



(51) International Patent Classification:

G01N 21/21 (2006.01) G01R 33/032 (2006.01)

(21) International Application Number:

PCT/SG2017/050237

(22) International Filing Date:

08 May 2017 (08.05.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

10201603665S 09 May 2016 (09.05.2016) SG

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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,

CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— of inventorship (Rule 4.17(iv))

Published:

— with international search report (Art. 21(3))

(54) Title: APPARATUS AND METHOD FOR KERR IMAGING

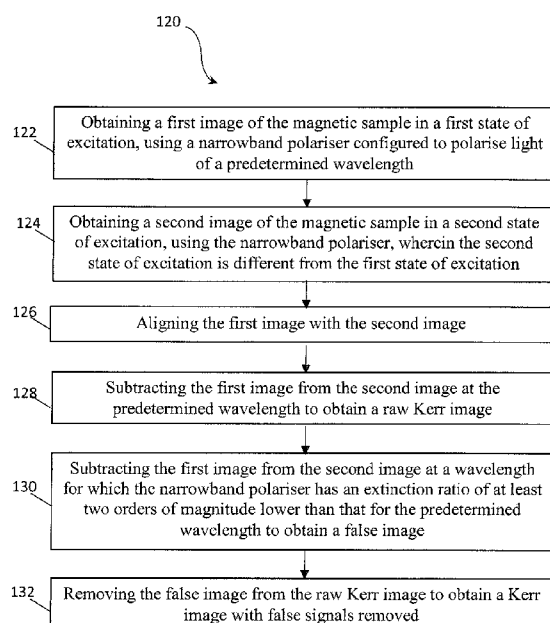


Figure 4(a)

(57) Abstract: An apparatus and method for Kerr imaging is disclosed. The apparatus comprises a light source and a polariser operable to provide polarised light for incidence on a magnetic sample. An analyser is provided to convert differences in polarisation of the polarised light, after reflection from the magnetic sample, into differences in light intensity and a detector is provided to detect the differences in light intensity for display as a Kerr image. At least one non-planar lens is employed between the polariser and the analyser and at least one corrective lens is provided to reduce polarisation aberrations introduced by the at least one non-planar lens. The method relates to removing a false signal from a Kerr image of a magnetic sample by subtracting unpolarised light signals from polarised light signals of interest.

Apparatus and Method for Kerr Imaging

Field of the Invention

[0001] The present invention relates to an apparatus and method for Kerr imaging.

Background

[0002] Kerr imaging (also known as Kerr microscopy) is an important technique in the study of spintronics as it provides a fast, non-destructive and convenient means of observing magnetization (see references 1-3 listed at the end of the present description). Polarised light incident on a magnetic sample causes a rotation of a polarisation plane, depending on the direction of magnetization. By detecting an angle of rotation of the polarisation plane, a Kerr image containing a magnetization distribution of a sample can be composed. Kerr imaging is advantageous when compared to conventional magnetometry methods such as those employing a vibrating magnetometer or a superconducting quantum interfering device because it is an imaging method. In addition to providing information on an overall magnetization of the sample, Kerr imaging can also map the magnetization with a resolution as small as the diffraction limit of light (which is approximately 200 nm).

[0003] However, because polarisation rotation is typically a weak effect and atomically thin magnetic films are often used, the incident light must be highly plane polarised for a microscope to obtain a meaningful signal. This problem is compounded by the fact that polarised light incident on dielectric surfaces at non-zero incident angles experiences polarisation aberrations (also known as depolarisation) due to polarisation rotation and retardation that has spatial dependence. Therefore, the use of highly curved microscope objective lenses results in a beam that is non-uniformly polarised. It has been shown that the amount of polarisation aberration observed grows exponentially with the microscope's numerical aperture. This has led to a dilemma for many Kerr microscopists whereby high resolution and high sensitivity are mutually conflicting requirements (see references 4-6 listed at the end of the present description).

[0004] Several existing methods can reduce the impact of depolarisation on Kerr imaging sensitivity. One such technique is to place a cross-shaped cut-out of an

opaque material that blocks off the depolarised light while letting light of good polarisation quality to pass through (see reference 7 listed at the end of the present description). While this method represents the best trade-off between resolution and sensitivity, the resolution in the off-axial directions is still compromised. Dark-field observation methods can reduce the amount of depolarisation while maintaining the polarisation but they also reduce the amount of light available for imaging (see reference 8 listed at the end of the present description). Furthermore, microscopists have used confocal imaging methods that theoretically have an infinite extinction ratio (see reference 9 listed at the end of the present description). However, confocal systems are much more complex and expensive than traditional microscopes and most of them rely on some form of scanning that does not offer simultaneous capture of an entire field of view which is important in dynamic studies of magnetic materials.

[0005] Moreover, some form of image subtraction must be implemented in order to obtain a good contrast (see references 5-6 listed at the end of the present description). In the most common implementation of differential imaging, a reference image of the magnetic sample is first obtained at saturation. Any subsequent images taken after an excitation is provided, either by application of an external magnetic field through an electromagnet or by electrical pulses through electrical probes, will be subtracted by the reference image. The resulting difference only shows the changes in the sample caused by the external excitation. Differential imaging techniques can thus allow the observation of magnetization textures which would otherwise be unresolvable in a single frame grab. However, at large magnifications, the image depth of field is extremely shallow and is thus sensitive to vibrations or stage drift. While in-plane drift can be easily corrected by image alignment algorithms, an out-of-plane drift introduces a focus blur that cannot be corrected. Therefore, in differential imaging systems, such physical movement always results in a false contrast that degrades the overall quality of the differential image.

[0006] In Kerr imaging techniques, the method of background subtraction employed is critical to the contrast observed in the Kerr image. In the prior art (see reference 10 listed at the end of the present description), frequency-dependent polarisation rotation is used, i.e. for the same experiment geometry, a 600 nm light will experience less rotation than a 500 nm light. Therefore, if the extinction ratio is tuned for 500 nm light, the magnetization contrast generated will be stronger for 500 nm light and weaker for

the 600 nm light. However, this difference is quite small, usually within a factor of ten and therefore an un-tuned light channel (i.e. for 600nm light) will still contain some magnetization information and therefore subtracting the un-tuned light signal will remove some useful signal.

[0007] It is therefore an aim of the present invention to provide an apparatus and method for Kerr imaging that helps to ameliorate one or more of the above problems.

Summary of the invention

[0008] Aspects of the present invention relate to the construction of a highly-sensitive wide-field reflected polarising microscope to image the polarisation rotation and retardation induced by a sample. In particular, the microscope is configured to detect Kerr rotation and ellipticity of light reflected from a magnetic sample. However, in wide-field microscopes, the presence of polarisation aberrations reduces the polarisation quality in a spatially inhomogeneous manner which disallows the use of conventional waveplates for corrections. By introducing a corrective lens, polarisation aberrations are reduced. Thus, the extinction ratio of the system is increased and a high sensitivity to the Kerr effect is achieved. This sensitivity is further increased by using a white light-emitting diode (LED) light source in conjunction with a narrowband polariser to produce light with polarised and unpolarised channels. Operating in a differential imaging mode with crossed polarisers, a colour-sensitive sensor can detect the polarisation rotation by performing image subtraction on the polarised light channel. Sample drift can be identified simultaneously by analysing the light channel that is unpolarised. Since the unpolarised light cannot contain any polarisation information, any signal must result from stage drift or other unwanted effects.

