

ZONE PLATE

Cross-Reference To Related Application

5 [0001] This application claims the benefit of priority of Singapore patent application No. 201303601-7, filed 9 May 2013, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

10

[0002] Various embodiments relate to a zone plate, a microscope including the zone plate and an imaging device including the zone plate.

Background

15

[0003] The quest for flawless imaging has propelled scientists and engineers for centuries to carry out fundamental studies and experiments, which have greatly boosted the development of modern optics, electronics and biology thanks to quite a few milestone works.

20 [0004] Nowadays, even though the resolution limit of optical microscopy has been pushed to about 200 nm, optical microscopy still suffers from diffraction limit and therefore, its advantages cannot be fully enjoyed. Although a lot of commercially available technologies such as atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), etc., offer various methods
25 that facilitate users to visualize nano-objects, however these technologies exhibit certain disadvantages such as high cost, beam ionization and damage, special sample preparation and handling difficulty.

Summary

[0005] According to an embodiment, a zone plate is provided. The zone plate may include a mask layer that is at least substantially non-transmissive to an electromagnetic radiation impinging on the zone plate, and a plurality of apertures defined through the mask layer, the plurality of apertures being at least substantially transmissive to the electromagnetic radiation, wherein the plurality of apertures are distributed in at least one concentric pattern so as to diffract the electromagnetic radiation and focus the diffracted electromagnetic radiation to a desired focal plane.

[0006] According to an embodiment, a microscope is provided. The microscope may include a zone plate as described herein.

[0007] According to an embodiment, an imaging device is provided. The imaging device may include a source configured to provide an electromagnetic radiation, and a zone plate as described herein, the zone plate arranged to diffract the electromagnetic radiation and focus the diffracted electromagnetic radiation for imaging an object.

Brief Description of the Drawings

[0008] 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:

[0009] FIG. 1A shows a schematic top view of a zone plate, according to various embodiments.

[0010] FIG. 1B shows a schematic perspective view of the zone plate of FIG. 1A.

[0011] FIG. 2A shows a schematic top view of a zone plate, according to various embodiments.

[0012] FIG. 2B shows a schematic top view of a zone plate, according to various embodiments.

[0013] FIG. 3A shows a schematic perspective view illustrating a nanoimaging process with a holey Fresnel zone plate lens(FZPL)-based nanoscope, according to various embodiments.

[0014] FIG. 3B shows a schematic top view of the holey Fresnel zone plate lens(FZPL) of FIG. 3A.

[0015] FIG. 4 shows a scanning electron microscopy (SEM) image of a holey Fresnel zone plate lens (HFZPL) of various embodiments.

[0016] FIG. 5A shows plots of measured result of a focal spot obtained with a holey Fresnel zone plate lens(HFZPL)-based optical nanoscope. The scale bars represent 0.4 μm .

[0017] FIG. 5B shows a plot of the cross-sectional profile of the intensity corresponding to the focal spot of FIG. 5A.

[0018] FIG. 6A shows a scanning electron microscopy (SEM) image of double airy slits, while FIG. 6B shows a resolved nanoimage of the double airy slits of FIG. 6A obtained using the holey Fresnel zone plate lens(HFZPL)-based nanoscope of various embodiments.

[0019] FIG. 7 shows an image of the double airy slits of FIG. 6A obtained using a conventional solid immersion lens.

Detailed Description

[0020] 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.

[0021] Embodiments described in the context of one of the devices are analogously valid for the other devices.

[0022] 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.

5 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.

[0023] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or
10 elements.

[0024] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

[0025] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

15 [0026] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0027] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or
20 more of the associated listed items.

[0028] Various embodiments may provide a zone plate. The zone plate may be an optical zone plate. The zone plate may be a Fresnel zone plate (FZP), for example a holey Fresnel Zone Plate lens (HFZPL). Various embodiments may further provide a nanoscope, for example an optical nanoscope. The nanoscope may include the zone plate
25 (e.g. HFZPL) of various embodiments.

[0029] Various embodiments may provide a holey Fresnel Zone Plate (FZP) lens, which may be able to produce one super-resolution focal spot and may achieve (optical) imaging resolution beyond the diffraction limit. The FZP lens or HFZPL may be employed in conjunction with an optical microscope.

30 [0030] The FZP lens of various embodiments may be a thin planar lens with holey structures, and may be capable of forming a sub-diffraction limit focusing light spot at a

central lobe. The FZP lens may include radially distributed apertures, for example nano pinholes, that may be fabricated on or formed through an opaque metal film deposited on a transparent substrate (e.g. quartz). When illuminated by a laser source, for example a laser operating at a wavelength of about 632.8 nm, light impinging upon the zone plate may diffract around the opaque zone (i.e. portions of the metal film without the apertures) and may constructively interfere at a desirable focal length or focal plane, which may eventually form a focusing pattern at that focal plane. Parameters of the FZP lens, including but not limited to the diameter, the spacing and the number of the apertures or holes, may be specifically designed so as to achieve high performance focusing in terms of resolution and/or focal distance.

