

APPARATUS FOR GENERATING MAGNETIC FIELD, IMAGING DEVICE HAVING THE SAME, AND METHOD FOR IMAGING A SAMPLE

Cross-Reference To Related Application

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[0001] This application claims the benefit of priority of Singapore patent application No. 10201800208W, filed 9 January 2018, the content of it being hereby incorporated by reference in its entirety for all purposes.

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Technical Field

[0002] Various embodiments relate to an apparatus for generating a magnetic field, an imaging device having the apparatus, and a method for imaging a sample.

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Background

[0003] Kerr microscopy is a powerful observation technique for the study of magnetic materials for use in permanent magnets, motors, and spintronic devices. The technique irradiates the magnetic sample with polarized light and detects the changes in polarization upon reflection. However, the polarization rotation is typically weak and differential imaging techniques are frequently used to increase the magnetic contrast. In the most common implementation of differential imaging, a strong magnetic field is applied such that the magnetization is saturated in the field direction, thus forming an image that only contains the non-magnetic background signal. By subtracting subsequent images with the background image, the magnetic contrast is greatly amplified. However, to saturate the magnetization, a strong magnetic field is usually required.

[0004] To supply the intense magnetic fields required, the most common strategy is to use a double pole electromagnet configuration in which two electromagnet cores are in a coplanar configuration with current flowing in the same handedness. In such a configuration, most of the magnetic flux is contained in a highly permeable material, thus producing a uniform and intense magnetic field in the region between the poles. However, the use of a double pole

electromagnet imposes stringent spatial constraints that will limit the use of imaging objectives, i.e., when imaging is conducted in the direction of the magnetic field. Furthermore, high magnification objectives have a short working distances of less than 1 cm, which makes it impractical to construct the second pole between the samples and objectives. Therefore, the use of known double pole configurations is unsuitable for a Kerr microscope.

[0005] The second challenge of electromagnet design for Kerr imaging lies in the effect of stray field on the microscope objectives. Light passing through a dielectric medium under an applied magnetic field experiences a Faraday rotation in polarization. Therefore, when the objectives are exposed to the intense magnetic fields that are used to saturate the sample, the light polarization is rotated. The known method to alleviate this problem is using a rotatable analyzer. The analyzer is rotated to compensate the additional Faraday rotation induced by the objectives. However, this method requires a tedious calibration process to quantify the amount of Faraday rotation experienced at various applied magnetic fields. Furthermore, analyzers often have a spatially non-uniform polarization angle; rotating the polarizer will not exactly compensate for the Faraday rotation. Therefore, imaging at high magnetic fields remains a significant challenge.

Summary

[0006] The invention is defined in the independent claims. Further embodiments of the invention are defined in the dependent claims.

[0007] According to an embodiment, an apparatus for generating a magnetic field is provided. The apparatus may include a device configured to generate the magnetic field with a corresponding magnetic flux emanating from a first region of the device and returning to a second region of the device, and a magnetically permeable element, wherein the magnetically permeable element is adapted to be arranged to interact with the magnetic field to configure the apparatus in a closed flux configuration to provide a path directing the magnetic flux from the first region of the device towards the second region of the device, and wherein the magnetically permeable element is removable away from the magnetic field to configure the apparatus in an open flux configuration.

[0008] According to an embodiment, an imaging device is provided. The imaging device may include the apparatus as described herein.

[0009] According to an embodiment, a method for imaging a sample is provided. The method may include generating a magnetic field using the device of the apparatus as described herein, configuring the apparatus in the closed flux configuration, wherein the magnetically permeable element is arranged to interact with the generated magnetic field to provide a path directing the magnetic flux corresponding to the generated magnetic field from the first region of the device towards the second region of the device, positioning the sample between the device and the aperture of the magnetically permeable element, and imaging the sample through the aperture.

Brief Description of the Drawings

[0010] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0011] FIG. 1A shows a schematic view of an apparatus for generating a magnetic field, according to various embodiments.

[0012] FIG. 1B shows a schematic block diagram illustrating an imaging device, according to various embodiments.

[0013] FIG. 1C shows a flow chart illustrating a method for imaging a sample, according to various embodiments.

[0014] FIGS. 2A and 2B show perspective views of an apparatus in an open flux configuration, while FIGS. 2C and 2D show perspective views of an apparatus in a closed flux configuration.

[0015] FIGS. 3A to 3C show the numerically calculated magnetic flux distribution for a single pole open flux electromagnet design, while FIGS. 3D to 3F show the numerically calculated magnetic flux distribution for a B-shaped closed flux electromagnet design.

[0016] FIG. 4 shows a plot of the magnetic flux density along the z-axis for the electromagnets of FIGS. 3A to 3F.

