The magneto-optical response of two Faraday crystals from Matesy: a case study

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Abstract. This work analyses two Faraday crystals from the company Matesy to elucidate how their differences compromise experimental results for quantitative magnetometry. Our results show that the two crystals have different domain patterns and different hysteresis loops under the influence of a homogeneous magnetic field, which point to the importance of considering carefully the crystal selection and their individual characterization for its successful implementation in a magneto-optic measurement setup.

1. Introduction

Magneto-optical magnetometers based on the Faraday-effect are popular nowadays because they can be used as an effective method to visualize and qualitatively evaluate magnetic fields. A further step in the application of the Faraday-effect is to use it for quantitative measurement of magnetic fields. This is of interest considering the advantages of a magneto-optical setup with the Faraday crystals available today because one can obtain high sensitivity response at very fast speed and with no contact with the measured media.

The Faraday crystals produced by Matesy are composed of Bismuth substituted Yttrium Iron Garnet (Bi:YIG), which is one of the most characterized ferrimagnetic material available and used in magneto-optic measurements. The company Matesy is, perhaps, the only one worldwide delivering crystals with very high sensitivity (Verdet constant) of the order of $150 \times 10^6 \degree/Tm$.

A recent paper [1] studied the structural and compositional inhomogeneities in Bismuth-substituted rare earth iron garnet films and its authors found through high resolution X-ray diffraction techniques that there exist variations in the lattice parameters between the top and the bottom of the film, which changes the magneto-optical properties of the layer. The authors in [1] suggested that crystals with such structural anomalies could compromise experimental results if they are used as magneto-optic sensors.

The quantitative analysis of magnetic fields in a Faraday magnetometer can be obtained through the calibration of the rotation angle of the polarized light passing the Faraday crystal, which is related to the intensity contrast of the resulting image. Nevertheless, several critical issues should be addressed carefully before getting measurements with good accuracy. It is the aim of this paper to highlight the importance of individual characterization and prior knowledge of the response of the Faraday crystal for the correct implementation of a Faraday magnetometer.
2. Materials and method

A Matesy type A Faraday crystal from the company with dimensions of 1.5×1 cm$^2$ was obtained for the development of a Faraday magnetometer. Additionally, a MagView unit from the same company was already available at the institute. The MagView includes a crystal of the same type and with dimensions of 2×1.5 cm$^2$, which was removed from the MagView device for the experiments. According to the information supplied by the company Matesy their A type crystal should be used in the linear range from 0.05 to 2 kA/m with a calibrated sensitivity slope of 2°/kA/m. The saturation of Faraday rotation is specified to be about 8°, which is obtained at 3.5 kA/m. For the sake of clarity, we will denote both crystals from now on as small (SC) and large (LC), respectively.

The measurement setup was built with the possibility to obtain a 1 to 1 image of the crystal and a 7x magnification through a slight variation by introducing an extension tube between the camera and the objective. A detailed description of the Faraday magnetometer used in this work is described in another paper of the authors presented at this conference [2]. The magnetic responses of both crystals were studied with the help of a pair of Helmholtz coils that were placed in the optical path assuring that the analysed crystal is in the homogeneous magnetic field area. A monochromatic Mako G-223 B/C camera from Allied Vision with a resolution of 2048 (h) by 1088 (v) pixels was used as recording device. A set of 100 images were taken and averaged for every value of applied magnetic field in the Helmholtz coils to cope with the noise of the camera experienced.

3. Results and discussion

Figure 1 shows the average hysteresis loops of both crystals in the first quadrant. These loops were obtained by averaging the values of all pixels from the camera. An external magnetic field up to 4 kA/m was applied to guarantee magnetic saturation. The vertical line at 2 kA/m was traced to mark the upper value of the measurement range proposed by Matesy. We have marked three distinctive regions denoted as A (0-1 kA/m), B (1-2 kA/m), and C (2-4 kA/m).