[0009] In accordance with a first aspect of the invention there is provided a method for removing a false signal from a Kerr image of a magnetic sample comprising:

- a) obtaining a first image of the magnetic sample in a first state of excitation, using a narrowband polariser configured to polarise light of a predetermined wavelength;
- b) obtaining a second image of the magnetic sample in a second state of excitation, using the narrowband polariser, wherein the second state of excitation is different from the first state of excitation;

- c) subtracting the first image from the second image at the predetermined wavelength to obtain a raw Kerr image;
- d) subtracting the first image from the second image at a wavelength for which the narrowband polariser has an extinction ratio of at least two orders of magnitude lower than that for the predetermined wavelength to obtain a false image; and
- e) removing the false image from the raw Kerr image to obtain a Kerr image with false signals removed.

[0010] Thus, embodiments of the first aspect of the invention provide a method for removing a false signal from a Kerr image of a magnetic sample by subtracting unpolarised light signals from the polarised light signals of interest. This helps to remove artefacts due to sample movement whilst preserving the polarisation information. Although it is known in the prior art, to use different light channels to generate backgrounds for subtraction, a different method of manipulating the light channels is employed in the present invention. More specifically, the present invention uses a narrowband polariser with an extinction ratio at the false image wavelength of at least two orders of magnitude lower than that for the predetermined wavelength. Thus, it is expected that the signals at the false image wavelength contain no useful polarisation information and therefore no real information about the magnetisation of the sample. Accordingly, embodiments of the present invention, effectively subtract an unpolarised light signal from the polarised light signal to remove background noise that is not attributable to the magnetisation of the sample.

[0011] The method may further comprise aligning the first image with the second image prior to step c).

[0012] The first state of excitation may be down-saturated or up-saturated. Similarly, the second state of excitation may be down-saturated or up-saturated. In a particular embodiment, the first state of excitation is down-saturated and the second state of excitation is up-saturated. In another embodiment, the first state of excitation is up-saturated and the second state of excitation is down-saturated. In other embodiments, the first and/or second state of excitation may not be a saturated state.

[0013] The predetermined wavelength may be that of green light (i.e. approximately 500-510nm).

[0014] The false image may be obtained at a wavelength of red light (i.e. approximately 650nm), yellow light (i.e. approximately 570nm) or blue light (i.e. approximately 475nm).

[0015] In embodiments of the invention, the narrowband polariser is configured to have an extinction ratio at the predetermined wavelength that is at least 3, at least 4 or at least 5 orders of magnitude higher than that of the false image wavelength.

[0016] One or more alignment marks may be used for aligning the first image with the second image.

[0017] In accordance with a second aspect of the invention there is provided an apparatus for Kerr imaging comprising:

- a light source and a polariser operable to provide polarised light for incidence on a magnetic sample;

- an analyser configured to convert differences in polarisation of the polarised light, after reflection from the magnetic sample, into differences in light intensity; and

- a detector configured to detect the differences in light intensity for display as a Kerr image;

- wherein at least one non-planar lens is employed between the polariser and the analyser and at least one corrective lens is provided to reduce polarisation aberrations introduced by the at least one non-planar lens.

[0018] Thus, embodiments of present aspect provide an apparatus for Kerr imaging which is able to correct for polarisation aberrations and therefore a higher extinction ratio can be achieved. Polarisation aberrations may result from the curved nature of non-planar lenses since a beam of polarised light passing through a curved surface will experience different amounts of bending across a width of the beam depending on when the light enters and exits the curved surface. However, the amount of bending of the polarised light will generally be unknown until it is mapped out. Accordingly, the polarisation aberrations introduced by the apparatus may need to be characterised before a corrective lens is chosen to counteract the observed aberrations.

[0019] It should be noted that the sequence of the non-planar lens and corrective lens is not critical and therefore the corrective lens may be positioned before or after the

non-planar lens to achieve the same de-polarisation effect. In some embodiments of the invention, the corrective lens is used to create an aberration that is similar to that of the non-planar lens. Accordingly, a waveplate (e.g. a half-wave plate) may be provided to reverse the polarity of the polarisation aberrations such that the corrective lens effectively cancels out the reversed polarisation aberrations.

[0020] The corrective lens may comprise one or more concave or convex elements. In some embodiments, the corrective lens may comprise one or more components comprising a convex lens element adjacent a complementary concave lens element. In a particular embodiment, four such components may be employed. Each component may be identical or may comprise convex and concave elements with different physical and/or optical properties.

[0021] The at least one non-planar lens may be constituted by an objective lens, a convex lens, a concave lens, a tube lens etc.

[0022] The light source may be a white light source. The light source may be an LED light source.

[0023] The polariser may be a narrowband polariser. For example, the polariser may be configured to polarise green light but not red or blue light. In particular embodiments, the polariser may be configured to provide at least a 10 times decrease in extinction ratio for a wavelength that is 50nm away from the predetermined wavelength.

[0024] The analyser may be a narrowband polariser arranged in a crossed (e.g. perpendicular) configuration with the polariser. In particular embodiments, the analyser may be configured to provide at least a 10 times decrease in extinction ratio for a wavelength that is 50nm away from the predetermined wavelength.

[0025] An electromagnet may be provided to apply an in-plane or out-of-plane magnetic field to the sample.

[0026] The method of the first aspect of the invention may be applied to images obtained using the apparatus of the second aspect of the invention.

Brief description of the drawings

[0027] Embodiments of the invention will now be described, by way of example only, with reference to the following drawings, in which:

Figure 1 is a schematic diagram of an apparatus for Kerr imaging in accordance with an embodiment of the invention;

Figure 2 shows images of a back focal plane of an objective lens at different analyser settings;

In particular, Figure 2(a) shows an image produced when the analyser is rotated two degrees counter-clockwise with respect to a perpendicular crossed configuration with a polariser;

Figure 2(b) shows an image produced when the analyser is in a perpendicular crossed configuration with a polariser;

Figure 2(c) shows an image produced when the analyser is rotated two degrees clockwise with respect to a perpendicular crossed configuration with a polariser;

Figure 3(a) shows images of a back focal plane of an objective lens with and without a corrective lens according to embodiments of the present invention;

Figure 3(b) shows a cross-sectional view of a corrective lens employed according to embodiments of the present invention;

Figure 3(c) shows a schematic illustration of the effect of a corrective lens on incident polarised light including the spatial configuration of the polarised light as it passes through each component in its path;

Figure 4(a) shows a flow diagram of a method for removing a false signal from a Kerr image of a magnetic sample in accordance with an embodiment of the present invention;

Figure 4(b) illustrates a method for removing a false signal from a Kerr image of a magnetic sample in accordance an embodiment of the present invention; and

Figure 5 shows extinction ratio and transmission (%) for a narrowband polariser used in embodiments of the present invention.

