

Advanced MOKE Magnetometry in Wide-Field Kerr-Microscopy

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The measurement of MOKE (Magneto-Optical Kerr Effect) magnetization loops in a wide-field Kerr microscope offers the advantage that the relevant domain images along the loop can be readily recorded. As the microscope's objective lens is exposed to the magnetic field, however, the loops are usually strongly distorted by non-linear Faraday rotations of the polarized light that occur in the objective lens and that are superimposed to the MOKE signal. In this paper an experimental method, based on a motorized analyzer, is introduced which allows to compensate the Faraday contributions, thus leading to pure MOKE loops. A wide field Kerr microscope, equipped with this technology, works as well as a laser-based MOKE magnetometer, but additionally offering domain images and thus providing the basis for loop interpretation.

I. INTRODUCTION

The analysis of magnetic microstructure (i.e. magnetic domains and their substructures) is of importance, both from fundamental and application points of view. Domain imaging grants access to the basic physical properties of magnetic materials on the mesoscale. Also phenomena like hysteresis, energy loss or magnetoresistive effects in classical applications of magnetic materials as well as in modern spintronic- and spin caloritronic devices directly or indirectly depend on the underlying domain structure, which, in most cases, can only be gained by direct imaging. Various techniques for magnetic domain imaging are currently available, each with its own advantages and drawbacks. A review on domain imaging can be found in ref. [1].

Among all methods, digitally enhanced magneto-optical (MO) wide-field Kerr microscopy has emerged to become a well-established, most versatile and flexible laboratory technique for the investigation of magnetic domains. The method is based on the MO Kerr effect², i.e. small alterations of the polarization plane of linearly polarized light upon reflection from a non-transparent magnetic specimen, which are then detected and used for magnetic domain image formation. A typical wide-field Kerr microscope is based on an optical polarization reflection microscope that applies the Köhler illumination technique for homogeneously illuminated samples^{3,4}.

Depending on the relative orientation of light the incidence plane, light polarization plane and magnetization orientation, three types of the Kerr effect are distinguished: *longitudinal*, *polar*, and *transverse* effect. The first two effects lead to a rotation of the polarization plane of the light, possibly superimposed by elliptical

contributions, whereas the latter results in an amplitude variation rather than a rotation of the reflected light^{1,3,5}. As a simple rule, resulting from the symmetry of the dielectric tensor of the Kerr effect^{3,5}, the Kerr contrast is proportional to the magnetization component along the propagation direction of the incident light beam. As illustrated in Fig. 1(a) for the case of oblique light incidence and *p*-polarized light (longitudinal Kerr effect), the reflected light can be seen as a superposition of a regularly reflected amplitude \mathbf{A}_N and the Kerr amplitude \mathbf{A}_K , leading to the rotation of the polarization plane by the (small) angle $\pm\Phi_K \approx \mathbf{A}_K/\mathbf{A}_N$. The sign (\pm) depends on the orientation of the magnetization at the sample surface. A domain contrast is produced then by blocking the reflected light from one domain type by the analyzer as indicated in Fig. 1(b). For perpendicular incidence and thus perpendicular reflection of the light, only out-of-plane magnetization components will lead to a Kerr contrast according to the mentioned rule (polar Kerr effect). At oblique incidence, however, there is always sensitivity to in- and out-of-plane magnetization.

Since the introduction of digital image processing⁶ the standard technique to obtain pure domain contrast, free of topographic information, is to subtract an image with domain information from a background image that is free of domains. Such a reference image is typically obtained by saturating the specimen in an external magnetic field, requiring some electromagnet around the sample. As the objective lens of the microscope has to be placed very close to the surface of the specimen (the distance is ranging between hundreds of micrometers for high magnifying lenses and some millimeters for low magnifying objectives), the applied magnetic field may induce a parasitic Faraday effect⁷ that is superimposed to any light rotation being caused by the magnetism of the specimen