[0031] In various embodiments, a sub-diffraction-limited focal spot with a resolution of ~ 248 nm (Full width at half maximum (FWHM)) at a distance of about 6.78 μm (more than ten wavelengths away from the FZP lens for a 632.8nm laser used for the measurement) may be achieved with a conventional optical microscope incorporating the FZP lens. Upon installation of the FZP lens of various embodiments in place of the conventional solid immersion lens (SIL) in an optical microscope, the image of subwavelength objects may be obtained by scanning the sub-diffraction limit focusing spot over the subwavelength or nano-objects. The resolution limit of a conventional optical microscope may be given by $\gamma = 1.22 \lambda / (\text{NA}_{\text{obj}} + \text{NA}_{\text{con}})$, where γ is the resolution (e.g. the smallest resolvable distance between two objects), λ is the imaging wavelength and NA is a general term for the numerical aperture of the microscope, where NA_{obj} and NA_{con} refer to the numerical apertures of the objective and the condenser (environment), respectively. At a wavelength of about 632.8 nm, the resolution limit of traditional or conventional optical microscopes is approximately 330 nm (with $\text{NA}=0.95$). By integrating with the holey FZP lens of various embodiments, a conventional bright-field optical microscope may be directly upgraded to a nanoscope that may break the barrier of diffraction limit. As a consequence, the nanoscope may offer a non-invasive nanoimaging paradigm and may have a great potential for wide applications from laboratory to industries.

[0032] The HFZPL of various embodiments, with its combination of apertures or holey structures and design, may be different as compared to conventional lenses. Firstly, the

apertures or the holey structures of the HFZPL may be defined and distributed in a predetermined arrangement to form a Fresnel zone plate (FZP) lens that may offer a sub-diffraction-limited focal spot. Secondly, the apertures or the holey structures with predetermined feature sizes including but not limited to width, spacing and numbers corresponding to the apertures or the holey structures may be designed and employed to produce a superfocusing spot to improve resolution at the far field. The HFZPL of various embodiments takes advantage of diffractive light to work at the far field, which is different from near-field plasmonic lenses.

[0033] The nanofabricated HFZPL having apertures or holey structures on or through an opaque layer may be able to create a subwavelength resolution focal spot ($\approx \lambda/2.55$, λ = imaging wavelength) at the far field (e.g. about 6.78 μm). The imaging performance of the HFZPL may be capable of resolving 140-nm objects ($\approx \lambda/4.52$, λ = imaging wavelength), which is far beyond the resolution limit (≈ 330 nm) of a conventional microscopy device operating at the same wavelength of about 632.8nm. Still, further improvements to the performance of the HFZPL may be achieved, for example by modifications of the design or parameters of the HFZPL. Theoretically, the HFZPL of various embodiments has no physical limit in terms of resolution. In addition, the HFZPL may be specifically designed to work at any wavelength from X-rays to microwaves, including near-mid-far infrared (IR) and other microscopy imaging.

[0034] In contrast to technologies such as AFM, SEM and TEM, a microscope (e.g. an optical microscope) equipped with the zone plate (e.g. HFZPL) of various embodiments may be simply upgraded to become a nanoscopy device that may beat the diffraction limit. The HFZPL may be a thin planar lens that may be easily attached to any existing objective lens or in place of an objective lens, in conjunction with an optical microscope or other tools or microscopy devices. Its resolution may be further improved through structural optimization and theoretically this approach or method may be free from the physical limit. At the same time, it still offers all the advantages of traditional microscopes such as low cost, flexibility and easy handling, as compared to the above-mentioned technologies.

[0035] FIG. 1A shows a schematic top view of a zone plate 100, according to various embodiments, while FIG. 1B shows a schematic perspective view of the zone plate 100 of FIG. 1A, when used for imaging.

[0036] The zone plate 100 includes a mask layer 102 that is at least substantially non-transmissive to an electromagnetic radiation 120 impinging on the zone plate 100, and a plurality of apertures 104 defined through the mask layer 102, the plurality of apertures 104 being at least substantially transmissive to the electromagnetic radiation 120, wherein the plurality of apertures 104 are distributed in at least one concentric pattern 106 so as to diffract the electromagnetic radiation 120 and focus the diffracted electromagnetic radiation 120a to a desired focal plane 124.

[0037] In other words, the zone plate 100 may include a mask layer 102 that may be at least substantially non-transmissive (e.g. opaque) to an electromagnetic radiation 120 incident on or received by the zone plate 100. This may mean that the mask layer 102 may at least substantially block transmission of the electromagnetic radiation 120. The zone plate 100 may include a plurality of apertures (or openings) 104 formed or fabricated through the mask layer 102. As a non-limiting example, the apertures (or openings) 104 may completely penetrate through the mask layer 102, i.e. defined through the entire thickness of the mask layer 102. In other words, the mask layer 102 may be perforated with the plurality of apertures (or openings) 104. The plurality of apertures 104 may allow transmission of the electromagnetic radiation 120 through the apertures 104. The plurality of apertures 104 may be arranged or positioned so as to define at least one concentric pattern (or zone) 106. The plurality of apertures 104 and their corresponding arrangement in at least one concentric pattern (or zone) 106 may help in diffracting the electromagnetic radiation 120 and focusing (or converging) the electromagnetic radiation 120a that has been diffracted to a focal plane 124, for example to a focal spot 122 located on the plane 124. Therefore, the zone plate 100 may receive an electromagnetic radiation 120 that is external to the zone plate 100, and subsequently the zone plate 100 may diffract the electromagnetic radiation 120 and focus the diffracted electromagnetic radiation 120a to a focal plane 124.

