# Interpretation of Kerr microscopic domain contrast on curved surfaces

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**In this letter we address a technical peculiarity of wide-field magneto-optical Kerr microscopy, which may easily lead to a misinterpretation of the domain contrast on curved surfaces. On the example of circumferentially magnetized domains in ferromagnetic microwires we show that the checkerboard domain pattern, which typically shows up in polar Kerr sensitivity, is caused by the superposition of longitudinal Kerr contrasts that arise from in-plane magnetization components and inclined light incidence rather than from the magnetization components perpendicular to the focal plane as claimed in the literature. Experimental ways to avoid such peculiar contrasts are demonstrated.**

*Index Terms*—**Magnetism in solids, magnetic domains, Kerr microsccopy, magnetic microwires.**

Extending planar, two-dimensional structure geometries into the three-dimensional space is of fundamental current interest in multiple disciplines [SFK+16], [DS20]. Among others, glass-coated amorphous, ferromagnetic microwires have attracted a lot of attention due to their potential for applications as sensors for numerous physical quantities (temperature, field, stress), as bio sensors, etc. [ABC+20], [BLPR19]. Possessing outstanding magnetic properties like the giant magneto-impedance effect, magnetic bistability, high domain wall mobility including the potential break of the Walker limit [YKGH10], and magnetic softness, they become also important elements of modern electrical engineering [ZZ09], [Váz20].

Widely used and established methods for the magnetic characterisation of the microwires with different composition and magnetic softness are vibrating sample magnetometry (VSM) [NKE+22], [RBC+17] as well as direct magnetoimpedance-, inductive hysteresis-, and Barkhausen type measurements [NKE+22], [BIR+09], [ABC+20], [PDN+19]. All these methods, however, deliver integral magnetic properties comprising the whole wire volume while local features like the magnetization behaviour at the wire surface are not accessible. From the surface domain structure, however, one can possibly get access to the complete domain structure of a wire by combining surface domain observation with the results of integral measurements [VBLR20]. Investigation of local surface features is possible by applying wide-field magneto-optical Kerr microscopy, which has developed into an effective tool for the microscopic characterisation of all kinds of magnetic materials in research and industrial applications [KSFH15], [McC15]. This method, being widely used to investigate surface magnetism of planar samples like magnetic films, bulk samples, or planar micro- and nanowires [HS98], was only rarely applied to samples with curved topography [RTV14], [ES10], [Váz20], [VRVM21]. For the amorphous wires in glass it has the advantage of being a non-invasive technique that utilizes the transparency of the glass coating and the ability to observe the position and shape of the domain walls [CVZ+08], [RTVM20].

The magneto-optical Kerr effect (MOKE) leads a rotation of the polarization plane of linearly polarised light upon the reflection from the surface of a magnetic sample [HS98], [KSFH15]. Depending on the mutual orientations of magnetization, polarization of the light, incident light angle and direction, three basic Kerr geometries are conventionally considered: *polar* (magnetisation of specimen is out-of-plane), *longitudinal* (magnetisation is in-plane and along the plane of incidence) and *transversal* (magnetisation in-plane but transverse to the incidence plane) [HS98].

Like any other instrument, the magneto-optical Kerr microscope requires some skills and understanding of the basic principals in order to correctly interpret the observed signals. In case of planar structures, ignoring a possible intermixing of longitudinal and transversal Kerr contrasts for p-polarized incident light [SZL+21], in a first order approximation the MOKE signals are proportional to the magnetization component along the direction of light propagation so that a contrast interpretation is relatively straightforward. For finite samples, however, one needs to consider that even a paramagnetic sample holder [MNBBG20] or magnetic stray fields emerging from the sample edges [MNBBG20] may result in spurious, superimposed signals. Even the region of interest within the image, used for magnetization loop analysis is important [SAS20]. In case of curved surfaces like microwires, a reliable interpretation of the Kerr signals requires special caution and can easily lead to a misinterretation of the observed contrast. An example, which we also address in this letter, can be

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found in the work by *Stupakiewicz et. al.* [SCT$^{+}$14] and in a follow-up work by *Chizhik et. al.* [CSZG16]. where the contrast observed within the image have been incorrectly attributed to be originating from the magnetization component perpendicular to focal plane of microscope.

An analytical calculation of the magneto-optical contrast on the surface of ferromagnetic cylinders was nicely performed by *Richter et. al.* [RTV17]. It was shown that even in case of a non-magnetic wire the polarised light, incident along the cylinder axis, may result in spurious contrasts across the wire so that additional caution has to be taken during the analysis [RTV14], [RTVM20].