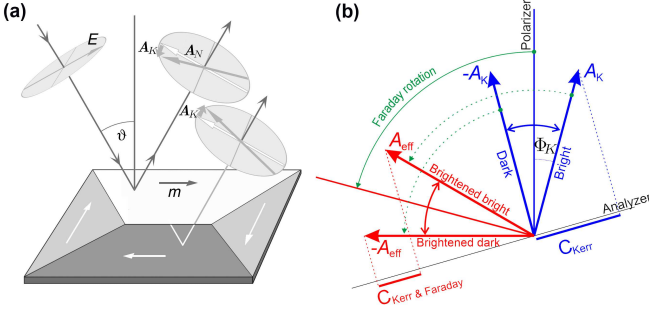


FIG. 1. (a) Elementary illustration of the longitudinal Kerr effect. (b) Pure Kerr contrast C_{Kerr} upon light reflection from the sample surface (in blue) and superposition of Kerr and Faraday amplitudes (in red) upon the propagation of the light within lenses subjected to the magnetic field

(see Fig. 1(b)). This effect is substantial for magnetic fields applied along the objective axis, but also inhomogeneous in-plane fields or stray fields emerging from the sample may produce Faraday rotations in the lenses⁸. Such contributions may decrease the quality of the domain images, lead to a misinterpretation of experimental data⁸ or bring substantial errors into vectorial Kerr microscopy^{9,10}. The most severe impact of the Faraday effect occurs if MOKE magnetization loops are measured in the Kerr microscope by plotting the intensity of the whole or locally selected regions of the image as a function of magnetic field (MOKE magnetometry). Highly distorted loops may emerge as will be shown below on various examples. Laser-based room temperature MOKE magnetometers do not experience such distortions as the optical elements are sufficiently away from the magnet.

In the case of in-plane applied magnetic field, an elegant solution for suppressing Faraday contributions was recently proposed^{4,8}. It is based on an LED (light emitting diode) lamp, in which the light from eight diodes is guided to the microscope by glass fibers, the ends of which are symmetrically arranged around the central axis of the microscope (see ref. [4] for details on this advanced light source). By activating oppositely placed LEDs and subtracting the obtained domain images at opposite directions of incidence, the condition of *pure in-plane* Kerr sensitivity is achieved. If this activation and subtraction are done in a pulsed mode synchronously with the camera exposure, and if the pulse frequency is higher than about 10 Hz, “real-time” domain images with pure in-plane Kerr contrast are obtained and the magnetization loop can be recorded under the same conditions. Interestingly, it is not just the polar Kerr contrast that is annihilated, but also the *polar Faraday effect* in the objective lenses. All polar field components, caused by non-uniform in-plane fields or by stray-field emerging from the edges of magnetized bulk samples, do not lead to image- and loop distortions anymore⁸.

The situation is different, however, if perpendicularly magnetized media is measured in perpendicular magnetic field (polar Kerr microscopy and -magnetometry). In this

geometry the polar Faraday effect in the objective lens is maximum. With rising applied field it may even overwhelm the Kerr signal from the sample as demonstrated in Fig. 2(a). Although magnetic saturation of the CoPt film is achieved immediately after the magnetic field has exceeded the coercivity, the measured intensity fairly increases rather than leveling off as usual for a magnetization loop beyond saturation. The intensity increase is caused by the Faraday effect that adds a field-dependent contrast to the Kerr signal [compare Fig. 1(b)]. Above some critical field (not shown) the camera of the Kerr microscope, which at the same time acts as detector for MOKE magnetometry, may even get “saturated”, i.e. leaving its sensitivity range.

As demonstrated in Fig. 2(b), the Faraday contribution can be removed by measuring the loop slope above nominal saturation and by digitally subtracting it along the total loop. This method, however, only works reliably if the Faraday contribution can be considered as *linear* within the field range and if sample *saturation* is guaranteed for the field region in which the Faraday slope is measured, perhaps from comparison with some other magnetometry method (like Vibrating Sample Magnetometry) that delivers the absolute magnetization rather than the relative as is the case for MOKE magnetometry. Non-linear Faraday contributions may become severe in strong applied fields, as shown below, and for small opening angles of the analyzer. If they are superimposed to the Kerr signal, they cannot be easily determined from the total MOKE loops and then subtracted without risking unjustified data manipulation. The Faraday effect thus limits the accuracy and sensitivity of microscopy-base MOKE magnetometry. Anyway, even if for MOKE loops the parasitic Faraday contribution can be subtracted under favorable conditions, the Faraday effect is nevertheless fatal if the difference imaging technique is applied to enhance the domain contrast. For the difference images shown in Fig. 2(c), the background image was taken at zero field after negative saturation. Thus, with the application of positive field the domain intensity, biased by the Faraday intensity, changes although the domains themselves stay magnetized constantly. Beyond positive or negative saturation the total brightness finally is out of the intensity regime of the chosen bit level. A further example of such unfavorable imaging can be seen in the report by Gareev *et al.*¹¹ on ultrathin Co-Fe-B/MgO-based heterostructures with perpendicular anisotropy. To get high-quality domain difference images nevertheless, the background image may be taken at a magnetic field right before the switching process is initiated. If the switching occurs within a small field range, the Faraday effect will not significantly change the total image intensity during switching so that the difference images will not leave the intensity regime of the bit level. If, however, the domain evaluation process takes place in an extended field range, fresh background images have to be repeatedly recorded during reversal. In this case the difference images represent not the real domain state (as