[0038] Accordingly, the portions of the mask layer 102 without the plurality of apertures 104 may be at least substantially non-transmissive (or opaque) to the

electromagnetic radiation 120, or in other words, may form a non-transmissive (or opaque) zone.

[0039] When the electromagnetic radiation 120 impinges or is incident on the zone plate 100, the mask layer 102 and the plurality of apertures 104 may cooperate to diffract the electromagnetic radiation 120 that is received by the zone plate 100, where for example, the electromagnetic radiation 120 may be diffracted around the non-transmissive (or opaque) zone. The diffracted electromagnetic radiation 120a may subsequently interact, for example the diffracted electromagnetic radiation 120a may interfere, for example constructively interfere, at a desired focal plane 124 to enable focusing of the electromagnetic radiation 120 impinging on the zone plate 100 to the focal plane 124.

[0040] In various embodiments, the zone plate 100 may be a diffractive element (e.g. a diffractive zone plate). The zone plate 100 may diffract the electromagnetic radiation 120 and then focus the electromagnetic radiation 120a that has been diffracted by the plurality of apertures 104 to a desired focal plane 124, for example focused into a subwavelength focal spot 122.

[0041] In the context of various embodiments, the focal plane 124 may be a far-field focal plane, for example located several tens of wavelengths away from the zone plate 100. In other words, the zone plate 100 may converge or focus the electromagnetic radiation 120, which may be diffracted by the zone plate 100, into a superfocusing spot 122 at the far field.

[0042] In the context of various embodiments, the term “zone plate” may mean a device or element which may focus an electromagnetic radiation, and which may operate by means of diffraction. This may mean that the zone plate 100 may be a diffractive zone plate.

[0043] In various embodiments, the plurality of apertures 104 may be distributed in a plurality of concentric patterns 106. This may mean that the plurality of concentric patterns 106 may be arranged one after another in a radial direction of the zone plate 100. The plurality of apertures 104 may be distributed, for example, in 20 or more (e.g. from 20 to infinite) concentric patterns 106. This may mean that the at least one concentric

pattern 106 or the plurality of concentric patterns 106 may include 20 or more concentric patterns.

[0044] In various embodiments, the plurality of apertures 104 distributed in a plurality of concentric patterns 106 may have diameters that change in a radial direction of the zone plate 100. For example, the change in the diameters may be uni-directional in the radial direction of the zone plate 100. The diameters of the plurality of apertures 104 may decrease in the radial direction, outwardly in a direction from an inner portion of the zone plate 100 to an outer portion of the zone plate 100. As a non-limiting example, the diameters of the plurality of apertures 104 may change from about 800 nm to about 100 nm radially towards the outer portion of the zone plate 100.

[0045] In various embodiments, adjacent concentric patterns 106 of the plurality of concentric patterns 106 may be arranged relative to each other at a distance in a range of between 0 (e.g. immediately or directly adjacent) and about 1 μm (1000 nm), for example depending on the focusing property and the working (or imaging) wavelength, for example between 0 and about 500 nm, between 0 and about 200 nm, between 0 and about 100 nm, between about 100 nm and about 1000 nm, between about 500 nm and about 1000 nm, or between about 200 nm and about 500 nm.

[0046] In various embodiments, a number of the plurality of apertures 104 distributed in each concentric pattern 106 may be equal to 10 or more (e.g. from 10 to infinite), for example ≥ 20 , ≥ 30 , ≥ 50 , ≥ 80 , or any higher number.

[0047] In various embodiments, the plurality of apertures 104 may have a diameter in a range of between about 0.1 nm and about 1 μm (1000 nm), for example between about 0.1 nm and about 500 nm, between about 0.1 nm and about 200 nm, between about 0.1 nm and about 100 nm, between about 100 nm and about 1000 nm, between about 300 nm and about 1000 nm, or between about 200 nm and about 500 nm.

[0048] In various embodiments, the plurality of apertures 104 may have a thickness in a range of between about 10 nm and about 10 μm (10000 nm), for example between about 10 nm and about 5 μm , between about 10 nm and about 1 μm , between about 10 nm and about 500 nm, between about 10 nm and about 100 nm, between about 500 nm and about 10 μm , between about 500 nm and about 1 μm , or between about 1 μm and about 10 μm .

In various embodiments, the thickness of the plurality of apertures 104 may be at least substantially similar or identical to the thickness of the mask layer 102.

[0049] In various embodiments, the plurality of apertures 104 may be distributed periodically spaced apart from each other in each concentric pattern 106. In other words, neighbouring or adjacent apertures 104 in each concentric pattern 106 may have a constant or equidistant spacing. However, it should be appreciated that the plurality of apertures 104 may also be distributed randomly or non-periodically spaced apart from each other in each concentric pattern 106, e.g. neighbouring or adjacent apertures 104 in each concentric pattern 106 may have a non-constant spacing.

[0050] In various embodiments, the plurality of apertures 104 may be spaced apart from each other in each concentric pattern 106 at a spacing in a range of between about 0.1 nm and about 1 μm (1000 nm), for example between about 0.1 nm and about 500 nm, between about 0.1 nm and about 200 nm, between about 0.1 nm and about 100 nm, between about 100 nm and about 1000 nm, between about 300 nm and about 1000 nm, or between about 200 nm and about 500 nm. The spacing between adjacent or neighbouring apertures 104 may refer to the edge-to-edge distance between the adjacent apertures 104 in each concentric pattern 106.