In this letter we point out a technical particularity of wide-field Kerr microscopy, which can lead to peculiar magneto-optical contrasts and, as a consequence, to the mentioned [SCT$^{+}$14], [CSZG16] misinterpretation of the data obtained. We present magnetic domain images on the surface of a glass coated ferromagnetic amorphous $\mathrm{Co_{71}Fe_{5}B_{11}Si_{10}Cr_{3}}$ microwire (total diameter/metal core diameter: $D/d = 29/25$ $\mu$m) under different illumination conditions by applying a special light source that allows for selective Kerr sensitivity [SS17]. A 100x oil immersion lens with a numerical aperture of 1.3 was used to obtain high-resolution Kerr images of microwires. The surface domains of the wire are magnetized circumferentially as indicated in Fig. 1 and as having been the case in Refs. [ [SCT$^{+}$14], [CSZG16]]. The microwire has a positive value of magnetostriction constant and, thus, together with mechanical stress presented in the outer wire layer, the circumferential domains are expected at the surface [NKE$^{+}$22], [AKR$^{+}$21]. Experimental possibilities to avoid the peculiar contrasts are discussed.

In a simplified view we may assume that the Kerr sensitivity is defined by the direction of light incidence [SS17], [SZL$^{+}$21]. In a conventional wide-field Kerr microscope [SCT$^{+}$14], [HS98] it is adjusted by properly positioning a slit aperture diaphragm in the fully illuminated aperture plane (also known as diffraction or conoscopic plane), while in advanced microscopes [SS17] the incidence direction can be defined via independent light-emitting diodes (LEDs), the light of which is guided via optical fibres to the conoscopic plane of the microscope. Both possibilities are schematically indicated in Fig.1.

If the microscope is adjusted for in-plane sensitivity transverse to the wire axis by choosing the appropriate slit position or by turning on the corresponding LEDs (Fig.1(a)), one expects to observe a longitudinal Kerr contrast between the circumferential, oppositely magnetized domains that will change sign for opposite directions of incidence. The contrast is generated by the magnetization component laying *in the focus plane* and the grey level within one domain should remain the same (either black or white for a given incidence direction), when scanned across the circumferential domains as the projection of the magnetization on the focus plane follows a cosine dependence and varies only little within the visible top area of the wire. If, however, the microscope is set to polar sensitivity by choosing an effective perpendicular incidence (Fig.1 (b)), one may expect that the contrast is produced by the magnetization component *perpendicular to the focus plane*. The grey level, following the perpendicular component of magnetisation, should gradually change from dark to bright along the surface for one domain and from bright to dark for the neighbouring domain, being the same for both right at the top of the wire where the perpendicular magnetization component vanishes. Such behaviour should then result in a checkerboard pattern as it was indeed reported in Ref. [SCT$^{+}$14]. In the following we will show, however, that the interpretation of the checkerboard contrast as being caused by the polar Kerr effect is incorrect.

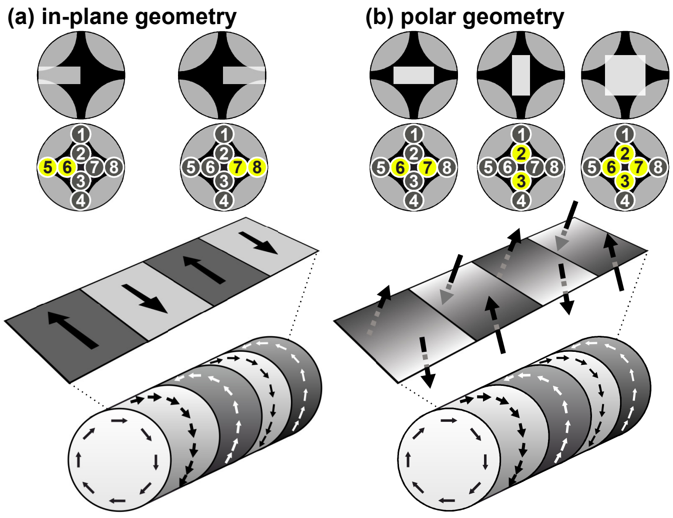

Fig. 1. Schematics of circumferentially magentized domains on the wire surface and their images, obtained in a wide-field Kerr microscope adjusted for the longitudinal Kerr effect with "in-plane" sensitivity direction transverse to the wire axis **(a)** and in polar configuration **(b)** as wrongly suggested in Ref. [SCT$^{+}$14]. Also indicated are the appropriate positions of the slit aperture and, alternatively, of the fibre ends as seen in the back-focal plane of the microscope.