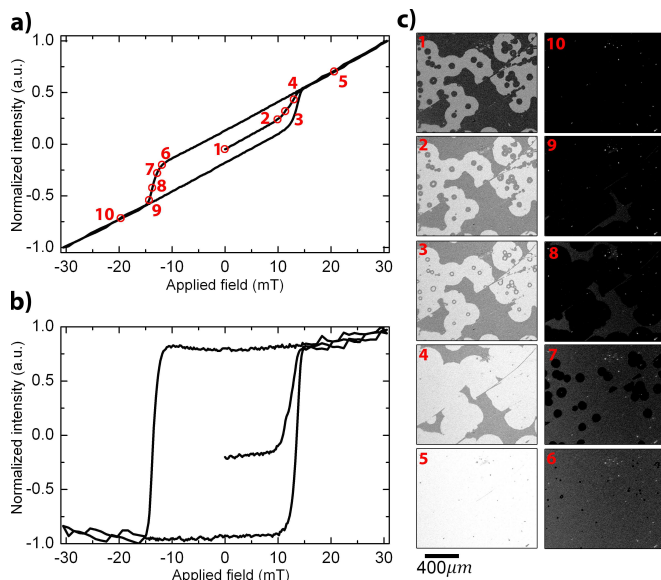


FIG. 2. MOKE loops and domain images obtained in the polar mode on a $[\text{Co} (0.3 \text{ nm})/\text{Pt} (0.7 \text{ nm})]_3$ multilayer, measured and observed in a wide-field Kerr microscope. The directly measured loop in (a) was corrected for the linear Faraday slope in (b), thus revealing the “true” loop. The domain images in (c) were taken during the external magnetic field sweep as indicated by the numbers in (a) and (c). Shown are difference images for which the background image was recorded at zero field after negative saturation. The image at zero field was obtained after the sample was demagnetized in an AC field of 20 Hz (Sample courtesy *M. Kopte*, Dresden).

it would be for the case when the background image is taken at saturation), but rather it’s change with respect to the reference image.

The application of the pure in-plane imaging mode, mentioned before, would effectively suppress intensity contributions arising from the polar Faraday effect also under polar measurement conditions, independent from its complexity. It would, however, also suppress the polar *Kerr* effect — perpendicularly magnetized domains would become invisible and there would be no polar Kerr signal anymore that would lead to the desired polar magnetization loop. We have therefore developed a method that suppresses Faraday contributions in wide-field polarization microscopy under arbitrary measurement conditions, thus leading to pure MOKE loops and domain contrast that only depend on the magnetization of the specimen. The method is presented in the next section for the extreme case of polar MOKE magnetometry and microscopy, i.e. in the following text the external field, applied to the sample is always out-of-plane (polar) and along the objective axis.

II. DESIGN OF THE SYSTEM

The principle of separating Kerr- and parasitic Faraday contributions in the objective lens upon the application of external magnetic fields is based on the fact that the latter manifests itself as an additional rotation of the light polarization plane that is field dependent whereas the Kerr rotation angle is conserved as illustrated in Fig. 1(b). Thus, to preserve the contrast between $+A_k$ and $-A_k$, the analyzer has to be rotated by the same angle that was gained through the Faraday rotation of the polarization plane as the light passes the lenses of the objective. Such indemnifying rotation can be done manually, which works reasonably well for quasistatic domain imaging. But as the angle by which the analyzer has to be set to compensate the change of the image brightness is rather fine, no manual in-situ compensation is possible during the (dynamic) measurement of magnetization loops. An automatized version is to be preferred in that case.