[0051] In the context of various embodiments, the zone plate 100 may further include at least one concentric aperture defined through the mask layer 102 and arranged concentrically with the at least one concentric pattern 106, the at least one concentric aperture being at least substantially transmissive to the electromagnetic radiation 120. The at least one concentric aperture may cooperate with the plurality of apertures 104 to diffract the electromagnetic radiation 120 and focus the diffracted electromagnetic radiation 120a to the desired focal plane 124. In various embodiments, the least one concentric aperture may be a ring structure or a ringy structure.

[0052] In various embodiments, each concentric aperture may have a width in a range of between about 1 nm and about 1 μm (1000 nm), for example between about 1 nm and about 500 nm, between about 1 nm and about 200 nm, between about 1 nm and about 100 nm, between about 100 nm and about 1000 nm, between about 300 nm and about 1000 nm, or between about 200 nm and about 500 nm.

[0053] In various embodiments, a number of the at least one concentric aperture may be equal to 1 or more (e.g. from 1 to infinite), for example ≥ 2 , ≥ 5 , ≥ 10 , or any higher number.

[0054] In the context of various embodiments, the zone plate 100 may include a plurality of concentric apertures defined through the mask layer 102 and arranged concentrically with the at least one concentric pattern 106. The plurality of concentric apertures may be at least substantially transmissive to the electromagnetic radiation 120. The plurality of concentric apertures may cooperate with the plurality of apertures 104 to diffract the electromagnetic radiation 120 and focus the diffracted electromagnetic radiation 120a to the desired focal plane 124. In various embodiments, the plurality of concentric apertures may be ring structures or ringy structures.

[0055] In various embodiments, adjacent concentric apertures of the plurality of concentric apertures may be arranged spaced apart from each other at a spacing in a range of between about 0.1 nm and about 1 μm (1000 nm), for example between about 0.1 nm and about 500 nm, between about 0.1 nm and about 200 nm, between about 0.1 nm and about 100 nm, between about 100 nm and about 1000 nm, between about 300 nm and about 1000 nm, or between about 200 nm and about 500 nm.

[0056] In various embodiments, each concentric aperture may have a thickness in a range of between about 10 nm and about 10 μm (10000 nm), for example between about 10 nm and about 5 μm , between about 10 nm and about 1 μm , between about 10 nm and about 500 nm, between about 10 nm and about 100 nm, between about 500 nm and about 10 μm , between about 500 nm and about 1 μm , or between about 1 μm and about 10 μm . In various embodiments, the thickness of each concentric aperture may be at least substantially similar or identical to the thickness of the mask layer 102.

[0057] As a non-limiting example, each concentric aperture may completely penetrate through the mask layer 102, i.e. defined through the entire thickness of the mask layer 102.

[0058] In various embodiments, the plurality of apertures 104 may be distributed in a plurality of concentric patterns 106, and wherein the plurality of concentric apertures may be arranged alternately with the plurality of concentric patterns 106. For example, a respective concentric pattern 106 may be sandwiched by at least one concentric aperture

on either side of the respective concentric pattern 106, or a respective concentric aperture may be sandwiched by at least one concentric pattern 106 on either side of the respective concentric aperture.

[0059] In the context of various embodiments, each concentric aperture may be 2-dimensional or 3-dimensional, or may include 2-dimensional and/or 3-dimensional features.

[0060] A non-limiting example of a zone plate with a plurality of apertures distributed in a plurality of concentric patterns may be as shown in FIG. 2A. The zone plate 200a as shown in FIG. 2A may include a mask layer 202 that may be at least substantially non-transmissive to an electromagnetic radiation (e.g. 120, FIG. 1B) impinging on the zone plate 200a, and a plurality of apertures (or openings) 204 defined through the mask layer 202, the plurality of apertures 204 being at least substantially transmissive to the electromagnetic radiation, wherein the plurality of apertures 204 may be distributed in a plurality of concentric patterns (zones) 206 so as to diffract the electromagnetic radiation and focus the diffracted electromagnetic radiation to a desired focal plane.

[0061] For example, a first plurality of apertures 204a may be arranged in a first concentric pattern 206a, and a second plurality of apertures 204b may be arranged in a second concentric pattern 206b, and so on. It should be appreciated that, for ease of understanding and clarity purposes, only two concentric patterns 206a, 206b are shown in FIG. 2A. Nevertheless, it should be appreciated that the plurality of apertures 204 may be arranged in more than two concentric patterns 206, as indicated by the dotted lines. The first plurality of apertures 204a may have a diameter, d_1 , while the second plurality of apertures 204b may have a diameter, d_2 , where $d_1 > d_2$.

[0062] A non-limiting example of a zone plate having a plurality of apertures and at least one concentric aperture may be as shown in FIG. 2B. The zone plate 200b as shown in FIG. 2B may include a mask layer 202 that may be at least substantially non-transmissive to an electromagnetic radiation (e.g. 120, FIG. 1B) impinging on the zone plate 200b, and a plurality of apertures (or openings) (e.g. 204a and/or 204b) defined through the mask layer 202, the plurality of apertures being at least substantially transmissive to the electromagnetic radiation, wherein the plurality of apertures may be distributed in at least one concentric pattern (or zone) (e.g. 206a and/or 206b) so as to diffract the

electromagnetic radiation and focus the diffracted electromagnetic radiation to a desired focal plane. The zone plate 200b may further include at least one concentric aperture (e.g. 208a and/or 208b) defined through the mask layer 202 and arranged concentrically with the at least one concentric pattern, the at least one concentric aperture being at least substantially transmissive to the electromagnetic radiation.