Detailed description

[0028] Exemplary embodiments of the invention are related to the construction of a wide-field reflected microscope apparatus that uses a corrective lens to correct for polarisation aberrations and also the use of narrowband polarisers to identify and reduce the false signal obtained from polarisation-sensitive differential imaging techniques.

[0029] In accordance with a first embodiment of the present invention there is provided an apparatus 10 for high-sensitivity Kerr imaging as illustrated in Figure 1. The apparatus 10 comprises a white light LED light source 12 and a narrowband polariser 14 operable to provide polarised light for incidence on a magnetic sample 16. An analyser 18 is also provided to convert differences in polarisation of the polarised light, after reflection from the magnetic sample 16, into differences in light intensity. A detector in the form of a complementary metal-oxide-semiconductor (CMOS) sensor 20 is configured to detect the differences in light intensity for display as a Kerr image. In this embodiment, a non-planar objective lens 22 is employed between the polariser 14 and the analyser 18 and a corrective lens 24 is further provided to reduce polarisation aberrations introduced by the objective lens 22.

[0030] In operation, the white LED light source 12 is used to supply a broad spectrum beam of light 26 (which is initially collimated) for illumination of the magnetic sample 16. The collimated light 26 from the light source 12 is first focused on to an aperture diaphragm 28 by a first convex lens 30 before encountering a field diaphragm 32. The field diaphragm 32 is placed on a sample conjugate plane 33 to modify a field of view. Thereafter, the light 26 is focused by a second convex lens 34 such that, after passing through the polariser 14 and being reflected by a pellicle beamsplitter 36, the light 26 is focused on a back focal plane 35 of the objective lens 22. The magnetic sample 16 is placed at a focal length of the objective lens 22 such that the light source 12 is in perfect defocus while the magnetic sample 16 is in focus. The magnetic sample 16 is provided on or adjacent an electromagnet 38 which is operated to apply an out-of-plane magnetic field to the magnetic sample 16 during illumination. In other embodiments, an in-plane magnetic field may be applied.

[0031] The light 26 is reflected from the magnetic sample 16 and is collimated by the objective lens 22 and transmitted through the pellicle beamsplitter 36 and corrective lens 24. A wave retarder 40 is employed before the analyser 18, which is constituted by a narrowband polariser arranged in a near perpendicularly crossed-configuration

with the polariser 14. A tube lens 42 provides additional magnification to the light 26 and a concave lens 44 is arranged at the end of the path of the light 26 to form an image on the sensor 20. The additional magnification provided by the tube lens 42 is dependent on a ratio of focal lengths between the tube lens 42 and concave lens 44.

[0032] In this embodiment, a Koehler illumination technique is employed whereby the field diaphragm 32 and aperture diaphragm 28 are arranged to change the divergence and spot size of the incident beam of light 26.

[0033] It should be noted that the chosen location of the narrowband polarisers that constitute the polariser 14 and the analyser 18 can contribute significantly to an extinction ratio of the apparatus. For Kerr imaging, beam intensity may be sacrificed in order to produce a collimated beam of light 26 with near zero angle of incidence with both the polariser 14 and analyser 18. Therefore, the second convex lens 34 has a longer than usual focal length to focus the beam of light 26 onto the back focal plane of the objective lens 22. The placement of the second convex lens 34 after the polariser 14 is not recommended as this would expose the polarised beam to a curved surface that will result in spatial depolarisation.

[0034] The use of a pellicle beamsplitter 36 for epi-illumination almost entirely removes ghosting effects which can cause a significant light leak when the polariser 14 and analyser 18 are crossed. However, as with the use of any beamsplitter, the reflected polarised beam can suffer from a retardation which results in elliptical polarisation. For minimal retardation, a polarisation axis of the analyser 18 is aligned with one of the s- or p- directions.

[0035] The light entering the objective lens 22 was checked for polarisation quality. Any depolarisation that occurs from this point on can be attributed to the curvature of the objective lens 22. For quantification of the depolarisation effect caused by the objective lens 22, the corrective lens 24 was removed and a Bertrand lens (not shown) was placed after the wave retarder 40 and analyser 18 to capture an image of the back focal plane of the objective lens 22 (as explained in more detail in reference 7). Images obtained using this set-up are shown in Figure 2 for different positions of the analyser 18. Figure 2(a) shows an image 50 produced when the analyser 18 is rotated two degrees counter-clockwise with respect to a perpendicular crossed configuration (represented by a vertical line 56) with the polariser 14. Figure 2(b) shows an image

52 produced when the analyser 18 is in a perpendicular crossed configuration with the polariser 14. Figure 2(c) shows an image 54 produced when the analyser 18 is rotated two degrees clockwise with respect to a perpendicular crossed configuration (represented by a vertical line 56) with the polariser 14.

[0036] When the analyser 18 and polariser 14 are in a true perpendicularly crossed configuration (i.e. the analyser 18 is aligned with the vertical line 56) as shown in Figure 2(b), the image 52 includes a dark cross that is characteristic of depolarisation caused by curved surfaces such as those of the objective lens 22. The bright regions are explained by a rotation or retardation of the polarised light such that it is no longer perpendicular to an axis of the polariser 14 or analyser 18. By rotating the analyser 18 (or polariser 14) slightly in each direction, the dark cross splits into two arcs which gradually retreat towards the edges of each image 50, 54. The polarisation axes of the light from the objective lens 22 can be mapped out by rotating the analyser 18 and recording an angle at which a point is darkest. Since this is a spatially dependent effect, no polariser-analyser configuration exists where total extinction can be obtained so a best-fit analysis may be performed. Also, unlike for a transmission microscope, the effect of phase shifts during reflection from the magnetic sample 16 or transmission through the beamsplitter 36 may be significant and can alter the depolarisation.

[0037] Figure 3(a) shows a first image 60 of a back focal plane of an objective lens 22 without polarisation correction (similar to that of Figure 2(b)) and a second image 62 of a back focal plane of the objective lens 22 with polarisation correction by employing the corrective lens 24 of Figure 1 according to an embodiment of the invention. Both images 60, 62 were taken at the same exposure settings and with the polariser 14 and analyser 18 in a crossed-configuration to produce an optimum extinction ratio (i.e. where the majority of the pixels are at their darkest). In this case, the difference in brightness is due to a difference in the amount of depolarised light. In other words, the image 62 produced using the corrective lens 24 greatly reduces the amount of depolarised light due to the non-planar nature of the objective lens 22 such that the pixels are more uniformly dark across the image 62 and the dark cross of image 60 is much less apparent.

[0038] Although the maximal amount of correction provided by the present corrective lens 24 is insufficient to completely repolarise the light, its use was shown to increase the extinction ratio of the objective lens 22 from 600 to 1600. Consequently, the

apparatus is significantly more sensitive and a greatly enhanced Kerr image can be achieved as a result.

[0039] The image 62 was produced used a corrective lens 24 having a configuration illustrated in Figure 3(b). Thus, in this embodiment, the corrective lens 24 consists of four components of closely packed pairs of concave elements 72 and convex elements 74 such that there is a total of four concave, four convex and eight planar surfaces. In other embodiments, a single highly curved corrective lens 24 may be employed. However, the configuration shown in Figure 3(b) is currently used because highly curved lenses are uncommon and the four components shown can achieve the same corrective effect as a highly curved lens. In this instance, the concave elements 72 and convex elements 74 are all identical so that the overall optical power of the corrective lens 24 is zero and the optical path is not substantially altered. However, it is noted that the corrective lens 24 employed in any given apparatus will be chosen to provide the required amount of polarisation correction based on observed polarisation aberrations produced by the optical components present.