To create such a self-acting compensation system, we have equipped the standard analyzer of our AxioScope-type Carl Zeiss polarization microscope with a bipolar stepper motor¹² and a gear with a reduction ratio of 1670 to 1. The motor is operated by a microstepping motor driver with a built-in translator based on an A3967 microchip¹³ with capability to full-, half-, quarter-, and eighth-step modes. The driver is powered with 5 V from an USB port with a following conversion¹⁴ to 12 V. The direction of rotation and the steps are controlled by a signal-acquisition card with digital outputs¹⁵. With a 15° step size, reduction gear and belt transmission in the analyzer slider (with a reduction ratio of 35:17) the analyzer is rotated by approx. 4 mdeg per step in the full-step and by 0.5 mdeg in the eighth-step mode. Such a small angle step size is essential to have a smooth control of the image brightness during stabilization.

The existing image acquisition software of our combined Kerr microscope and magnetometer system is extended by an additional module for the analyzer stepper motor control. If the microscope is only used for domain imaging in the difference image mode, it is sufficient to keep the overall brightness of the *live* image constant to prevent over- or underexposure of the difference image. Alternatively, a certain region of interest (ROI) within the image can be chosen and used as a reference. If the evolution of the domain structure (i.e. the magnetization process) is to be imaged by sweeping the magnetic field in a step-like manner, the intensity correction (adjustment of the gray level within a ROI) is performed for each field step before taking the image of interest. In this case, apparently, no field dependency of the integral magnetization (magnetization loop) can be derived as the average intensity of the image remains on the same level throughout the whole experiment, even though a contrast between oppositely magnetized domains is observed.

For MOKE magnetometry both intensity contributions, the magnetic Kerr response of the sample and the

Faraday effect in the optics, have to be separated in-situ. This requires an in-situ measurement of the pure Faraday contribution, which can be easily achieved if the imaged surface has non-magnetic areas next to the magnetic material. Such areas can be intentionally created by patterning or during film growth. Alternatively, a metallic mirror of non-magnetic material can be placed on top of the specimen, a small part of which being visible in the image, or the sample can similarly be placed on top of the mirror. The intensity of the non-magnetic area, contributing pure Faraday rotation, is then used as a reference for the analyzer position feedback, while the MOKE magnetization loop is recorded on the magnetic area. The intensity adjustment process (number of steps, step size, etc.) is based on a standard PID controller with the live image brightness as input data. As the compensation of the Faraday effect has to be done for each field step, a longer recording time of the loop is required compared to non-compensated recording.

To compensate the large Faraday rotations in strong perpendicular field, it is necessary to rotate the analyzer by relatively large angles of up to some 10° . This may possibly change the contrast conditions of the live image with respect to the background image, giving eventually rise to the appearance of topographic sample defects in the difference image. This disturbance, however, is minimal and has no influence on the loop quality. In case of strong elliptical Kerr contributions of the reflected light, a so-called compensator (typically a rotatable quarter-wave plate) may help to improve the MOKE contrast. This device has to be located between polarizer and analyzer, either on the illumination or reflection path of the microscope. Once a compensator setting for optimum Kerr contrast is found, this setting can be kept constant while the Faraday compensation is achieved by analyzer rotation.

III. RESULTS

The compensation of the parasitic Faraday effect in the objective lens is vital for microscopy-based MOKE magnetometry on materials where the application of high external fields is required to achieve magnetic saturation. An example of an optical hysteresis loop, measured on an FePd/FePt/FePd extended thin film in polar sensitivity, is shown in Fig. 3(a). In this unprocessed curve, the magnetic response from the sample can hardly be identified as the observed signal is dominated by a strong parasitic Faraday contribution. Moreover, the camera settings (exposure time, gain, brightness) were adjusted for low contrast, otherwise the intensity of the live image would have left the 12-bit camera A/D converter range. Similar to the case of small fields (see Fig. 2), a linear part with its slope determined in the high-field region at magnetic saturation, can be subtracted [Fig. 3(b)]. The result, however, is very unsatisfactory and far away from the “true” MOKE curve. This is due to the fact that