[0063] It should be appreciated that, for understanding purposes, two concentric patterns (e.g. first concentric pattern 206a and second concentric pattern 206b) and two concentric apertures (e.g. first concentric aperture 208a and second concentric aperture 208b) are shown in FIG. 2B and the zone plate 200b is described based on such an arrangement.

Nevertheless, it should be appreciated that the zone plate 200b may include a plurality of apertures 204a (or 204b) arranged in one concentric pattern 206a (or 206b) and having one concentric aperture 208a or 208b. Further, it should be appreciated that the zone plate 200b may instead include a plurality of apertures arranged in more than two concentric patterns and having more than two concentric apertures, collectively as indicated by the dotted lines. The first plurality of apertures 204a may have a diameter, d_1 , while the second plurality of apertures 204b may have a diameter, d_2 , where $d_1 > d_2$.

[0064] As shown in FIG. 2B, the plurality of apertures 204a, 204b may be arranged in a plurality of concentric patterns 206a, 206b that are arranged alternately with the plurality of concentric apertures 208a, 208b, one after another. However, it should be appreciated that a respective concentric pattern may be sandwiched by any number of concentric apertures on either side of the respective concentric pattern. Further, it should be appreciated that a respective concentric aperture may be sandwiched by any number of concentric patterns on either side of the respective concentric aperture.

[0065] It should be appreciated that features corresponding to the zone plate 100 of FIG. 1A and the descriptions provided in the context of the zone plate 100 of FIG. 1A may be similarly applicable to the zone plates 200a, 200b.

[0066] In the context of various embodiments, the plurality of apertures 104, 204, 204a, 204b may define a lens layer. The lens layer may act to diffract the electromagnetic radiation (e.g. 120, FIG. 1B) and focus the diffracted electromagnetic radiation to the desired focal plane. The term "lens layer" may refer to the mask layer 102 perforated with the plurality of apertures 104, which may be hole structures. In other words, the lens layer

may include a combination of the mask layer 102 and the plurality of apertures (e.g. holey structures) 104.

[0067] In the context of various embodiments, the plurality of apertures 104, 204, 204a, 204b may include 2-dimensional and/or 3-dimensional features.

5 [0068] In the context of various embodiments, a respective aperture 104, 204, 204a, 204b of the plurality of apertures 104, 204, 204a, 204b may have a shape selected from the group consisting of a circle, a ring, a triangle, a square, a rectangle and an ellipse. However, it should be appreciated that other geometrical shapes may also be provided, including polygonal shapes.

10 [0069] In the context of various embodiments, the plurality of apertures 104, 204, 204a, 204b may include holey structures. For example, the plurality of apertures 104, 204, 204a, 204b may be holes or pinholes. The term "holey structures" may mean structures that are at least substantially completely hollow, or in other words, a cross-section of a holey structure is at least substantially completely hollow. A respective holey structure or
15 the holey structures may have a shape such as a circle, a triangle, a square, a rectangle, an ellipse or other geometrical shapes, including polygonal shapes. In various embodiments the holey structures may include 2-dimensional and/or 3-dimensional features.

[0070] In various embodiments, the holey structures may have a thickness in a range of between about 10 nm and about 10 μ m (10000 nm), for example between about 10 nm
20 and about 5 μ m, between about 10 nm and about 1 μ m, between about 10 nm and about 500 nm, between about 10 nm and about 100 nm, between about 500 nm and about 10 μ m, between about 500 nm and about 1 μ m, or between about 1 μ m and about 10 μ m. In various embodiments, the thickness of the holey structures may be at least substantially similar or identical to the thickness of the mask layer 102.

25 [0071] In the context of various embodiments, the concentric pattern 106, 206, 206a, 206b may include but not limited to a circle, a square or a rectangle.

[0072] In the context of various embodiments, the mask layer 102, 202 may include an (optically) opaque material.

[0073] In the context of various embodiments, the mask layer 102, 202 may include at
30 least one of a metal, a semiconductor or a polymer.

[0074] The metal as the material of the mask layer 102, 202 may include but not limited to gold (Au), silver (Ag), aluminum (Al), chromium (Cr) and nickel (Ni). However, it should be appreciated that any metals that may be non-transmissive or opaque to the electromagnetic radiation 120 may be used.

5 [0075] The semiconductor as the material of the mask layer 102, 202 may include but not limited to silicon (Si), germanium (Ge) and gallium arsenide (GaAs). However, it should be appreciated that any semiconductors that may be non-transmissive or opaque to the electromagnetic radiation 120 may be used.

[0076] The polymer as the material of the mask layer 102, 202 may include but not
10 limited to ROPAQUE™ Opaque Polymer from Dow Chemical, acrylonitrile butadiene styrene (ABS), polyphenylene oxide (PPO), polyaryletheretherketone (PEEK), polyphenylene sulphide (PPS). However, it should be appreciated that it should be appreciated that any polymers that may be non-transmissive or opaque to the electromagnetic radiation 120 may be used.