[0017] FIGS. 5A and 5B show photographs illustrating a front view of the apparatus of various embodiments in the open flux configuration and in the closed flux configuration respectively

during imaging of a sample, FIG. 5C shows a photograph illustrating a side view of the apparatus of FIG. 5A, while FIG. 5D shows a plot of magnetic flux density as a function of applied current for the open flux and closed flux electromagnets.

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Detailed Description

[0018] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

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[0019] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

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[0020] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

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[0021] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

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[0022] In the context of various embodiments, the term “about” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0023] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0024] Various embodiments may provide an electromagnet design, for example, for Kerr imaging. Exemplary embodiments of the technology may be related to the design of a B-shaped

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closed flux apparatus with an electromagnet. An experimental setup that uses the apparatus for Kerr imaging will be described further below.

[0025] Exemplary embodiments relate to a closed-flux electromagnet design that may enable high-field *in-situ* Kerr imaging. The application of a strong magnetic field is critical for creating reference magnetization images for Kerr imaging. However, known single pole electromagnets are unable to produce a strong magnetic field and subject the microscope objectives to a strong magnetic field. The latter causes the polarization to be rotated by Faraday's effect. These challenges may be addressed by using a B-shaped apparatus/electromagnet design with an imaging aperture as will be described further below. The closed flux design may ensure that the magnetic field permeating into the objectives are kept to a minimum while allowing a large magnetic field to be applied across the observation sample. The design of various embodiments may also allow easy reconfiguration between the closed-flux and open flux states for maximum versatility.

[0026] In various embodiments, there may be provided an electromagnet including an electromagnet core element having a base portion and a tapered portion, wherein the electromagnet core element may be placed on a planar support such that the base portion of the electromagnet core element contacts the planar support and the tip of the tapered portion of the electromagnet core element faces away from the planar support. An n-shaped (or C-shaped) cover may be arranged over the electromagnet core element.

[0027] The cover may have two side walls and a horizontal surface which extends between the ends of the two side walls. The other ends of the side walls opposing to the horizontal surface may be placed, attached or affixed on the planar support. The side walls may have a planar surface or a curved surface.

[0028] Further, the cover may include an aperture which may be aligned with the tip of the tapered portion of the electromagnetic core element. The aperture may be provided to allow imaging of a sample placed at or adjacent to the tip of the electromagnetic core element.

[0029] The middle section of the horizontal surface of the cover, in which the aperture may be formed, may be thinner as compared to the two adjacent sections. This may allow objectives (lens) with shorter working distances to be placed on or adjacent to the middle section for sample imaging.

[0030] FIG. 1A shows a schematic view of an apparatus 100 for generating a magnetic field, according to various embodiments. The apparatus 100 includes a device 102 configured to generate the magnetic field with a corresponding magnetic flux (represented by dashed lines 106) emanating from a first region 108a of the device 102 and returning to a second region 108b of the device 102, and a magnetically permeable element 104, wherein the magnetically permeable element 104 is adapted to be arranged to interact with the magnetic field to configure the apparatus 100 in a closed flux configuration to provide a path directing the magnetic flux 106 from the first region 108a of the device 102 towards the second region 108b of the device 102, and wherein the magnetically permeable element 104 is removable away from the magnetic field to configure the apparatus 100 in an open flux configuration.

[0031] In other words, an apparatus 100 capable of providing a magnetic field is provided. The apparatus 100 may include a device 102 that may generate a magnetic field with an associated magnetic flux 106. The device 102 may be positioned on a surface. The magnetic flux 106 may emanate from one region 108a of the device 102 towards or to another region 108b of the device 102, thereby closing the flux loop. It should be appreciated that a magnetic flux associated with a magnet generally forms a continuous flux loop through the magnet, and emanating from the magnet into free space outside of the magnet and returning to the magnet.

[0032] The first region 108a may be an upper region or portion of the device 102. The second region 108b may be a lower region or portion of the device 102, e.g., a base region of the device 102. The first region 108a and the second region 108b may be opposite end regions of the device 102.

[0033] The apparatus 100 may further include a magnetically permeable element 104. The magnetically permeable element 104 may be adapted to be arranged to interact with the magnetic field (for example moving the magnetically permeable element 104 as illustrated by the solid arrow into a suitable position) so as to configure the apparatus 100 in a closed flux configuration to provide a (magnetic) path that may re-direct the magnetic flux 106 from the first region 108a towards (or to) the second region 108b, and wherein the magnetically permeable element 104 may be removed away from the magnetic field (or from the magnetic flux 106) (for example moving the magnetically permeable element 104 out of position as

illustrated by the open arrow) to configure the apparatus 100 in an open flux configuration. The magnetically permeable element 104 may define a frame.

[0034] In the context of various embodiments, the magnetic field associated with the device 102 means the area or region around or in the vicinity of the device 102 in which there is a magnetic force.