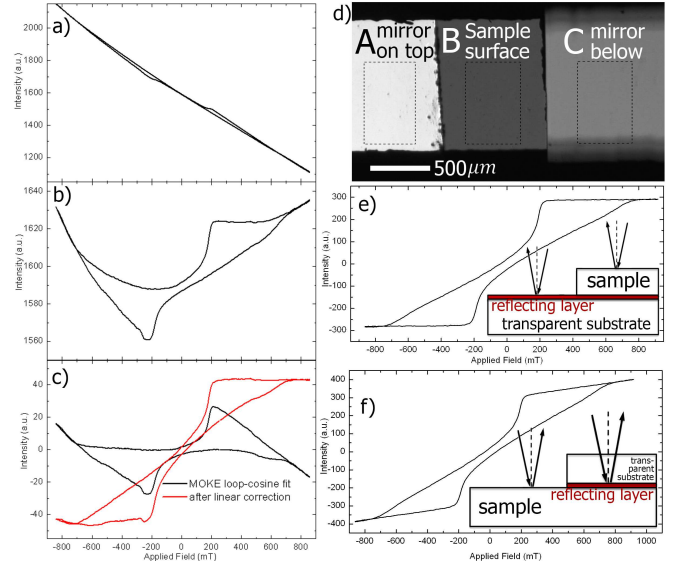


FIG. 3. Polar MOKE loops obtained on an FePd (10 nm)/FePt(25 nm)/FePd(10 nm) film sample, measured by using a 5x/0.13 objective lens: (a) As measured, (b) after digital subtraction of the linear part, (c) after digitally subtracting a cosine-square fit. The loop in (d) is a direct measurement with in-situ Faraday effect compensation by using a mirror placed below the sample. (e) Specimen on top of the mirror with additional mirror located on top of the sample. The rectangles indicate the ROI for loop measurement (magnetic area) and reference (non magnetic areas). (f) Direct measurement with in-situ Faraday effect compensation. The mirror was placed on top with the reflecting layer close to sample surface. As metallic mirror we have utilized a thin layer of Al, deposited on a 50 μm thick glass substrate (magnetic sample courtesy *L. Ma and S.M. Zhou, Tongji*)

the intensity of the light, passing the analyzer, depends on the angle α between the light's polarization direction (acquired on passing the lenses) and the axis of the analyzer in a non-linear manner according to Malus' law as $I = k_0 I_0 \cos^2(\alpha)$. Here k_0 is the transmittance of the analyzer and I_0 is the intensity of the light before entering the analyzer. Whereas in small fields this dependency can be roughly approximated by a linear fit, the non-linearity becomes pronounced in the high field regime. The rotation of the light polarization plane due to the Faraday effect is linear with the field, thus the total intensity is $I = k_0 I_0 \cos^2(\alpha) = k_0 I_0 \cos^2(\frac{\pi}{2} + \nu B \pm \varphi + \theta_0)$, where ν is the Verdet constant (with unit radian per Tesla), specified for the particular lens. The term $\frac{\pi}{2}$ reflects the fact that the axis of the analyzer is almost perpendicular to the axis of the polarizer, being opened only by a small angle θ_0 , and $\pm\varphi$ is the Kerr rotation caused by the magnetization at the sample surface. A direct fit of the experimental data with a cosine-square dependency improves the loop shape significantly [Fig. 3(c)] and after the additional subtraction of a residual linear contribution, originating from a low fitting accuracy (the fit includes both contributions, that of the magneto-optic re-