Firstly note that also in the case of oblique incidence there will (generally) always be a superposition of longitudinal and polar contrast [KSFH15]. For a cylindrical surface and light incidence transverse to the wire axis, however, this fact is not relevant. In Fig. 2 this is demonstrated for oblique incidence from the right (a) and left (b) at a location with a transverse domain wall in the middle of the images that separates two domains with oppositely winding magnetization. Image processing (i.e. subtracting a background image of the saturated state from the domain state and displaying a digitally enhanced difference image) was applied to increase the domain contrast. The corresponding unprocessed, topographic images are displayed in (d) and (e), respectively, showing that only one half of the wire is (partly) illuminated. By comparison with Fig. 1 it is evident that the inversion of contrast in Fig. 2(a) and (b) along the same circumferential domains can be caused by both, polar and longitudinal magnetization components in the focal plane. Independent of the origin of the contrast changes, the circumferential domain character becomes evident by running the microscope in the *pure in-plane* longitudinal Kerr effect mode [SS17]. Here two images obtained at opposite oblique incidence are subtracted (in Fig. 2(c) these are LEDs (5,6) and (7,8)). For the contrast symmetry of our wire this

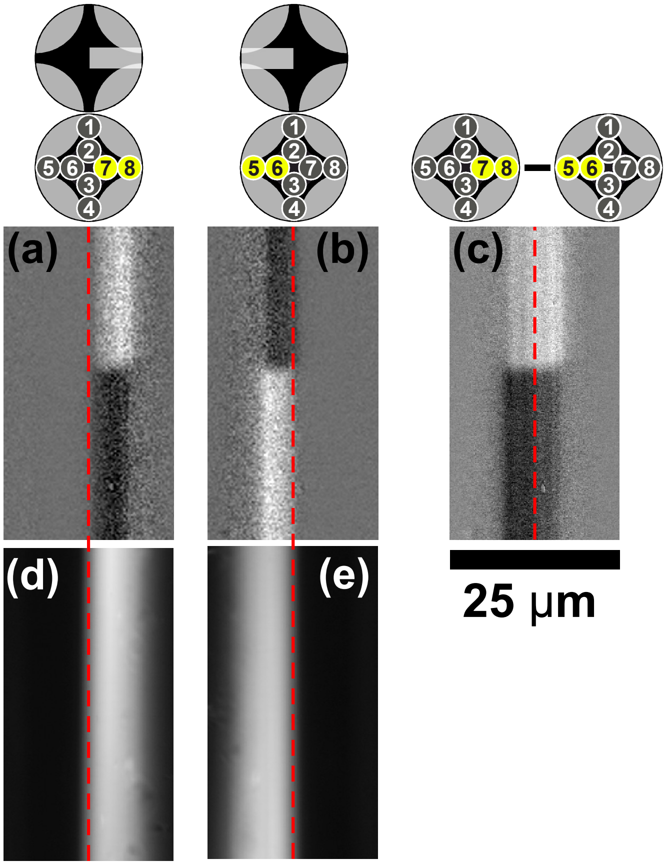

Fig. 2. Circumferential domains at the surface of 25 $\mu$m $Co_{71}Fe_5B_{11}Si_{10}Cr_3$ wire, observed in longitudinal Kerr sensitivity with p-polarised light coming from the right **(a)** and left **(b)** side. The correspondent topographic images are displayed in **(d)** and **(e)**. An image taken with pure in-plane sensitivity is shown in **(c)**. The dashed line lineates the center of the wire.