[0040] It has been observed that the corrective lens 24 of Figure 3(b) can produce a polarisation rotation that reduces the depolarisation caused by optical components in the apparatus, including those due to the non-planar nature of the objective lens 22. Since the amount of polarisation rotation produced by the corrective lens 24 depends on an angle of incidence, the position of the corrective lens 24 along the objective axis can be modified to increase or decrease the amount of polarisation rotation. For improved illumination efficiency and compactness, a single deeply curved glass meniscus lens could constitute the corrective lens 24 used instead of the design shown in Figure 3(c). In this case, the gain in illumination efficiency would result from a decrease in the absorption length and lower number of reflection surfaces within the corrective lens 24.

[0041] Figure 3(c) shows a schematic illustration of the effect of the corrective lens 24 (in this case constituted by a single glass meniscus) on incident polarised light 26 including the spatial configuration of the polarised light 26 as it passes through each component in its path. It will be noted that the order of the components in the optical path presented in Figure 3(c) is different from that described above in relation to Figure 1 and is for illustrative purposes only. The spatial configuration of the polarised light 26 along a cross-section of the light beam is represented by lines shown on the left-hand

side of Figure 3(c). After passing through the polariser 24, the polarised light 26 has a uniform spatial configuration represented by multiple horizontal lines. As the polarised light 26 is incident on the corrective lens 24, a positive aberration results, whereby the lines in the top of the light beam are tilted downwardly and inwardly and the lines in the bottom of the light beam are tilted upwardly and inwardly. The positive aberration is reversed by the half-waveplate 40 to become a negative aberration (whereby the lines in the top of the light beam are tilted upwardly and inwardly and the lines in the bottom of the light beam are tilted downwardly and inwardly). Finally, when incident on the curved surface of the objective lens 22, a positive aberration is incurred, which cancels the negative aberration and results in uniformly polarised light 26.

[0042] Figure 4(a) shows a flow diagram of a method 120 for removing a false signal from a Kerr image of a magnetic sample comprising:

- a) Step 122 of obtaining a first image of the magnetic sample in a first state of excitation, using a narrowband polariser configured to polarise light of a predetermined wavelength;
- b) Step 124 of obtaining a second image of the magnetic sample in a second state of excitation, using the narrowband polariser, wherein the second state of excitation is different from the first state of excitation;
- c) An optional Step 126 of aligning the first image with the second image;
- d) Step 128 of subtracting the first image from the second image at the predetermined wavelength to obtain a raw Kerr image;
- e) Step 130 of subtracting the first image from the second image at a wavelength for which the narrowband polariser has an extinction ratio of at least two orders of magnitude lower than that for the predetermined wavelength to obtain a false image; and
- f) Step 132 of removing the false image from the raw Kerr image to obtain a Kerr image with false signals removed.

[0043] Figure 4(b) illustrates in more detail a method 80 for removing a false signal from a Kerr image of a magnetic sample 16 in accordance with the general method outlined in Figure 4(a). The method 80 comprises obtaining a first image 82 of the magnetic sample 16 in a first state of excitation (in this case, up-saturated

magnetisation 84), using a narrowband polariser 14 configured to polarise light of a predetermined wavelength (in this case, green light) and obtaining a second image 86 of the magnetic sample 16 in a second state of excitation (in this case, down-saturated magnetisation 88), using the narrowband polariser 14. In step 90, the first image is aligned with the second image (although this step may not be required if the system is extremely stable and the images are aligned when they are both captured) and then the first image 82 is subtracted from the second image 86 at the predetermined (green) wavelength to obtain a raw Kerr image 92. In addition, the first image 82 is subtracted from the second image 86 at a wavelength (e.g. red) for which the narrowband polariser 14 has an extinction ratio of four orders of magnitude lower than that for the predetermined (green) wavelength to obtain a false image 94. In other embodiments, a wavelength for which the narrowband polariser 14 has an extinction ratio of at least two orders of magnitude lower than that for the predetermined wavelength may be employed. The raw Kerr image 92 is then divided by the false image 94 in step 96 to obtain an output Kerr image 98 with false signals removed.

[0044] As shown in Figure 4(b), the magnetic sample 16 comprises a 1µm wide magnetic nanowire 100 with four accompanying Au contact pads 102 for alignment, provided on a substrate. The highlighted areas in both of the first 82 and second 86 images indicate the magnetic materials. To the naked eye, the first 82 and second 86 images appear almost identical because the change in light intensity due to polarisation rotation is too weak to be observed in the presence of the background non-magnetic signal. Subtracting the images in a differential imaging mode can remove the background signal and only show the magnetization changes in the magnetic sample 16. Before subtraction, the first 82 and second 86 images can be aligned by detecting phase shifts in Fourier space and introducing a negative phase in one of the images. However, due to out-of-plane stage drift (i.e. movement of the magnetic sample 16), both the first 82 and second 86 images are taken in a different focal plane which will result in the formation of halos on the edges of the magnetic materials in the subtracted image. Such artefacts severely degrade the image quality and complicate analysis, especially when the amount of Kerr rotation is small.

[0045] In the present embodiment of the invention, an RGB CMOS sensor was used to capture the images and narrowband 520nm polarisers were used (as the polariser and analyser) to polarise only the green channel of the light spectrum. Accordingly, the subtraction of the first image 82 from the second image 86 in the green channel reveals

the changes in polarisation in the raw Kerr image 92. However, the effects of stage drift are also present. After the subtraction, image equalisation was performed such that zero contrast is represented by the middle intensity value in a grayscale and any other signal is represented by either white or black contrast. In this embodiment, during magnetic field application or excitation, only the top two alignment marks 102 and the nanowire 100 experienced magnetisation reversal as evidenced by their dark contrast in the raw Kerr image 92. However, in addition to the black contrast resulting from the magnetisation reversal, the non-magnetic electrical contacts also produced an unwanted signal. To identify the unwanted signal originating from the stage drift in this example, image subtraction in the red channel was used. As the red channel is largely unpolarised, the difference between the first 82 and second 86 images show only the false signal resulting from the stage drift, as shown in the false image 94. The false image 94 is displayed in an absolute scale, with no signal represented by black. As such, the false image 94 is largely black, except for the outline of the electrical contacts. This indicates that the false image 94 is only generated at the non-magnetic electrical contacts. A low-pass Gaussian filter was applied to the false image 94 to produce a softer image. The raw Kerr image 92 was then divided by the false image 94, resulting in a cleaner output Kerr image 98 with false signals (e.g. due to stage drift) removed. For comparison, different output images obtained using a conventional differential imaging method verses the proposed method 80 are shown in the raw Kerr image 92 and output Kerr image 98, respectively. As such, it can be seen that embodiments of the present invention provide a method 80 for effectively removing a false signal from a Kerr image of a magnetic sample 16.