15 [0077] In the context of various embodiments, the mask layer 102, 202 may have a thickness ranging from about 10 nm to several microns, for example a thickness in a range of between about 10 nm and about 10 μm , e.g. between about 10 nm and about 5 μm , between about 10 nm and about 1 μm , between about 10 nm and about 500 nm, between about 10 nm and about 100 nm, between about 100 nm and about 10 μm ,
20 between about 500 nm and about 10 μm , between about 1 μm and about 10 μm , or between about 5 μm and about 10 μm .

[0078] In the context of various embodiments, the mask layer 102, 202 may be of a sufficient thickness that may render the mask layer 102, 202 non-transmissive to the electromagnetic radiation 120. For example, the thickness of the mask layer 102, 202
25 may be enough to make the mask layer 102, 202 at least substantially opaque to light.

[0079] In the context of various embodiments, the zone plate 100, 200a, 200b may further include a substrate, wherein the mask layer 102, 202 may be arranged over the substrate, and wherein the substrate may be at least substantially transmissive to the electromagnetic radiation 120. The electromagnetic radiation 120 impinging on the zone
30 plate 100, 200a, 200b may first be received by the substrate and then propagate through

the substrate towards the mask layer 102, 202 and the plurality of apertures 104, 204, 204a, 204b.

[0080] In the context of various embodiments, the substrate may be at least substantially transparent to the electromagnetic radiation 120. The substrate may include a solid material that may be at least substantially transmissive or transparent to the electromagnetic radiation 120. The substrate may be or may include quartz. The substrate may be at least substantially planar or flat.

[0081] In the context of various embodiments, the zone plate 100, 200a, 200b may produce a super-resolution focal spot and/or achieve optical imaging resolution beyond the diffraction limit. The zone plate 100, 200a, 200b may be capable of forming a sub-diffraction limit focusing spot.

[0082] In the context of various embodiments, the zone plate 100, 200a, 200b may be at least substantially planar or flat.

[0083] In the context of various embodiments, the zone plate 100, 200a, 200b may be an optical zone plate.

[0084] In the context of various embodiments, the zone plate 100, 200a, 200b may be a Fresnel Zone Plate (FZP). For example, the zone plate 100, 200a, 200b may be a holey Fresnel Zone Plate lens (HFZPL).

[0085] In the context of various embodiments, the electromagnetic radiation 120 may include at least one of X-ray, microwave, infrared (IR) or optical light.

[0086] In the context of various embodiments, the electromagnetic radiation 120 may have a wavelength in a range of between about 370 nm and about 780 nm, for example between about 450 nm and about 780 nm, between about 600 nm and about 780 nm, between about 370 nm and about 500 nm, or between about 450 nm and about 650 nm.

[0087] In the context of various embodiments, the electromagnetic radiation 120 may be provided by a laser source. The laser source may emit an electromagnetic radiation 120 having a wavelength of about 632.8 nm.

[0088] Various embodiments may also provide a microscope including a zone plate as described herein, e.g. any one of zone plates 100, 200a, 200b. The microscope may be an optical microscope.

[0089] Various embodiments may also provide an imaging device including a source configured to provide an electromagnetic radiation, and a zone plate as described herein, the zone plate arranged to diffract the electromagnetic radiation and focus the diffracted electromagnetic radiation for imaging an object. For example, the zone plate may be any one of zone plates 100, 200a, 200b. The source may include or may be a laser source. The laser source may emit an electromagnetic radiation having a wavelength of about 632.8 nm.

[0090] The imaging device may further include a detector.

[0091] The imaging device may include or may be an imaging scope, for example a nanoscope.

[0092] The imaging device may be an optical imaging device.

[0093] In the context of various embodiments, the microscope and the imaging device may be configured to image one or more objects of a subwavelength dimension.

[0094] Various embodiments may further provide a holey Fresnel zone plate lens (HFZPL) including a mask layer that is opaque to light (e.g. a light having a wavelength from about 380 nm to about 780 nm) from a light source, a lens layer having a plurality of holey structures, or a plurality of holey structures combined with ringy structures, where the plurality of holey structures and the ringy structures are transparent to the light, and a flat substrate that is transparent to the light. The flat substrate may include solid materials that may be at least substantially transparent to the light. The HFZPL may be provided in an optical nanoscope. It should be appreciated that the lens layer may refer to the mask layer perforated with the plurality of holey structures. In other words, the lens layer may include a combination of the mask layer and the plurality of holey structures, or a combination of the mask layer and the plurality of holey structures combined with the ringy structures.

[0095] A method of fabricating the zone plate (e.g. HFZPL) of various embodiments will now be described by way of the following non-limiting example. The holey FZP lens (HFZPL) may be fabricated on a transparent substrate (e.g. quartz). Initially, an opaque metallic film may be deposited onto the substrate. A resist may then be deposited on the opaque metallic film. Through an electron-beam lithography (EBL) process, apertures and/or holey structures and/or nano pinholes may be patterned on the resist and

the resulting pattern may then be transferred into the metal film by a dry etching process. The resist may then be stripped, and the HFZPL structures may thus be formed.