[0035] In the context of various embodiments, the term “magnetic flux” may include a reference to the “magnetic field lines”, and that a property of magnetic flux is that the magnetic flux emanates from a source and return to it (e.g., emanating from the north pole and returning to the south pole of a magnet), thereby closing the flux loop. In a further technical description, the term “magnetic flux” may define a measurement unit where “magnetic flux is the product of the average magnetic field times the perpendicular area that it penetrates”. Both definitions of magnetic flux are equivalent, although explained differently. The first definition emphasises the properties/characteristics, while the latter definition is from a fundamental point of view. Using the more technical explanation to magnetic flux (in terms of a measurement unit), the skilled person can also arrive at the definition relating to the property of flux. Further, correspondingly, the term “magnetic flux density” may mean the measurement of the “density of the field lines”.

[0036] In the context of various embodiments, in the closed flux configuration, the presence of the magnetically permeable element 104 presents a low resistance (hence permeable) path for the magnetic flux 106 and helps in closing the flux loop. The magnetic flux 106 may pass into and through the magnetically permeable element 104. In this way, the magnetically permeable element 104 may provide a “shortcut” path for the magnetic flux 106 to return to(wards) the device 102. An analogy in electrical circuit is that it forms a short circuit where the electrical current (magnetic field) is maximized. With the lower path resistance provided by the magnetically permeable element 104, the magnetic flux 106 is likely to be stronger. Without the “shortcut” path (i.e., the magnetically permeable element 104), the resistance is high and the magnetic field may be less or weaker.

[0037] In the context of various embodiments, in the open flux configuration, a significant amount of flux path is in a non-permeable material, for example, free space. In other words, a substantial amount or portion of the magnetic flux 106 may permeate in or through a non-magnetically permeable material.

[0038] In various embodiments, the magnetically permeable element 104 may have a symmetrical structure about a central axis of the magnetically permeable element 104.

[0039] The magnetically permeable element may have a continuous or monolithic structure.

[0040] In the closed loop configuration, the magnetically permeable element 104 may be arranged adjacent to or in proximity with the device 102 such that the magnetically permeable element 104 may interact with the magnetic field. The magnetically permeable element 104 may be arranged over the device 102. The magnetically permeable element 104 may at least substantially surround the device 102. The magnetically permeable element 104 may extend or project from the first region 108a towards or to the second region 108b of the device 102 for the purpose of closing the flux loop. The magnetically permeable element may extend throughout a (entire) height or length of the device 102.

[0041] In the closed loop configuration, the magnetically permeable element 104 may be arranged spaced apart from the device 102, including, being spaced apart from the first region 108a of the device 102. In other words, there may be a (small) gap (e.g., air gap) in between the magnetically permeable element 104 and the device 102. This may be useful for imaging purpose where a sample that is to be imaged may be placed therebetween at the gap region. The magnetically permeable element 104 may be arranged completely spaced apart from the device 102.

[0042] In the closed loop configuration, the magnetically permeable element 104 may provide a path to re-direct the magnetic flux 106. The magnetically permeable element 104 may provide a path of least magnetic reluctance or resistance for the magnetic flux 106. The magnetically permeable element 104 may help in providing a closed loop path for the magnetic flux 106.

[0043] In the closed loop configuration, the magnetically permeable element 104 may help to trap the magnetic flux 106 emanating from the first region 108a of the device 102 and returning or leading the magnetic flux 106 to(wards) the second region 108b of the device 102.

[0044] In the open loop configuration, the magnetically permeable element 104 may be removed from or arranged distal to the device 104 so as to minimise or avoid interaction with the magnetic field or the associated magnetic flux 106. The magnetically permeable element 104 may be removed entirely away from the magnetic field. As such, the magnetic flux 106 may emanate from the first region 108a freely into free space.

[0045] In the open loop configuration, while the flux 106 is allowed to permeate into free space, the flux 106 eventually returns to the second region 108b. However, having such a significant portion of the magnetic flux 106 in air increases the magnetic reluctance of the magnetic flux path (or path of the magnetic flux 106). A high magnetic reluctance (or resistance) reduces the magnetic field strength for the same amount of input energy. In the closed loop configuration, the magnetically permeable element 104 may be arranged to provide a path of least magnetic reluctance or resistance to close the flux loop. A stronger magnetic field may be achieved with the closed loop configuration as the magnetically permeable element 104 may help to amplify its strength.

[0046] In various embodiments, the magnetically permeable element 104 may include a magnetic material. Any suitable type of magnetic materials may be used to achieve the closed flux configuration. The magnetically permeable element 104 may include a material having a magnetic permeability that is higher than that of free space. The magnetically permeable element 104 may, preferably, include a high saturation magnetisation and low coercivity magnetic material. The magnetically permeable element may include, but not limited to, permalloy, supermalloy (nickel-iron alloys), pure iron, mild steel, iron-cobalt alloys such as HiperCo.

[0047] It should be appreciated that the apparatus 100 may be a magnetic apparatus having at least one magnetic element.