[0046] Figure 5 shows a graph 110 of extinction ratio 112 and transmission (%) 114 for a narrowband polariser used in embodiments of the present invention. This shows that at 505 nm (green light), the extinction ratio is roughly $2.5E7$ whereas for red light (600 nm) or blue light (<470 nm), the extinction ratio drops below 1000. Accordingly, there is four orders of magnitude difference in the extinction ratio. It is therefore expected that the red and blue light channels contain no information about magnetisation, when compared to the green light channel. Consequently, a pure magnetisation signal can be obtained by taking the difference between the green (polarised) light and the non-green (unpolarised) light.

[0047] Embodiments, of the invention relate to the use of a corrective lens 24 to correct for the depolarisation in an epi-illuminated polarising microscope. The

corrective lens 24 comprises at least one refractive material with at least one curved surface which rotates the polarisation in an equal and opposite manner to the induced depolarisation. In embodiments of the invention, the retardation caused by a pellicle beamsplitter 36 may be significant and should be taken into considered. The ideal shape and form of the corrective lens 24 may be calculated by mapping the polarisation axes.

[0048] Some embodiments of the invention relate to a method 80 for effectively removing a false signal from a Kerr image of a magnetic sample 16. This may comprise obtaining a raw Kerr image 92 at a wavelength for which the extinction ratio of the polariser 14 is maximum and dividing it by a false image 94 at a wavelength for which the extinction ratio of the polariser 14 is at least two orders of magnitude lower so as to remove false signals not relating to polarisation rotation.

[0049] Although only certain embodiments of the present invention have been described in detail, many variations are possible in accordance with the appended claims. For example, features described in relation to one embodiment may be incorporated into one or more other embodiments and vice versa.

References

[0050] The following references are incorporated herein by reference, with regards to the background of the invention.

- 1 Chiba, D. *et al.* Electric-field control of magnetic domain-wall velocity in ultrathin cobalt with perpendicular magnetization. *Nat Commun* 3, 888, doi:10.1038/ncomms1888 (2012).
- 2 Jiang, W. *et al.* Blowing magnetic skyrmion bubbles. *Science* 349, 283-286, doi:10.1126/science.aaa1442 (2015).
- 3 Yamanouchi, M., Chiba, D., Matsukura, F., Dietl, T. & Ohno, H. Velocity of Domain-Wall Motion Induced by Electrical Current in the Ferromagnetic Semiconductor (Ga,Mn)As. *Phys Rev Lett* 96, 096601 (2006).
- 4 Shribak, M., Inoue, S. & Oldenbourg, R. Polarisation aberrations caused by differential transmission and phase shift in high-numerical-aperture lenses: theory, measurement, and rectification. *Optical Engineering* 41, 943-954 (2002).

- 5 Kuch, W., Schäfer, R., Fischer, P. & Hillebrecht, F. U. *Magnetic Microscopy of Layered Structures*. (Springer, 2015).
- 6 Hubert, A. & Schäfer, R. *Magnetic domains: the analysis of magnetic microstructures*. (Springer Science & Business Media, 2008).
- 7 Rohrmann, H. & Hoffmann, H. High-resolution Kerr observation of magnetic domains. *Thin solid films* 175, 273-279 (1989).
- 8 Thiaville, A., Boileau, F., Miltat, J. & Arnaud, L. Direct Bloch line optical observation (invited). *J Appl Phys* 63, 3153, doi:10.1063/1.340873 (1988).
- 9 Savoini, M., Ciccacci, F., Duo, L. & Finazzi, M. Apparatus for vectorial Kerr confocal microscopy. *Rev Sci Instrum* 82, 023709, doi:10.1063/1.3555757 (2011).
- 10 Hoshtanar, O, Dynamic Domain Observation in Grain-Oriented Electrical Steel Using Magneto-Optical Techniques, Thesis, Cardiff University, 2006.

Claims

1. A method for removing a false signal from a Kerr image of a magnetic sample comprising:
 - a) obtaining a first image of the magnetic sample in a first state of excitation, using a narrowband polariser configured to polarise light of a predetermined wavelength;
 - b) obtaining a second image of the magnetic sample in a second state of excitation, using the narrowband polariser, wherein the second state of excitation is different from the first state of excitation;
 - c) subtracting the first image from the second image at the predetermined wavelength to obtain a raw Kerr image;
 - d) subtracting the first image from the second image at a wavelength for which the narrowband polariser has an extinction ratio of at least two orders of magnitude lower than that for the predetermined wavelength to obtain a false image; and
 - e) removing the false image from the raw Kerr image to obtain a Kerr image with false signals removed.
2. The method according to claim 1 further comprising aligning the first image with the second image prior to step c).
3. The method according to claim 1 or 2 wherein either: i) the first state of excitation is up-saturated and the second state of excitation is down-saturated; or ii) the first state of excitation is down saturated and the second state of excitation is up-saturated.
4. The method according to any one of claims 1 to 3 wherein the predetermined wavelength is that of green light.
5. The method according to any one of claims 1 to 4 wherein the false image is obtained at a wavelength of red light, yellow light or blue light.
6. The method according to any one of claims 1 to 5 wherein the narrowband polariser is configured to have an extinction ratio at the predetermined wavelength that

is at least 3, at least 4 or at least 5 orders of magnitude higher than that of the false image wavelength.

7. An apparatus for Kerr imaging comprising:

a light source and a polariser operable to provide polarised light for incidence on a magnetic sample;

an analyser configured to convert differences in polarisation of the polarised light, after reflection from the magnetic sample, into differences in light intensity; and

a detector configured to detect the differences in light intensity for display as a Kerr image;

wherein at least one non-planar lens is employed between the polariser and the analyser and at least one corrective lens is provided to reduce polarisation aberrations introduced by the at least one non-planar lens.

8. The apparatus according to claim 7 wherein a waveplate is provided to reverse the polarity of the polarisation aberrations.

9. The apparatus according to claim 7 or 8 wherein the corrective lens comprises one or more concave or convex elements.

10. The apparatus according to any one of claims 7 to 9 wherein the corrective lens comprises one or more components comprising a convex lens element adjacent a complementary concave lens element.

11. The apparatus according to claim 10 wherein four such components are employed.

12. The apparatus according to claim 10 or 11 wherein each component comprises convex and concave elements with the same physical and/or optical properties.

13. The apparatus according to any one of claims 7 to 12 wherein at least one non-planar lens is constituted by an objective lens, a convex lens, a concave lens or a tube lens.

14. The apparatus according to any one of claims 7 to 13 wherein the light source is a white light source.

15. The apparatus according to any one of claims 7 to 14 wherein the light source is an LED light source.
16. The apparatus according to any one of claims 7 to 15 wherein the polariser is a narrowband polariser.
17. The apparatus according to any one of claims 7 to 16 wherein the polariser is configured to only polarise green light.
18. The apparatus according to any one of claims 7 to 17 wherein the analyser is a narrowband polariser arranged in a crossed configuration with the polariser.
19. The apparatus according to claim 18 wherein the analyser is arranged perpendicularly to the polariser.
20. The method according to any one of claims 1 to 6 applied to images obtained using the apparatus of any of claims 7 to 19.