[0096] FIG. 3A shows a schematic perspective view illustrating a nanoimaging process with a holey FZPL-based nanoscope 330, according to various embodiments. The holey FZPL-based nanoscope 330 may include a HFZPL 300 of various embodiments installed in place of an objective lens, for example, of a conventional optical microscope. In other words, the objective lens of a conventional optical microscope may be replaced by the HFZPL 300, thereby forming the nanoscope 330. The nanoscope 330 may include a light source (e.g. a laser source) 310, which may generate light 320 to be received by the HFZPL 300, at an input side of the HFZPL 300. The nanoscope 330 may also include a detector (e.g. a photomultiplier tube (PMT)) 312 arranged at an output side of the HFZPL 300.

[0097] FIG. 3B shows a schematic top view of the holey FZPL 300 of FIG. 3A. The HFZPL 300 is embedded with radially distributed holey structures or pinholes 304. The pinholes 304 may be defined through an at least substantially opaque mask layer 302, and arranged in a plurality of concentric patterns or zones. The radii of the pinholes 304 may vary (e.g. decrease) in a direction away from the central axis of the HFZPL 300. As a non-limiting example, the radii of the pinholes 304 may vary from about 50 nm at the outer portion of the HFZPL 300 to about 400 nm at the inner portion of the HFZPL 300.

[0098] The operational concept or working principle of the nanoimaging process using the HFZPL 300 is as illustrated in FIG. 3A. Upon illumination by light 320 from the laser source 310, for example operating at a wavelength of about 632.8 nm, light 320 may be diffracted by the HFZPL 300 to define light beams, where the HFZPL 300 may also then focus the diffracted or diffractive light beams 320a into a subwavelength focal spot 322.

The resulting focal spot 322 may be employed to image objects of subwavelength dimension, which may be 2-dimensional and/or 3-dimensional objects. As non-limiting examples, the objects of subwavelength dimension may be in the form of circular patterns 314a and/or line patterns 314b. Subsequently, the transmitted signal of intensity, after imaging or scanning the objects, may be collected via an immersion microscopic lens (not shown) and recorded by a photomultiplier tube (PMT) 312. The sub-diffraction-

limit resolution image may be directly reconstructed in a manner of point-to-point consecutive scanning process without any post-processing.

[0099] In various embodiments, considerations may be made to enable subwavelength resolution imaging with the HFZPL-based nanoscopy device 330. The HFZPL 300, as the key component, may be designed to ensure an accurate and constructive interference of waves to create a sub-diffraction-limit focus at a desirable far field, e.g. several tens of wavelengths away from the HFZPL 300. For example, the HFZPL 300 may include several tens of concentric zones or patterns, where multiple holey structures of various diameters and spacings may be arranged. Instead of manipulation of evanescent wave, the HFZPL 300 may directly converge diffractive light beams into a superfocusing spot at the far field. Further, subject to a scanning mode of a conventional optical microscope under illumination at a certain wavelength, the signals may be recorded by a detector, from which subwavelength images may be attainable immediately without any post processing. For example, the signals may be captured by moving the scan stage of a conventional optical microscopy system, where the HFZPL may be placed under light illumination from its backside.

[0100] FIG. 4 shows a scanning electron microscopy (SEM) image 430 of a holey Fresnel zone plate lens (HFZPL) 400 of various embodiments, obtained at a magnification of 3000. The HFZPL 400 is a holey chromium structure of HFZPL on a quartz substrate. The HFZPL 400 includes a plurality of apertures, in the form of holey structures (e.g. holes) 404, formed through a chromium (Cr) layer (mask layer) 402. While the SEM image 430 shows the holey structures 404 as bright rings, it should be appreciated that the holey structures 404 are completely hollow (i.e. hollow structures), or in other words, the holey structures 404 are complete through holes.

[0101] As may be observed, the holey structures 404 are distributed or arranged in a plurality of concentric patterns or zones. The concentric patterns are arranged one after another in a radial direction of the HFZPL 400. The diameters or radii of the holey structures 404 in respective concentric patterns decrease in a direction from an inner portion of the HFZPL 400 towards the outer portion of the HFZPL 400, varying from about 400 nm (inner portion) to about 50 nm (outer portion). In other words, there is a

decrease in the radii of the holey structures 404 in a direction away from the central axis of the HFZPL 400.

[0102] FIGS. 5A to 7 shows results of nanoimaging processes, with FIGS. 5A to 6B showing results of sub-diffraction-limited imaging with a HFZPL-based optical nanoscope.

[0103] FIG. 5A shows a two-dimensional (2D) plot 530 of measured result of a focal spot obtained at a wavelength of about 632.8 nm, illustrating the intensity distribution at the focal point ($Z = 6.78 \mu\text{m}$, where Z refers to the focal distance of the HFZPL) FIG. 5A also shows a three-dimensional (3D) plot 532 of the intensity distribution of the focal spot. The dashed circles indicate the position of the central spot or lobe.

[0104] FIG. 5B shows a plot 540 of the cross-sectional profile 542 of the intensity corresponding to the focal spot shown in FIG. 5A, illustrating that the measured full width at half maximum (FWHM) of the central focus spot is about 248 nm ($\approx \lambda/2.55$, $\lambda = 632.8 \text{ nm}$).