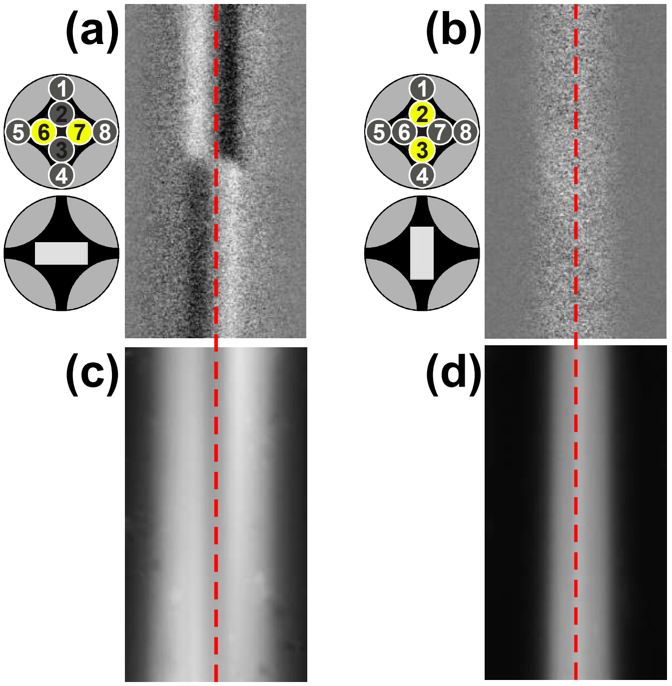

Fig. 3. Pure polar Kerr contrast, obtained with **(a)** transverse plane of incidence by simultaneously activating LEDs 6 and 7 (p-polarised light), and with **(b)** longitudinal plane of incidence by using LEDs 2 and 3 (s-polarised light). The same illumination conditions can be obtained by properly positioning an aperture slit in the back-focal plane as indicated. Images **(c)** and **(d)** show the corresponding topographic contrast in unprocessed images.

leads to identical domain contrasts for both halves of the wire within the focal depth (Fig. 2(c)).

*Pure polar contrast* is obtained either by adding the images taken at opposite incidence, or simply by driving oppositely located LEDs simultaneously [SS17] (compare Fig.1(b)). Alternatively, a symmetrically centred slit aperture can be applied as also sketched in Fig.1 **(b)**. If the plane of incidence is transverse to the wire axis, oppositely magnetized, circumferential domains then become visible in the mentioned checkerboard contrast as shown in Fig 3(a). If the polar Kerr effect is responsible for that contrast, a checkerboard contrast should a when the LEDs, arranged along the wire axis, are used for illumination (as sketched in Fig 3(b)). According to Fig 3(b), however, this is not the case. Consequently, the checkerboard contrast can only be due to the longitudinal Kerr contrast — at transverse incidence with LEDs 6 and 7 on simultaneously, or with the aperture slit symmetrically opened transverse to the wire axis. In this case the curved surface appears as if it would be independently illuminated from opposite sides, resulting in superposition of inverted domain contrasts on correspondent wire halves due to longitudinal Kerr effect generated by the in-plane magnetisation component. This results in the checkerboard contrast (Fig.3 (a)), which exactly resembles the contrast reported by Stupakiewicz [SCT$^+$14] and which was incorrectly interpreted to be generated by magnetization component perpendicular to the focus plane. In their experiment, the authors have used a centred, quadratic aperture slit to adjust for polar sensitivity. Due to the breaking of symmetry by the curved surface topography (for the light incident along the wire axis and transverse to it), the transverse light components are responsible for the longitudinal checkerboard contrast in that case. Also note the reduced visible wire area when illuminated along the wire axis (Fig. 3(d)) compared to a widened area for the transverse plane (Fig. 3(c)), proving the ”two-sided” illumination of the curved surface in the latter case. Interestingly, in the difference images (Fig. 3(a) and (b)) the zones with magnetic contrast appear with about the same width. It should be noticed that to get more homogeneous images and to avoid double peaks in intensity across the wire [RTV17], the focus of the microscope was set to a plane between the metal wire surface and the outer glass coating.

In summary, our investigations show the importance of an appropriate control of illumination in Kerr microscopy for the correct interpretation of the observed magnetic domain contrast on the surface of magnetic microwires. By using an advanced illumination scheme based on properly positioned LED light spots in the diffraction plane of the microscope, we have demonstrated that contrasts in ”conventional” setups in which the illumination is adjusted by properly placing a slit aperture in the diffraction plane of the microscope, can be easily misinterpreted: while a centred, quadratic slit leads to pure polar sensitivity on flat surfaces, this is not necessarily true for curved surfaces. The checkerboard contrast, found on microwires with circumferentially magnetized domains under those conditions, is not caused by the polar Kerr effect but rather by the longitudinal Kerr effect that changes sign for the light beams falling on the wire at oblique incidence transverse to the wire axis. To avoid such contrast artefacts, appropriate illumination paths should be chosen for polar Kerr microscopy: in a conventional setup, the aperture slit should be (symmetrically) aligned to generate a plane of incidence along the wire axis. In an advanced microscope, opposite LEDs in a line along the wire axis need to be simultaneously active. Circumferential domains can best be imaged by running the microscope in the pure in-plane mode with sensitivity transverse to the wire axis. Such considerations in principle apply to any curved surface.

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