[0048] In some embodiments, the device 102 may include a permanent magnet to generate the magnetic field. As such, the device 102 may be a magnetic device. As may be understood, a permanent magnet is a magnet made from a material that is magnetised and creates its own magnetic field. The magnetic field may be generated by the internal structure of the material itself. A permanent magnet always has a magnetic field and displays a magnetic behavior at all times. A permanent magnet may be made of a ferromagnetic material.

[0049] A region of the permanent magnet defining the first region 108a of the device 102 from where the corresponding magnetic flux 106 may emanate from may include a tapering portion. The tapering portion may help to concentrate the magnetic field. The tapering portion may converge to a tip region, for example, in a direction away from another region of the permanent magnet defining the second region 108b of the device 102.

[0050] In further embodiments, the device 102 may include an electromagnet to generate the magnetic field. As may be understood, an electromagnet refers to an element that generates a magnetic field when an electrical current passes through the element.

[0051] In various embodiments, the electromagnet may include an electrical conductor, and the electrical conductor may be configured to generate the magnetic field in response to an electrical current applied to and passing through the electrical conductor. A high electrical current may be applied. The electrical conductor may be a straight electrical conductor, or shaped as a circle or a loop. The electrical conductor may be a wire. The electrical conductor may be a superconductor or may include a superconducting material.

[0052] The electrical conductor may include a coil having at least one loop. This may mean that at least part of the electrical conductor may be shaped into at least one loop. In various embodiments, the electrical conductor may include a solenoid, in the form of a helix or a multi-loop coil or a multi-turn coil. This may mean that the coil may have a plurality of loops.

[0053] In various embodiments, the electromagnet may further include a magnetic core, wherein the coil may be arranged around the magnetic core. In other words, the magnetic core may be positioned in or within the coil. It should be appreciated that the coil has a hollow core and the magnetic core may be arranged within the hollow core. As a non-limiting example, the coil may be wound around a bobbin and placed around the magnetic core. The magnetic core may also be defined as an electromagnet core element. The magnetic core may help to enhance the magnetic field produced. The magnetic core may include a ferromagnetic material or a ferrimagnetic material. The magnetic core may be of a material having the same property(ies) as the magnetically permeable element 104. The magnetic core may, preferably, include a high saturation magnetisation and low coercivity magnetic material, which may be similar to that of the magnetically permeable element 104. In various embodiments, a region of the magnetic core and a region of the coil may together define the first region 108a of the device 102, while another region of the magnetic core and another region of the coil may together define the second region 108b of the device 102.

[0054] It should be appreciated that the electrical conductor itself may generate the magnetic field in response to an electrical current applied to and passing through the electrical conductor.

The magnetic core, when present, helps to enhance the magnetic field.

[0055] A high electrical current may be applied to the coil arranged around the magnetic core for generating the magnetic field. However, it should be appreciated that the means for achieving or conveying the high current, for example, in terms of the structure and/or material used, may not necessarily affect the performance of the electromagnet.

5 [0056] In various embodiments, a region of the magnetic core defining the first region 108a of the device 102 may include a tapering portion. The tapering portion may help to concentrate the magnetic field. The tapering portion of the magnetic core may converge to a tip region, for example, in a direction away from another region of the magnetic core defining the second region 108b of the device 102.

10 [0057] The apparatus 100 may further include a support structure to support the device 102, the support structure having a magnetic material. The support structure may help to enhance the flux closure. The support structure may be arranged proximal to the second region 108b of the device 102. The support structure may act as a base structure for the device 102. The support structure may be a planar structure. The support structure may be optional.

15 [0058] The support structure and the device 102 may be in contact with each other, e.g., the second region 108b of the device 102 may contact the support structure. The device 102 may be coupled to or affixed to the support structure. Where the device 102 includes a permanent magnet, the permanent magnet may be in contact with the support structure. Where the device 102 includes an electromagnet with a magnetic core, the magnetic core may be in
20 contact with the support structure.

[0059] The support structure may include or may be made from a magnetic material. In other words, the support structure may be a magnetic support structure. The support structure may preferably have the same property(ies) as the magnetically permeable element 104.

[0060] In the closed loop configuration, the support structure may interact with the magnetic
25 field to provide a (magnetic) path (re-)directing the magnetic flux 106 towards or to the second region 108b of the device 102.

[0061] In the closed loop configuration, the support structure may also support the magnetically permeable element 104. The magnetically permeable element 104 and the support structure may be in contact with each other. Such an arrangement may help to close the magnetic
30 flux 106. The magnetically permeable element 104 may be coupled to or affixed to the support structure. As a non-limiting example, dowel pins may be used on the magnetically permeable

element 104 and mating holes may be formed in the support structure to couple or affix the magnetically permeable element 104 to the support structure. This may allow for quick and easy exchange between the closed flux configuration and the open flux configuration. As another non-limiting example, screws from under the support structure may be used.