[0105] In order to show the optical image resolution of the HFZPL-based nanoscope of various embodiments, objects for imaging, in the form of double airy slits with a width of about 140 nm ($\approx \lambda/4.52$, $\lambda = 632.8 \text{ nm}$) with a spacing of about 260 nm embedded in an opaque metallic film, were fabricated via electron beam lithography followed by a dry etching process. FIG. 6A shows a scanning electron microscopy (SEM) image 630 of the fabricated double airy slits 632, 634. FIG. 6B shows a resolved nanoimage 640 of the double airy slits of FIG. 6A, obtained using the HFZPL-based nanoscope of various embodiments. The resolved double-slit image 640 obtained via the HFZPL shows double slits 632a, 634a, shown as two bright lines, which verifies that the HFZPL-based nanoscopy device may be able to perform sub-diffraction-limit resolution ($\approx \lambda/4.52$) imaging. For comparison purposes, a control imaging process without using the HFZPL of various embodiments was carried out and the result is shown in FIG. 7. FIG. 7 shows an image 730 of the double airy slits of FIG. 6A obtained using a conventional solid immersion lens ($100\times 1.3\text{NA}$). As shown in the image 730, the double airy slits 632, 634 of FIG. 6A, indicated in the image 730 within the dashed ellipse, were unresolved or irresolvable.

[0106] As described above, various embodiments may provide a holey Fresnel Zone Plate lens (HFZPL) and an optical nanoscope with the HFZPL, which may be capable of imaging nanoscale objects, and breaking the resolution limit of traditional microscopes. Further, all scanning-based conventional microscopes may be simply upgraded to an optical nanoscope by employing the HFZPL of various embodiments to perform non-destructive nanoscale imaging. The HFZPL of various embodiments may be easily integrated with any commercially available optical microscope for optics, electronics and biology applications, among others. In view of the above, there may be a great potential for the technology of various embodiments and a vast market from laboratory to industry may be available.

[0107] 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. A zone plate comprising:

a mask layer that is at least substantially non-transmissive to an electromagnetic radiation impinging on the zone plate; and

a plurality of apertures defined through the mask layer, the plurality of apertures being at least substantially transmissive to the electromagnetic radiation, wherein the plurality of apertures are distributed in at least one concentric pattern so as to diffract the electromagnetic radiation and focus the diffracted electromagnetic radiation into a subwavelength focal spot on a desired focal plane.

2. The zone plate as claimed in claim 1, wherein the plurality of apertures are distributed in a plurality of concentric patterns.

3. The zone plate as claimed in claim 2, wherein the plurality of apertures distributed in the plurality of concentric patterns have diameters that change in a radial direction.

4. The zone plate as claimed in claim 2 or 3, wherein adjacent concentric patterns of the plurality of concentric patterns are arranged relative to each other at a distance in a range of between 0 and about 1 μm .

5. The zone plate as claimed in any one of claims 1 to 4, wherein a number of the plurality of apertures distributed in each concentric pattern is equal to 10 or more.

6. The zone plate as claimed in any one of claims 1 to 5, wherein the plurality of apertures have a diameter in a range of between about 0.1 nm and about 1 μm .

7. The zone plate as claimed in any one of claims 1 to 6, wherein the plurality of apertures have a thickness in a range of between about 10 nm and about 10 μm .

8. The zone plate as claimed in any one of claims 1 to 7, wherein the plurality of apertures are distributed periodically spaced apart from each other in each concentric pattern.

5 9. The zone plate as claimed in any one of claims 1 to 8, wherein the plurality of apertures are spaced apart from each other in each concentric pattern at a spacing in a range of between about 0.1 nm and about 1 μ m.

10 10. The zone plate as claimed in any one of claims 1 to 9, wherein a respective aperture of the plurality of apertures has a shape selected from the group consisting of a circle, a ring, a triangle, a square, a rectangle and an ellipse.

11. The zone plate as claimed in any one of claims 1 to 10, wherein the plurality of apertures comprise holey structures.

15

12. The zone plate as claimed in any one of claims 1 to 11, further comprising at least one concentric aperture defined through the mask layer and arranged concentrically with the at least one concentric pattern, the at least one concentric aperture being at least substantially transmissive to the electromagnetic radiation.

20

13. The zone plate as claimed in claim 12, wherein each concentric aperture has a width in a range of between about 1 nm and about 1 μ m.

25 14. The zone plate as claimed in claim 12 or 13, further comprising a plurality of concentric apertures defined through the mask layer and arranged concentrically with the at least one concentric pattern.

30 15. The zone plate as claimed in claim 14, wherein adjacent concentric apertures of the plurality of concentric apertures are arranged spaced apart from each other at a spacing in a range of between about 0.1 nm and about 1 μ m.

16. The zone plate as claimed in claim 14 or 15, wherein the plurality of apertures are distributed in a plurality of concentric patterns, and wherein the plurality of concentric apertures are arranged alternately with the plurality of concentric patterns.
- 5 17. The zone plate as claimed in any one of claims 1 to 16, wherein the mask layer comprises at least one of a metal, a semiconductor or a polymer.
18. The zone plate as claimed in any one of claims 1 to 17, further comprising:
a substrate, wherein the mask layer is arranged over the substrate, and
10 wherein the substrate is at least substantially transmissive to the electromagnetic radiation.
- 19 A microscope comprising a zone plate as claimed in any one of claims 1 to 18.
- 15 20. An imaging device comprising:
a source configured to provide an electromagnetic radiation; and
a zone plate as claimed in any one of claims 1 to 18, the zone plate arranged to diffract the electromagnetic radiation and focus the diffracted electromagnetic radiation for imaging an object.