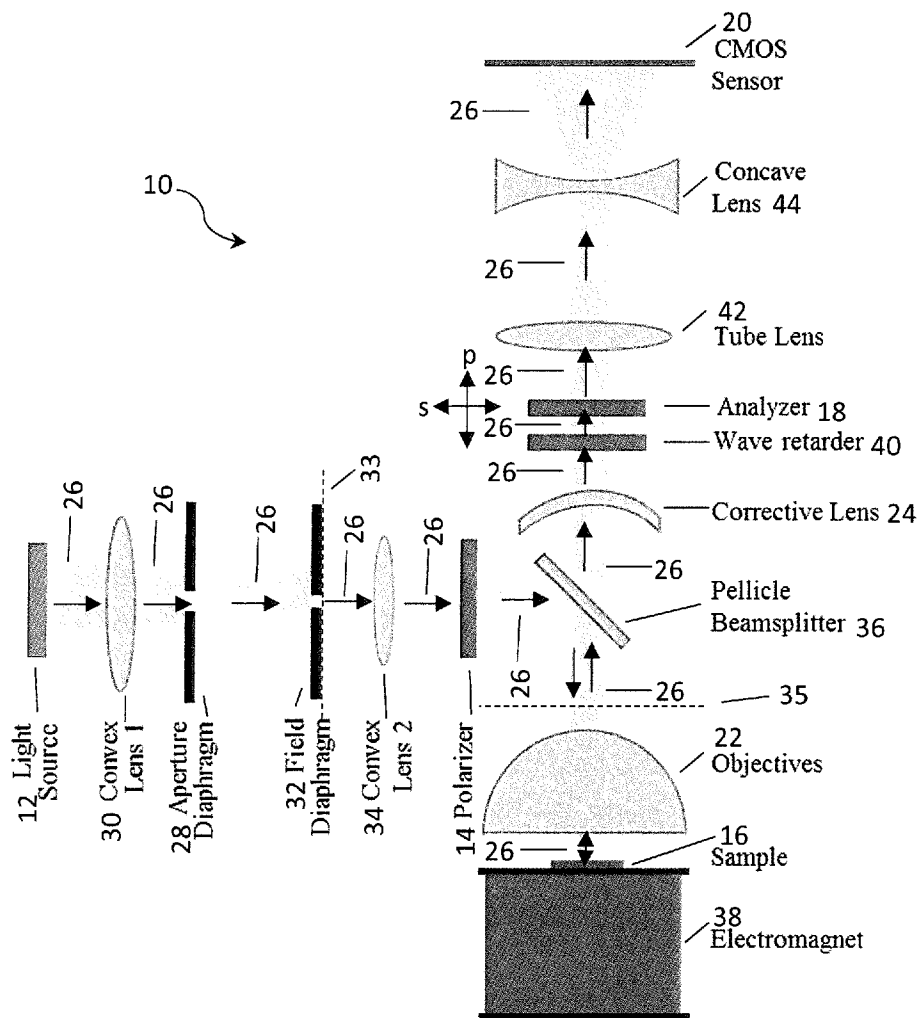


Figure 1

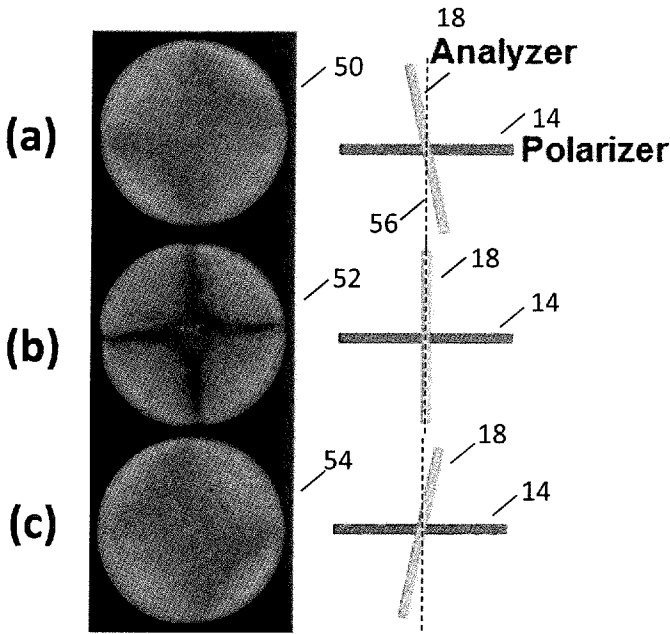