5 [0062] In the closed loop configuration, the magnetically permeable element 104 and the support structure may form a closed loop surrounding the device 102.

[0063] In various embodiments, the magnetically permeable element 104 may include a connection member 142, and a pair of arms 144a, 144b connected to the connection member 142, the pair of arms 144a, 144b being arranged spaced apart from each other and
10 projecting from the connection member 142, wherein, in the closed flux configuration, the magnetically permeable element 104 may be configured to be arranged with the connection member 142 proximal to the first region 108a of the device 102, and the pair of arms 144a, 144b extending in a direction from the first region 108a to the second region 108b of the device 102.

15 [0064] The pair of arms 144a, 144b may be connected to the connection member 142 at respective regions of the connection member 142, for example, at respective or opposite end regions of the connection member 142. The pair of arms 144a, 144b may define two side walls extending or projecting from the connection member 142. At least one arm or each arm of the pair of arms 144a, 144b may include or may be a planar structure or a curved structure. In
20 various embodiments, the magnetically permeable element 104 may be C-shaped, or V-shaped, or resemble the small letter “n” or the character “π”. The connection member 142 and the pair of arms 144a, 144b may be a continuous structure, for example, a monolithic structure.

[0065] In the closed loop configuration, the pair of arms 144a, 144b may extend throughout the (entire) height or length of the device 102, or may extend between the first region 108a and the
25 second region 108b of the device 102.

[0066] In the closed loop configuration, the pair of arms 144a, 144b of the magnetically permeable element 104 may be in contact with the support structure.

[0067] In various embodiments, the pair of arms 144a, 144b may project perpendicularly from the connection member 142. In the closed loop configuration, the magnetically permeable
30 element 104 may be arranged such that the connection member 142 may be horizontal, while

the pair of arms 144a, 144b may be vertical. The pair of arms 144a, 144b may be at least substantially parallel to the device 102 or to a longitudinal axis of the device 102.

[0068] In further embodiments, the pair of arms 144a, 144b may project non-perpendicularly from the connection member 142. This may mean that the arms 144a, 144b may extend from
5 the connection member 142 at an angle other than 90°.

[0069] In various embodiments, an aperture (or opening) may be defined in the connection member 142, and, in the closed flux configuration, the magnetically permeable element 104 may be configured to be arranged with the aperture aligned coaxially with the device 102. This may mean that the aperture and the device 102 may be aligned along a common axis. In this
10 way, the aperture and the device 102 may be arranged overlapping each other. In the closed flux configuration, where the device 102 includes a magnetic core having a tapering portion, the aperture may be aligned coaxially with the tip region of the magnetic core. The aperture may be circular. The (small) aperture is useful for the passage of light for imaging purposes. During imaging, an objective lens may be aligned with the aperture. The magnetically
15 permeable element 104 may help to shield the objective lens from the magnetic flux 106.

[0070] In various embodiments, a thickness of a first section of the connection member 142 may be less than a thickness of a second section of the connection member 142, and the aperture may be defined in the first section. The first section may be a central section of the connection member 142, for example, sandwiched between two second sections of the
20 connection member 142. In further embodiments, the thickness of the first section of the connection member 142 may be less than the thickness of the remaining part of the connection member 142. Having a thinner first section may help to avoid collision with an objective lens (for imaging) where the working distance (objective to sample distance) may be low for high-magnifications.

[0071] FIG. 1B shows a schematic block diagram illustrating an imaging device 110, according to various embodiments. The imaging device 110 includes the apparatus 100 for generating a magnetic field, where an aperture is defined in the connection member (142, FIG. 1A) of the magnetically permeable element (104, FIG. 1A) of the apparatus 100.
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[0072] In various embodiments, the apparatus 100 may be configured in the closed flux configuration, wherein the magnetically permeable element (104, FIG. 1A) may be arranged (in
30 proximity to the device (102, FIG. 1A)) to interact with the magnetic field to be generated by

the device of the apparatus 100 to provide a path directing the magnetic flux (106, FIG. 1A) corresponding to the magnetic field from the first region (108a, FIG. 1A) of the device towards (or to) the second region (108b, FIG. 1A) of the device.

[0073] In various embodiments, the imaging device 110 may be or may include a microscopy device (or microscope), for example, a Kerr microscopy device.

[0074] FIG. 1C shows a flow chart 120 illustrating a method for imaging a sample, according to various embodiments.

[0075] At 122, a magnetic field is generated using the device of the apparatus as described herein. An aperture is defined in the connection member of the magnetically permeable element of the apparatus.

[0076] At 124, the apparatus is configured in the closed flux configuration, wherein the magnetically permeable element is arranged (in proximity to the device) to interact with the generated magnetic field to provide a path directing the magnetic flux corresponding to the generated magnetic field from the first region of the device towards (or to) the second region of the device.