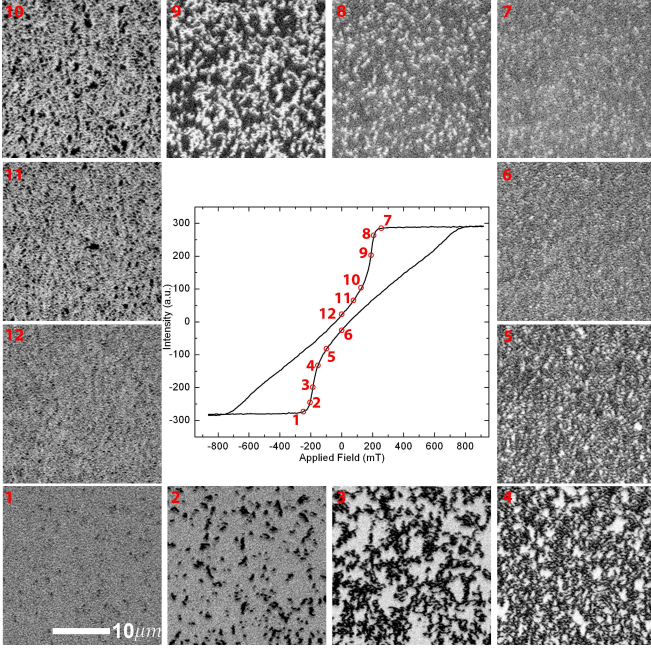


FIG. 4. Domain images obtained in the polar mode on the same FePd/FePt/FePd multilayer as in Fig. 3, obtained by difference imaging with the background image recorded at highest possible field during an external magnetic field sweep with in-situ Faraday compensation. As reference area for domain observation, the whole visible sample surface was used, while for the MOKE loop a mirror was placed on top

sponse of the magnetic sample and of the Faraday effect), the main characteristic features of the magnetization loop is finally revealed, with an unsatisfactory signal-to-noise ratio, though.

The employment of the motorized analyzer, described in Sec. II, drastically improves the quality of the obtained magnetization loops. If the sample is placed on top of the non-magnetic mirror as shown in the inset of Fig. 3(e) so that the magnetic film (region B) and part of the mirror (region C) are caught by the camera [Fig. 3(d)], the area of the mirror can be used to obtain the reference signal for the adjustment of the analyzer rotation angle. The hysteresis loop, measured with active compensation in this geometry, is shown in Fig. 3(e). A smooth and pure MOKE loop is obviously obtained by applying the motorized analyzer! As optimized camera settings can be used, not limited anymore by the necessity to accommodate the large intensity change from the Faraday contribution, also the absolute amplitude of the measured signal is larger and thus the sensitivity of the magnetometer.

As the specimen observed in Fig. 3 is an extended film, low magnifying objective lenses (with magnifications like 1.25x or 2.5x) can be used for MOKE magnetometry. They have the advantage of large focus lengths and -depths so that both, the sample and the mirror underneath can be measured in-focus at the same time. This, however, does not work in case of patterned structures

that are too small to be seen with low magnifying lenses. Higher magnifying objectives, such as 50x or 100x lenses, are to be used then. Their working distance, however, is of the order of half a millimeter and below, so that it is not possible to focus on sample and mirror simultaneously in the geometry of Fig. 3(e). In such cases the sample and the mirror can be arranged in a different way: rather than placing the sample on the mirror, it is rigidly mounted on a sample holder. Then a piece of thin (about 50 μm thick) transparent glass substrate with deposited mirror layer (like aluminum, copper or tantalum) is placed onto the sample with the reflecting layer in contact with the sample surface as shown in the inset to Fig. 3(f). Thus, the sample and non-magnetic mirror surface are both in focus as they are almost at the same distance from the objective lens. This can be seen in Fig. 3(d), where the stack of two mirrors with the sample in between is imaged with a 2.5x lens. The two horizontal edges of an inserted slit are imaged sharply together with the sample surface (region B), on which the microscope was focused. The edges also appear sharply on the left side of the image with the mirror on top (region A), whereas they appear blurred when the mirror is below the sample (right side - region C). As the light in the configuration shown in the inset of Fig. 3(f), reflected from the mirror and used for the compensation of the lens-induced Faraday effect, passes the glass substrate, it also experiences a rotation of the polarization plane due to the Faraday effect in the mirror substrate. However, this contribution is minor as the substrate thickness is small in comparison with the total length of the optical path in the objective lenses. The loop measured with intensity stabilization over such a mirror is shown in Fig. 3(f), the additional slope can be easily approximated by a linear fit and compensated digitally.

So keeping the intensity of a non-magnetic area, which is imaged together with the magnetic specimen, at a certain brightness level by analyzer rotation works well to compensate the parasitic Faraday effect during the recording of the magnetization loops in a wide field Kerr microscope. Just for domain imaging, however, a non-magnetic mirror surface is not required: independent of the magnification, it is sufficient if the *overall* (magnetic) image intensity is kept constant by the motorized analyzer during field sweep. This is demonstrated in Fig. 4 where the domains in the same FePd/FePt/FePd film as in Fig. 3 are imaged along the hysteresis loop. Shown are difference images with the background image recorded at highest possible field, but with the overall image brightness kept at that of the zero-field state. It is seen that, in contrast to the domains in Fig. 2, all the images recorded with stabilization have equally remarkable contrast and the complete magnetization process can be traced continuously.