Figure 2

3/6

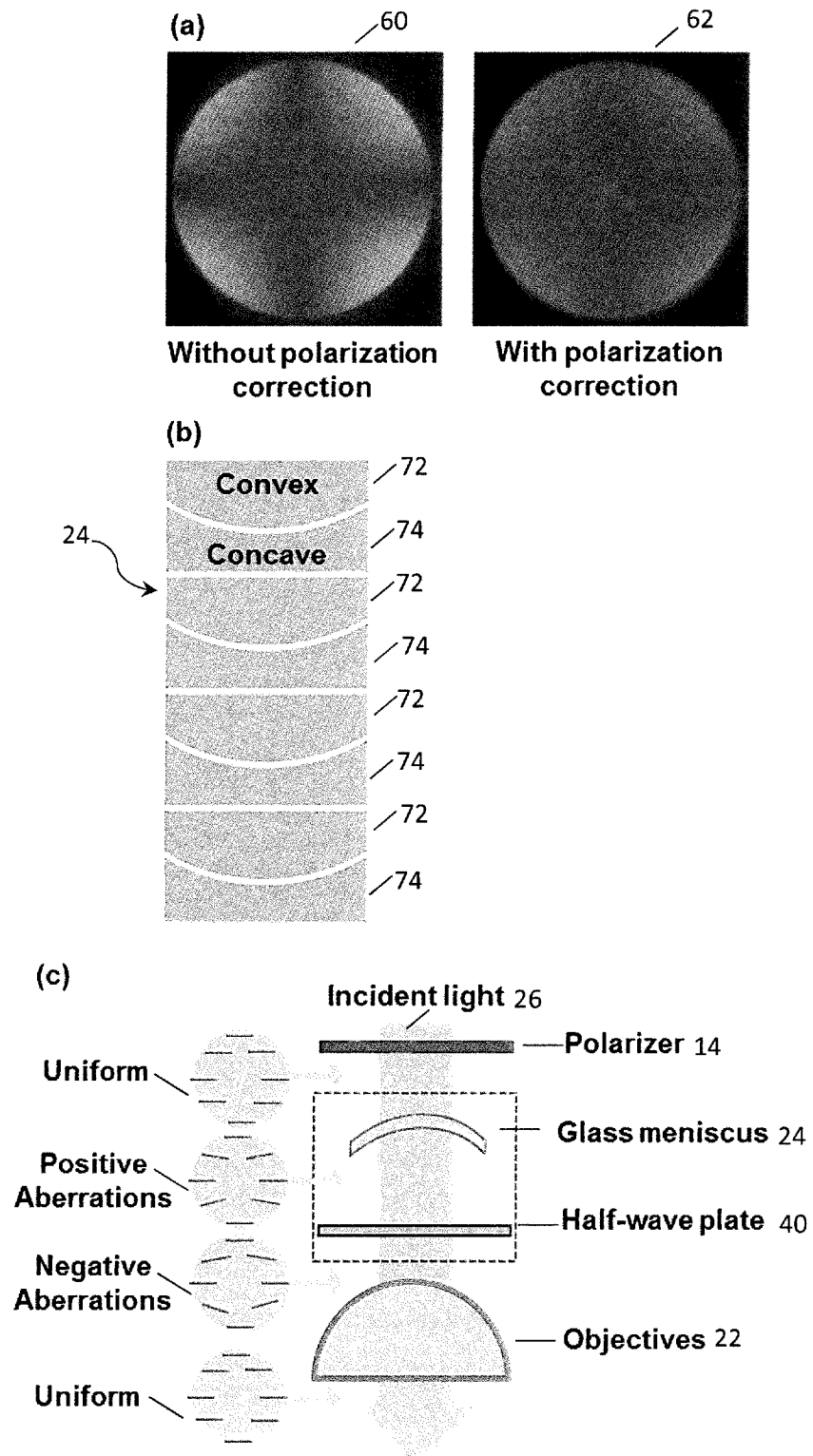
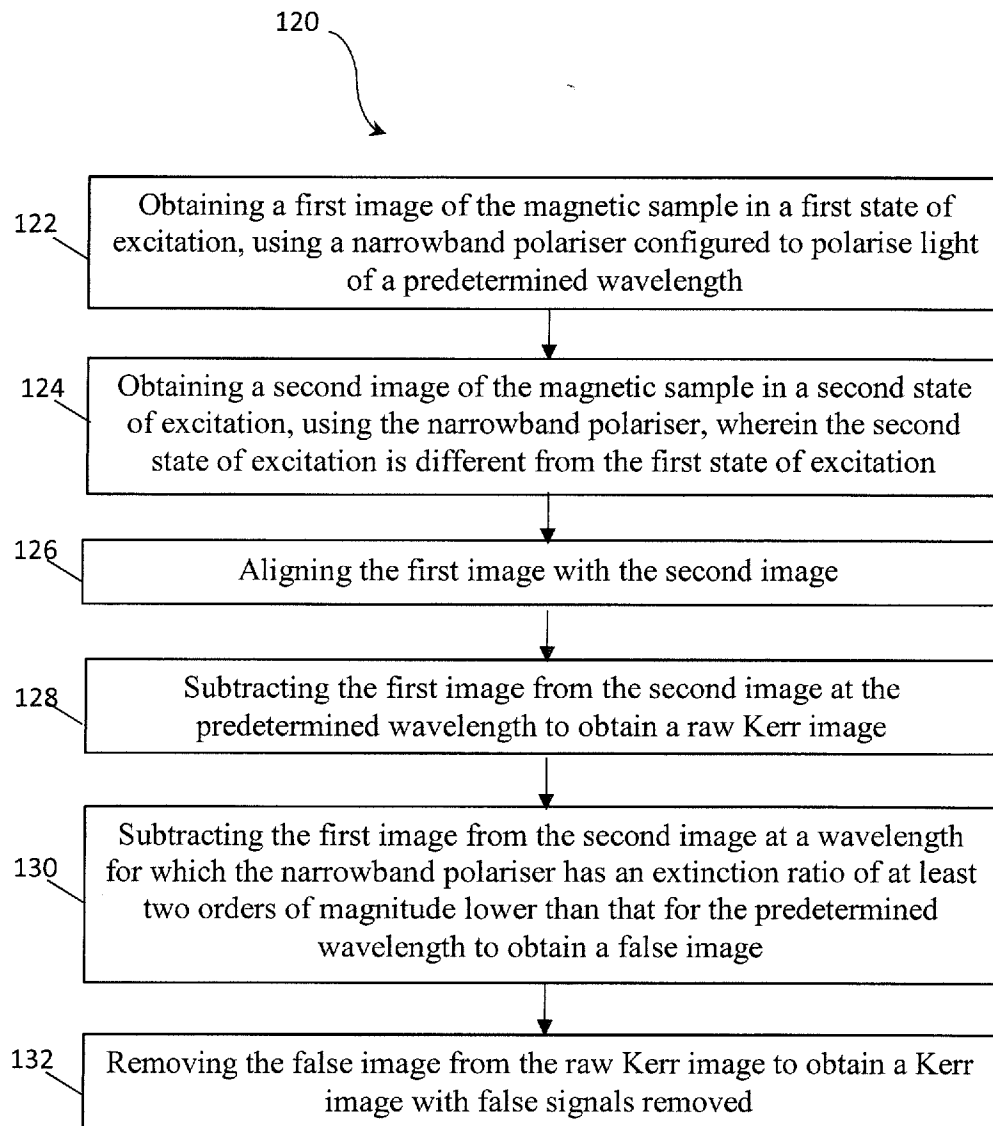