[0077] At 126, the sample is positioned between the device and the aperture of the magnetically permeable element. In this way, the sample may be positioned such that it interacts with the generated magnetic field or the magnetic flux corresponding to the generated magnetic field.

[0078] At 128, the sample is imaged through the aperture.

[0079] In various embodiments, the device of the apparatus may include an electromagnet for generating the magnetic field, and the method may further include varying an intensity of an electrical current applied to the electromagnet.

[0080] It should be appreciated that descriptions in the context of the apparatus 100 may correspondingly be applicable in relation to the method for imaging a sample described in the context of the flow chart 120.

[0081] FIGS. 2A and 2B show perspective views (3D views) of an apparatus 200a in an open flux configuration, illustrating an open flux electromagnet. The apparatus 200a for the open flux design may include a high permeability (magnetic) core 203 with a tapering portion 230 that converges to a tip region 232, as part of an electromagnet, and a support structure (or supporting base) 234. The use of tapering in electromagnets achieves the effect of concentrating

the magnetic field. As may be observed, the core 203 is in contact with the support structure 234.

[0082] The open flux design may allow a sample (e.g., for the purpose of imaging) to be placed directly onto the high permeability core 203 and an imaging objective to be positioned on the other side with the sample therebetween. This configuration is adopted as the sample and objectives may not face spatial constraints. Nevertheless, as will be described below, a closed flux configuration may also be achieved without a large loss in spatial freedom.

[0083] FIGS. 2C and 2D show perspective views (3D views) of an apparatus 200b in a closed flux configuration, illustrating a closed flux electromagnet. As may be observed, the apparatus 200b resembles the letter “B” (rotated 90° anti-clockwise). The B-shaped apparatus 200b may be formed by adding a C-frame 204 (as a magnetically permeable element) to the open flux apparatus 200a so as to close the magnetic flux (loop). The C-frame 204 includes a connection member 242 and two arms 244a, 244b connected to and projecting from the connection member 242. The two arms 244a, 244b may be coupled to the connection member 242 at opposite end regions of the connection member 242. As may be observed, the two arms 244a, 244b may project at least substantially perpendicularly from the connection member 242. The connection member 242 may include a (central) section 246 having a thickness that is less than the remaining sections of the connection member 242. As illustrated in FIGS. 2C and 2D, the section 246 may be a first section of the connection member 242 that is sandwiched between two second sections 247a, 247b that are thicker than the first section 246. An aperture 248 may be defined in the section 246, which, when used for imaging, an objective lens may be aligned with the aperture 248.

[0084] As may be observed in FIGS. 2A to 2D, mating holes 249 may be provided on the support structure 234 for attaching the C-frame 204 to the support structure 234. Dowel pins (not shown) may be provided for or with the C-frame 204, where the dowel pins may then be inserted into the mating holes 249 to couple or affix the C-frame 204 to the support structure 234.

[0085] The addition of a high (magnetic) permeability C-frame 204 may allow the magnetic flux emanating from the core, for example, from the tapering region 230, to be trapped and efficiently returned to the other (opposite) end 236 of the core 203. The resulting geometry therefore resembles a B-shape rotated anti-clockwise 90 degrees. In this configuration, a sample

(e.g., for the purpose of imaging) may be placed in the gap 238 between the core 230 and the C-frame 204. To allow for imaging, a circular slot 248 is machined into the middle of the C-frame 204. Despite the addition of the slot 248, the magnetic field from the B-shaped apparatus 200b may still be many times stronger than that of the apparatus 200a of the open flux design.

[0086] For the purpose of clearly showing the magnetic core 203 and its shape, an electrical conductor (e.g., a solenoid) is not shown in FIGS. 2A to 2D as part of the electromagnet. As will be described further below (see also FIGS. 5A to 5C), a solenoid may be provided around the core 203.

[0087] To visualize the underlying physics behind the improvement in magnetic flux closure and magnetic flux density, numerical calculations were performed using the COMSOL Multiphysics software. Numerically calculated magnetic flux distribution are shown in FIGS. 3A to 3C for a single pole open flux electromagnet design (apparatus 300a), and in FIGS. 3D to 3F for a B-shaped closed flux electromagnet (apparatus 300b), shown in cross-sectional views. Like features or components of the apparatus 300a, 300b that are similarly present in the apparatus 200a, 200b (FIGS. 2A to 2D) are denoted by like reference numerals increased by 100, and which may be as correspondingly described in the context of the apparatus 200a, 200b and therefore are omitted here. In FIGS. 3A to 3F, the rectangles 305 shown on either side of the core 303 are cross-sectional representations of an electromagnet coil that is arranged around the core 303. The approximate positions of the microscope objective 350, its light cone and the sample 352 are superimposed onto the images (see, for example, FIG. 3B). The magnetic flux density is used as a measurement unit for FIGS. 3B, 3C, 3E and 3F.