A further example demonstrates the importance of Faraday-corrected domain imaging. In Fig. 5(a) the optical hysteresis loop on a thin (4 nm) FePt film was measured in polar sensitivity with no Faraday compensation.

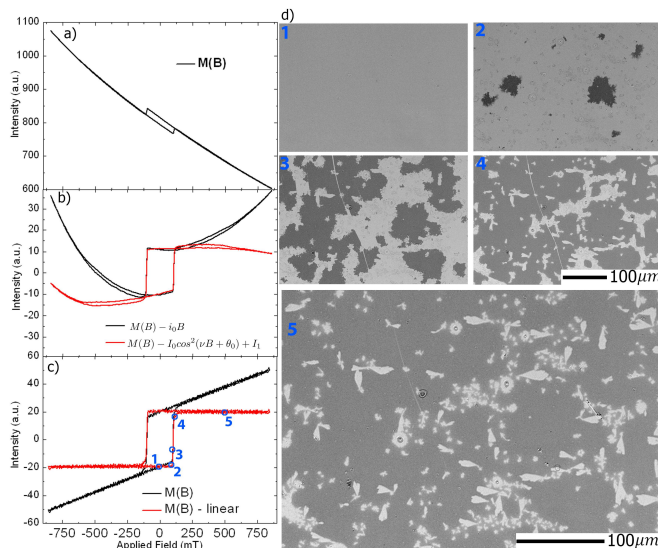


FIG. 5. MOKE loop of an FePt (4 nm)/Pt(50 nm)/MgO film sample, measured by polar Kerr magnetometry without Faraday effect compensation (a), with subsequent subtraction of linear and cosine dependence (b) and with stabilization of the image intensity of a non-magnetic mirror (c). (d) shows domain images that correspond to certain sample states during the hysteresis measurement in (c). (Sample courtesy J. Zehner, Dresden)

As in case of the FePd/FePt/FePd film discussed earlier, the parasitic Faraday effect in the objective lens dominates the whole loop, and subtraction of the linear part or a cosine fit [Fig. 5(b)] do not lead to satisfactory results. Measuring the same loop with motorized analyzer with the reference mirror on top of the sample [as shown in Fig. 3(f)], and subsequently subtracting the small linear slope that is induced in the glass substrate of the mirror leads to a sharp hysteresis loop with distinct switching-

and saturating fields [Fig. 5(c)]. The evolution of domains shown in the difference images in Fig. 5(d) with the background image taken at negative saturation proceeds by domain nucleation [Fig 5(c), d-2] upon the application of a positive field. The following growth of the domains with magnetization vector along the applied field [Fig 5 (d-2 \rightarrow 3)] is expected to persist until the saturation field is reached at which the magnetization within the whole sample is aligned with the field [Fig. 5(d-4)]. However, some contrast remains even in fields well beyond the saturation field [Fig. 5(d-5)]. The origin of this unexpected contrast is the presence of non-magnetic inclusions in the magnetic film, which are formed during the pulsed laser deposition process. As those inclusion areas are not magnetized, they remain equally gray in all fields, leading to the observed contrast between magnetic and non-magnetic regions of the sample. In conventional imaging with no Faraday compensation such a contrast would be overlooked, if a background image would have been taken only right before or during the switching process, as described at the end of Sec. I.

IV. CONCLUSION

A method to suppresses parasitic Faraday contributions in wide-field polarization microscopy under arbitrary measurement condition was introduced. By introducing a motorized analyzer into the microscope and tracing the brightness of the live image it can be kept at constant level, giving the opportunity for high quality polar domain imaging within the whole available field range. The use of non-magnetic areas as a reference for brightness stabilization leads to pure MOKE loops free from Faraday contributions. The potential of the technique was demonstrated by measuring extreme cases of polar MOKE loops on FePd/FePt/FePd and FePt thin films in combination with domain observation during the field sweep, broadening the opportunities of the experimental instrumentation for magneto-optical investigation.

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