Figure 3

4/6

**Figure 4(a)**

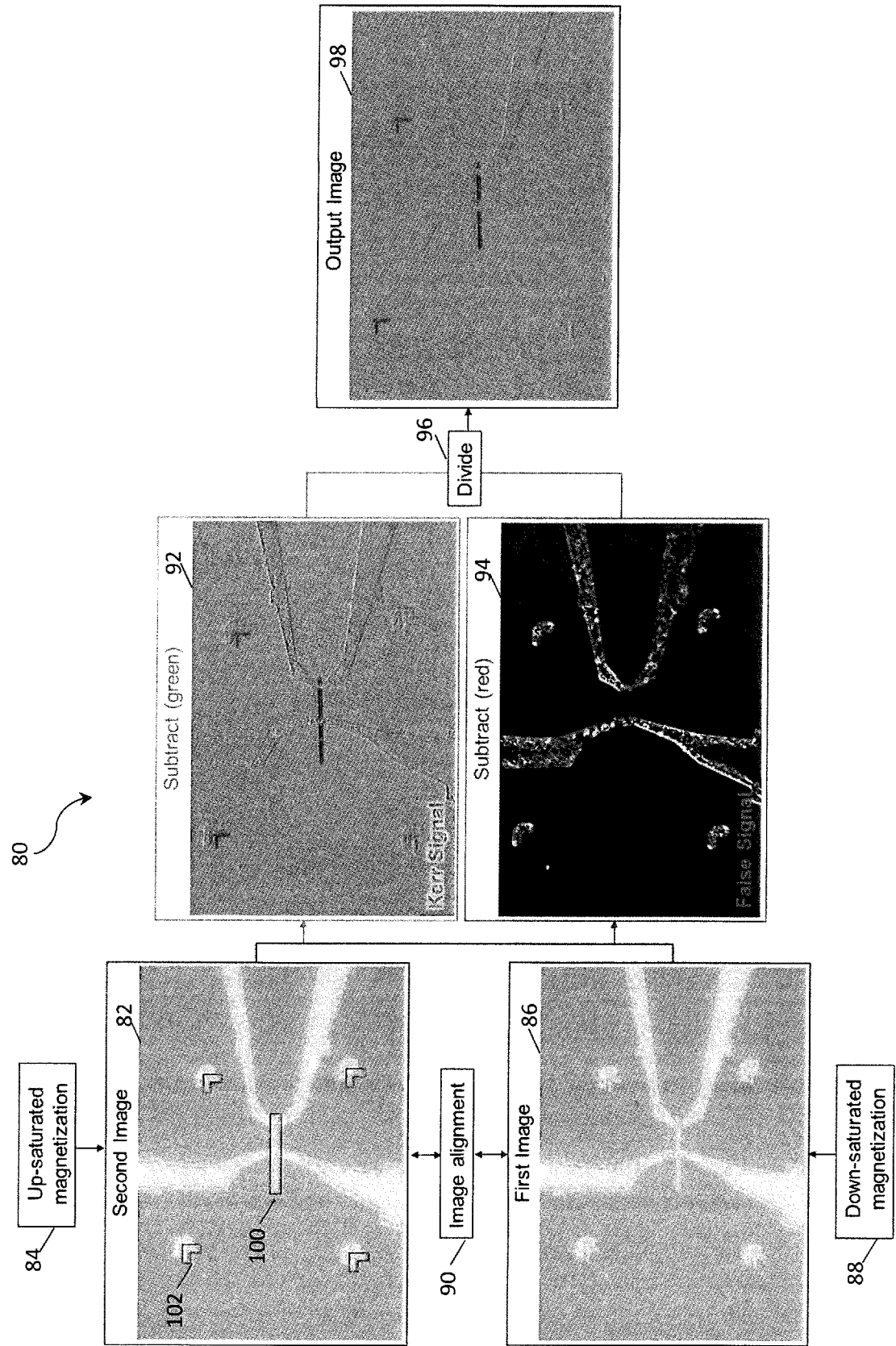


Figure 4(b)

6/6

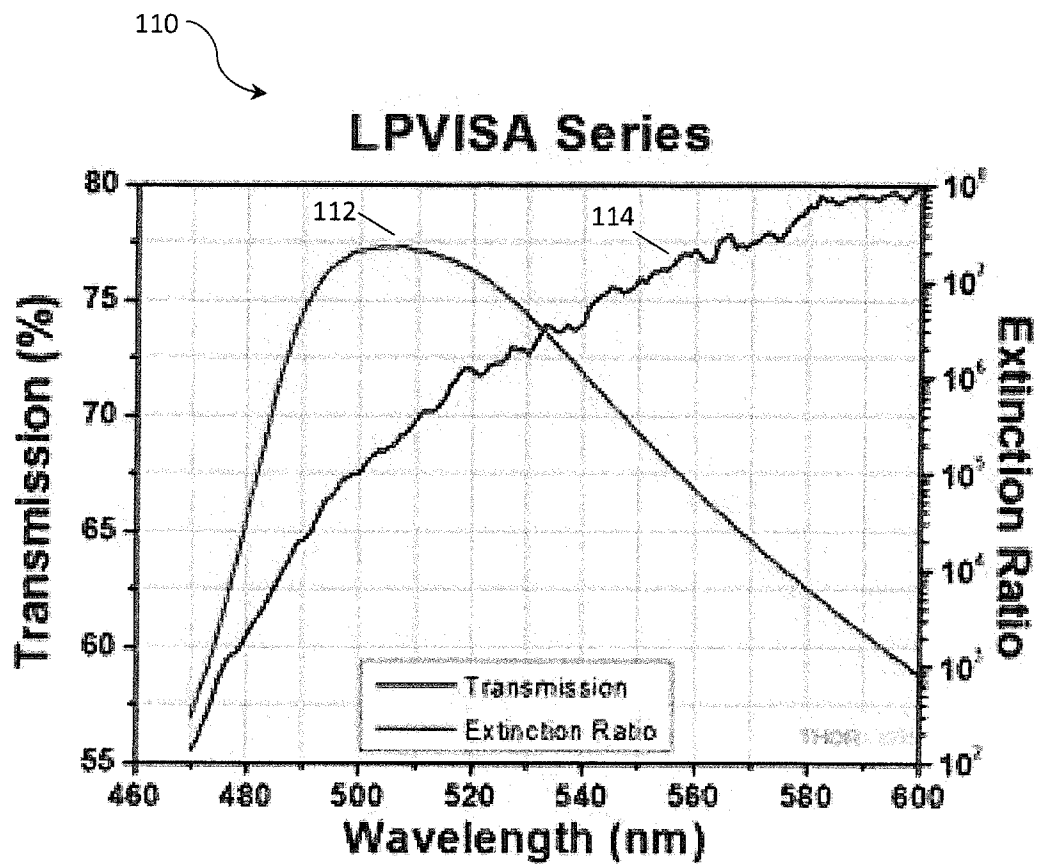


Figure 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2017/050237

A. CLASSIFICATION OF SUBJECT MATTER

G01N 21/21 (2006.01) G01R 33/032 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N, G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FamPat, IEEE: false image, artefact, background subtraction, magnetic contrast, extinction ratio and other related terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	MCCORD, J. Progress in magnetic domain observation by advanced magneto-optical microscopy. <i>Journal of Physics D: Applied Physics</i> , 16 July 2015, Vol. 48, No. 33, pages 333001:1-43 [Retrieved on 2017-06-22] <DOI: 10.1088/0022-3727/48/33/333001> Whole document especially pg. 17-18, 4.2 MO signal enhancement by digital image processing, fig. 20	1-6, 20
A	High Frequency Behaviour of Magnetic Thin Film Elements for Microelectronics. 20 February 2006 [Retrieved on 2017-06-22 from https://www.ifw-dresden.de/userfiles/groups/imw_folder/publications/theses/Dr_Chumakov.pdf] Whole document especially pg. 17-18, Background subtraction and contrast enhancement, fig. 2.3	1-6, 20
A	US 6593739 B1 (ARGYLE, B. E. AND MCCORD, J. G.) 15 July 2003 Whole document especially col. 4 line 30-col. 9 line 45, claim 1	1-6, 20
A	JP H07-167933 A (NIPPON KOGAKU KK) 4 July 1995 Whole document of the machine translation especially para. [0043]-[0070]	1-6, 20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

*Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

27/06/2017 (day/month/year)

Date of mailing of the international search report

12/07/2017 (day/month/year)

Name and mailing address of the ISA/SG



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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2017/050237

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:

because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:

because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:

because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please refer to Supplemental Box (Continuation of Box No. III).

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-6 (fully) and 20 (partially)

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2017/050237

Supplemental Box **(Continuation of Box No. III)**

This International Searching Authority found multiple inventions in this international application, as follows:

Invention 1: claims 1-6 (fully) and 20 (partially) relate to a method for removing a false signal from a Kerr image, characterised in that the false image is obtained at a wavelength for which a polariser has an extinction ratio of at least two orders of magnitude lower than that for a predetermined wavelength.

Invention 2: claims 7-19 (fully) and 20 (partially) relate to a Kerr imaging apparatus, characterised in that at least one corrective lens is provided to reduce polarisation aberrations.

Please refer to **Box No. IV** of Written Opinion of The International Searching Authority (Form PCT/ISA/237) for detailed explanation.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2017/050237

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 6593739 B1	15/07/2003	NONE	
JP H07-167933 A	04/07/1995	NONE	