[0088] For both electromagnets, the permeabilities were taken to be that of the HiperCo alloy with 700 turns of magnet wire carrying 10 amperes coiled around the core 303. In FIG. 3A, the magnetic flux (represented by the curved lines, some of which are indicated by 306a) emanating from the iron core 303 radiates almost vertically, indicating that a large amount of magnetic flux 306 passes through the imaging objectives 350. In comparison, FIG. 3D shows that the magnetic flux (represented by the curved lines, some of which are indicated by 306b) from the electromagnet of the B-shaped apparatus 300b is contained within the C-frame 304. The z -component of the magnetic field that is responsible for saturating the magnetic sample

and its distribution is shown in FIGS. 3B and 3E for the open flux and B-shaped designs, respectively. The magnetic flux from the open flux electromagnet decays quickly out of the magnetic core 303, whereas the closed flux design may trap most of the magnetic flux 306b in the air gap between the magnetic core 303 and the C-frame 304.

5 [0089] Referring to FIG. 3B, the magnetic flux density at the core 303 is about -0.5T. Referring to FIG. 3E, the magnetic flux density at the core 303 is about -1.5T, while the magnetic flux density at the arms 344a, 344b is about 1.5T.

[0090] As may be observed in FIGS. 3C and 3F, at the position of the sample 352, both electromagnets are shown to produce minimal amounts of magnetic flux in the x -direction. This is a desirable outcome for perpendicular electromagnets as they are intended to produce a magnetic field in the z -direction. Referring to FIG. 3C, the magnetic flux density at the right side of the support structure 334 and the top left corner of the core 303 is about 0.5T, while the magnetic flux density at the left side of the support structure 334 and the top right corner of the core 303 is about -0.5T. Referring to FIG. 3F, the magnetic flux density at the right side of the support structure 334, the left side of the connection member 342 and the top left corner of the core 303 is about 1.5T, while the magnetic flux density at the left side of the support structure 334, the right side of the connection member 342, and the top right corner of the core 303 is about -1.5T.

[0091] FIG. 4 shows a plot 370 of the magnetic flux density along the z -axis for the electromagnets of FIGS. 3A to 3F, illustrating the results for the magnetic flux density versus distance from sample, as produced by the open flux electromagnet design (see result 372) and the closed flux electromagnet design (see result 374). The horizontal line 376 represents zero field while the vertical line 378 represents the location of the objective lens at 10 mm distance. At the sample position, the closed flux apparatus 300b produces almost four times the amount of magnetic flux produced by the open flux apparatus 300a. This vastly improved performance reduces the amount of Joule heat produced, resulting in a more efficient design. Further, the magnetic flux density also quickly decays with distance away from the sample, resulting is a magnetic flux that is less than half at the imaging objectives, as compared to the open flux design.

30 [0092] To validate the numerical results, an apparatus with a closed flux electromagnet was fabricated with a removable C-frame. This allows for a fast and direct comparison between the

two configurations (i.e., open flux and closed flux). FIGS. 5A and 5B show photographs illustrating a front view of the apparatus 500a, 500b of various embodiments in the open flux configuration and in the closed flux (or closed loop) configuration respectively during imaging of a sample, with FIG. 5C showing a side view of the apparatus 500a, while FIG. 5D shows a plot 570 of magnetic flux density as a function of applied current for the open flux and closed flux electromagnet designs.

[0093] Each apparatus 500a, 500b includes an electromagnet 501 having a coil (or solenoid or multi-coil conductor) 505 of 828 turns, and a HiperCo alloy electromagnet core 503 supported on a support structure 534. The coil 505 is arranged around the magnetic core 503. The apparatus 500b further includes a removable C-shaped frame 504. Due to the larger size of the C-frame 504, mild steel is preferred for its better machinability. The C-frame 504 may be as correspondingly described in the context of the C-frame 204 of FIGS. 2C and 2D. FIGS. 5A and 5B show the easily interchangeable design between an open flux configuration and a closed flux configuration.

[0094] As shown in FIGS. 5A and 5B, an objective lens 550 may be provided for imaging a sample 552. As may be observed in FIG. 5B, the objective lens 550 may be aligned with an aperture 548 defined in the C-frame 504 and the sample 552. For microscopy purposes, it is preferable to place the sample 552, which is positioned in between the magnetic core 503 of the electromagnet 501 and the lens 550 (and also the C-frame 504), to be supported by a cantilever-like stage, such as a 5-axis stage 580 (partly visible in FIGS. 5A and 5B, and best seen in FIG. 5C). The 5-axis stage 580 is shown holding a glass slide (as support element) 582 to support and hold the sample 552 in place above the electromagnet 501. Nevertheless, the sample 552 may be directly placed on the magnetic core 503 of the electromagnet 501, where a stronger magnetic flux may be experienced by the sample. However, magnetostriction effects may potentially cause sample movements during imaging.