![Figure 1. Average hysteresis loops of the Faraday crystals SC (left) and LC (right).](image)

It is remarkably clear in Figure 1 that the macroscopic behaviour of both crystals differs dramatically even though they are delivered as the same type. A comparison between each region of both loops reveals that in region A the LC crystal has a nonlinear response due to hysteresis, which seems not to be the case for the SC crystal. In region B, differences in the inner area of the loops are evident, which should be related to magnetic losses. Regions A and B are within the proposed (by Matesy) measurement range for the A type crystal and the results presented in Figure 1 clearly suggest that the actual working range should be considered with concern. In region C two main differences are visible in the inner area of the loops and around saturation, but the most valuable information here is that both crystals approach saturation around 6°, indicating that the reported sensitivity is not correct. The qualitative analysis of the hysteresis loop shed light on the differences of these two crystals, and these differences could be related to the structural and compositional anomalies as suggested in [1].
The magnetic response of both crystals was obtained experimentally by applying a magnetic field from 0 to 2 kA/m to study the linear range only. Figure 2 shows the resulting average hysteresis loops of both crystals with a quasilinear response in the working range showing also hysteresis. The sensitivity of the crystal can be estimated roughly by a linear approximation over the entire range of applied magnetic field. For the SC and LC crystals, the sensitivities are about 1.3 and 1.7 °/kA/m, respectively, which represent a striking difference of 23%. If one considers that the reported Verdet constant of this type of crystal is $150 \times 10^6$ °/Tm, then the sensitivity difference between both crystals is of the order of $35 \times 10^5$ °/Tm, a value prohibitively high. It is important to note the error due to hysteresis in both crystals from the curves presented in Figure 2. Even though the values are different, the most critical issue is that the hysteresis uncertainty increases proportionally with the magnitude of the external magnetic field. Therefore, if the response of the crystal presents such problems the resolution of the magnetic field to be sensed could be compromised if one assumes a linear response.

Figure 2. Average hysteresis loops of the Faraday crystals SC (left) and LC (right).

Figure 3. Four snapshots (about $137 \mu m \times 322 \mu m$) of the SC crystal at four different values of external magnetic field during the magnetization from 0 to 4 kA/m.

To understand the differences of both crystals as shown previously in Figure 1, the measurement setup with a 7x magnification was used for a qualitative evaluation of the magnetic domain structure. The images were recorded from an approximately 0.042 mm$^2$ evaluation area in the centre of the crystals.

Figure 3 shows a snapshot sequence of the SC crystal during the magnetization from the demagnetized state (upper left) to saturation (lower right). It clearly shows that the SC crystal predominantly shows a pattern of parallel band magnetic domains. There is almost no change in the domain pattern from -1 A/m to 1989 A/m, whereas for a smaller increment from 1989 to 2534 A/m most of the light-coloured domains grow at the expense of the dark ones and only a few dark domains remain. At saturation, the result is as expected showing a homogeneous image.
Figure 4. Four snapshots (about 137 µm × 322 µm) of the LC crystal at four different values of external magnetic field during the magnetization from 0 to 4 kA/m.

On the other hand, Figure 4 shows the equivalent results to Figure 3 but for the case of the LC crystal, which predominantly shows a maze pattern of magnetic domains. In this case the light-coloured domains vanish and the dark-coloured domains increase in size.

It is important to emphasize the differences between the upper right images of Figures 3 and 4, which correspond to a magnetic field intensity of about 1990 A/m. Both images differ in the size of the dark domains, which could be a consequence of either the initial domain structure of each crystal or it is related to a different dynamic response. These observations suggest that the spatial resolutions that can be obtained from both crystals are quite different and a more detailed study should be performed to clarify this issue. On the other hand, if the dynamic magnetic domain pattern of each crystal is field dependent, a more detailed study should be performed by using different constant rates of temporal change (dH/dt) of the excitation field.

4. Conclusion

Two Faraday crystals from the same type delivered by the company Matesy were studied. The results presented in this paper reveal the complexity of the correct application of such devices for the quantitative analysis of magnetic fields. For a proper implementation of Faraday magnetometers, the crystal must be characterized carefully to determine its macroscopic behaviour in the proposed working range, which is not linear and should be corrected properly during calibration. Besides, the magnetic domain pattern of each single crystal seems to be quite different due to structural inhomogeneities, and this pattern could define the spatial resolution of the system. Even though the sensitivity of the studied crystals is very high, their variation from crystal to crystal of the same type is quite remarkable.

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