field using a Helmholtz coil arrangement.

3. Characterisation of setup
The characterisation mainly concerns the camera and optics as well as the crystal. Further analyses of these components but also of the LED and the Helmholtz coil are of interest, but have not been considered at this stage.

3.1. Characterisation of camera and optics
In [2] the author stated that the camera’s short-term temperature-dependence and to a similar degree the ratio of defective to functioning pixels can be neglected. Therefore, we concentrated on the SNR of the optical system for various exposures. As exposure is correlated to exposure time as well as illuminance, both would be viable candidates for modification in order to achieve different exposures.

Illuminance on the camera’s sensor could be altered by changing the magnification, the LED’s intensity or the filtering steps. As for the magnification, if the presented system is set up for magnification rather than 1:1-mapping, the illuminance uniformity decreases drastically. This means, that in order to avoid saturation of any pixel the achievable mean luminous exposure also decreases. We therefore kept the mapping at a 1:1-ratio. However, microscopic mapping – by turning the objective around – might also yield interesting results in the future. Same goes for changes in the LED’s intensity and of the filtering steps. This notwithstanding, we deemed those too prone to additional errors at the current state of the setup. For these reasons, we opted for the exposure time as the variable with which we influenced the exposure.
3.2. Characterisation of the crystal

In order to measure the magnetic properties of a material one potentially has to take its hysteretic behaviour into account. In the presented Faraday magnetometer, the crystal also shows hysteretic behaviour when subjected to an external field. This has to be considered and therefore characterised additionally. However, due to the existence of magnetic domains within the material, the behaviour is significantly different when viewed microscopically rather than macroscopically.

When the magnetisation of the crystal is averaged over the whole crystal, it shows a relatively smooth hysteretic behaviour close to its production specifications. Yet, even within the suggested range of usage, the crystal still has a clear hysteretic behaviour (Figure 2a). For a sample analysis this is unfavourable and so we restricted the range of usage to -1 to 1 kA/m, where the intensity hysteresis is negligible (Figure 2b). Figure 2b also shows the 95% confidence interval, which is about ±0.05° or ±3% of the maximum value.

![Figure 2a. Magnetisation behaviour of the crystal for a maximum field of 2 kA/m.](image1)

![Figure 2b. Magnetisation behaviour and 95% confidence interval of the crystal for a maximum field of 1 kA/m.](image2)

We additionally observed a time-dependent offset of the rotation, where the angular change roughly decays exponentially and after five hours reaches about -0.8°. At this stage we attribute this to a long-term temperature-drift of either the LED or the camera, but further investigation is necessary.

![Figure 3a. Magnetic pattern of crystal (left) at 0 kA/m and its spatial spectrum (right).](image3)

![Figure 3b. Magnetic pattern of crystal (left) at 2 kA/m and its spatial spectrum (right).](image4)
When observed in a sufficiently small area, the magnetisation behaves discontinuously due to the domain walls and their movement. The domain walls themselves show a stripy pattern. The exact pattern may change from crystal to crystal [3], but the structure size – i.e. the line width – shows little variation for a given external field. To illustrate this, the pattern and its spatial spectrum are shown in Figures 3a and 3b for two different external fields strengths respectively. It’s visible that the structure size shows little variation for a given external field and increases as the external field increases.

However, the domain wall’s exact position in dependence of the external field is not precisely reproducible and shows statistical behaviour. It is possible, though, to define an observation unit of an arbitrary size and empirically determine its degree of certainty, which ultimately corresponds to the comparison between spatial and amplitude resolution. We chose square observation units in order to have an analogy to the camera’s pixels.

4. Results and discussion
Given the analyses of the camera’s and optics’ as well as the crystal’s behaviour we can determine the interdependence of amplitude and spatial resolution as well as exposure time – and therefore acquisition speed. Figure 4 exemplarily shows the constraints of the amplitude resolution w.r.t. spatial resolution and exposure time. The amplitude resolution w.r.t. the spatial resolution was recorded at a seven times magnification to allow for better spatial understanding, while w.r.t. to the exposure time it was recorded at a 1:1-mapping to achieve the aforementioned uniform illuminance. In the latter case the measurement results were smoothed. For the purposes of this figure we chose the external field to be zero. It has to be noted, though, that this is does not generally serve as a suitable model. As shown in the Figures 3a and 3b, the external field also has to be considered, as with it the structure size increases and the spatial resolution decreases. For a measurement with a multitude of local field strengths – as it is expected when analysing magnetic structures – the weigh-up between amplitude and spatial resolution has to go by the highest field strength as it shows the most restrictive behaviour.

As expected the amplitude resolution improves with higher exposure time as well as size of the observation unit. Additionally, the structure size and regularity is hugely influential on the amplitude resolution, especially when the observation unit is very small.

![Figure 4](image-url)

**Figure 4.** Amplitude resolution as a function of observation unit size and exposure time.

**References**
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