[0095] FIG. 5D shows the measured magnetic field strength at a 1 mm distance from the top of the electromagnet core 503, with the result 572 for the open flux configuration and the result 574 for the closed flux configuration. The magnetic field strength corresponding to the closed flux configuration is on average 3.3 times stronger than that of the open flux configuration. Due to the use of the mild steel C-frame 504, the magnetic field may be observed to saturate above 7 amperes; nevertheless, using HiperCo preferably as the material for the C-

frame 504 may help to increase the saturation current and improve the performance of the closed flux apparatus 500b.

[0096] By designing removable C-frames, the apparatus may be configured both ways - in open flux and closed flux configurations - for maximum versatility. One scenario in which the open flux configuration may be used is when the microscope objectives have a shorter working distance. The smaller sample-to-objective distance may cause mechanical collision in a closed flux configuration. Another scenario is when a higher resolution magnetic flux is to be provided. The smallest magnetic flux step that may be applied is limited by the magnetic flux change when the current supply is increased by its minimum step size. In this case, the open flux configuration may have a lower overall permeability and a high resolution magnetic flux may be applied.

[0097] As described, a B-shaped closed flux apparatus with an electromagnet may produce peak magnetic flux densities that are about four times stronger while reducing the magnetic flux density experienced by the imaging objectives by half, as compared to known designs.

Therefore, the B-shaped closed flux apparatus may address or overcome the two main challenges faced in Kerr imaging electromagnet design.

[0098] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An apparatus for generating a magnetic field comprising:

a device configured to generate the magnetic field with a corresponding magnetic flux
emanating from a first region of the device and returning to a second region of the device; and

a magnetically permeable element comprising a connection member and a pair of arms
connected to the connection member, the pair of arms being arranged spaced apart from each
other and projecting from the connection member,

wherein, in a first mode of operation, the magnetically permeable element is adapted to
be arranged to interact with the magnetic field to configure the apparatus in a closed flux
configuration to provide a path directing the magnetic flux from the first region of the device
towards the second region of the device,

wherein, in a second mode of operation, the magnetically permeable element is removable
away from the magnetic field to configure the apparatus in an open flux configuration,

wherein, in the closed flux configuration, the magnetically permeable element is
configured to be arranged with the connection member proximal to the first region of the device,
and the pair of arms extending in a direction from the first region to the second region of the
device,

wherein an aperture is defined in the connection member, and

wherein, in the closed flux configuration, the magnetically permeable element is
configured to be arranged with the aperture aligned coaxially with the device.

2. The apparatus as claimed in claim 1, wherein the device comprises a permanent magnet
configured to generate the magnetic field.

3. The apparatus as claimed in claim 1, wherein the device comprises an electromagnet
configured to generate the magnetic field.

4. The apparatus as claimed in claim 3,

wherein the electromagnet comprises an electrical conductor, and

wherein the electrical conductor is configured to generate the magnetic field in response
to an electrical current applied to and passing through the electrical conductor.

5. The apparatus as claimed in claim 4, wherein the electrical conductor comprises a coil comprising at least one loop.

5 6. The apparatus as claimed in claim 5, wherein the electromagnet further comprises a magnetic core, wherein the coil is arranged around the magnetic core.

7. The apparatus as claimed in claim 6, wherein a region of the magnetic core defining the first region of the device comprises a tapering portion.

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8. The apparatus as claimed in any one of claims 1 to 7, further comprising a support structure to support the device, the support structure comprising a magnetic material.

9. The apparatus as claimed in claim 1, wherein the pair of arms project perpendicularly
15 from the connection member.

10. The apparatus as claimed in claim 1,
wherein a thickness of a first section of the connection member is less than a thickness of
a second section of the connection member, and

20 wherein the aperture is defined in the first section.

11. An imaging device comprising the apparatus for generating a magnetic field as claimed in any one of the preceding claims.

25 12. The imaging device as claimed in claim 11, wherein in the closed flux configuration, the magnetically permeable element is arranged to interact with the magnetic field to be generated by the device of the apparatus to provide a path directing the magnetic flux corresponding to the magnetic field from the first region of the device towards the second region of the device.

30 13. A method for imaging a sample comprising:

generating a magnetic field using the device of the apparatus as claimed in any one of claims 1 to 10;

configuring the apparatus in the closed flux configuration, wherein the magnetically permeable element is arranged to interact with the generated magnetic field to provide a path
5 directing the magnetic flux corresponding to the generated magnetic field from the first region of the device towards the second region of the device;

positioning the sample between the device and the aperture of the magnetically permeable element; and

imaging the sample through the aperture.

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14. The method as claimed in claim 13,

wherein the device comprises an electromagnet,

wherein generating a magnetic field comprises generating the magnetic field using the electromagnet, and

15 the method further comprises varying an intensity of an electrical current applied to the electromagnet.