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(54) Title: HIGH-RESOLUTION OPTICAL IMAGER

(57) Abstract: An optical imager comprises an interferometer, microscopic optics operative in combination with the interferometer to generate a reference image and an object image, and an image capture device configured to capture an interferometric image with a phase difference between the reference image and the object image. The optical imager further comprises a phase shifter operative to selectively control the phase difference and a controller operative to capture a plurality of interferometric images at a selected plurality of phase differences and combine the plurality of interferometric images into a processed image with in-plane resolution that is increased over optical wavelength and numerical aperture characteristics.

HIGH-RESOLUTION OPTICAL IMAGER

Araz Yacoubian

BACKGROUND OF THE INVENTION

[0001] Optical imaging is limited by the wavelength of light and by the numerical aperture of the collection optics. For example, in a high-power microscope, the resolution is limited by the wavelength of the illumination and by the numerical aperture (NA) of the objective lens. Some improvement of resolution is possible using liquid immersion objective lens, but the increase is not in orders of magnitude. In addition, the standard microscopic imaging depth of focus is limited by the objective lens.

[0002] Technologies other than microscopic imaging can result in high magnification images of a surface, such as scanning electron microscope (SEM) or atomic force microscope (AFM). However these methods have limitations. For example, SEM requires a large apparatus to generate and focus electron beams, is limited to a small sample area, and is relatively slow and expensive. AFM utilizes a scanning tip that wears out and needs replacement, and is relatively slow and limited to small sample sizes.

[0003] Interferometric optical microscopes have been used to produce out-of-plane (z direction) topographic measurements with accuracy much smaller than optical wavelengths. However, the in-plane (x,y direction) resolution of the instruments remains limited by diffraction limit of light, specifically limited by the source wavelength and NA of the objective lens.

SUMMARY OF THE INVENTION

[0004] In an illustrative embodiment, an optical imager comprises an interferometer, microscopic optics operative in combination with the interferometer to generate a reference image and an object image, and an image capture device configured to capture an interferometric image with a phase difference between the reference image and the object image. The optical imager further comprises a phase shifter operative to selectively control the phase difference and a controller operative to capture a plurality of interferometric images at a selected plurality of phase differences and combine the plurality of interferometric images into a processed image with in-plane resolution that is increased over optical wavelength and numerical aperture characteristics.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Embodiments of the invention relating to both structure and method of operation, may best be understood by referring to the following description and accompanying drawings:

FIGURE 1 is a schematic pictorial and block diagram illustrating an embodiment of an optical imager that enables high-resolution imaging;

FIGURE 2 is a pictorial diagram that depicts a sample mounted at an angle according to an embodiment of an optical imager;

FIGURE 3 is a pictorial diagram showing changes in the interference pattern induced by phase shift of various types that can be implemented in various embodiments of an optical imager;

FIGURE 4 are pictorial diagrams illustrating a comparison of microscope patterns that result from standard microscope imaging and high-resolution imaging using an embodiment of an illustrative optical imager;

FIGURE 5 is a schematic pictorial view showing an embodiment of an optical imager that can generate a phase shifted interference pattern by changing the physical position of the sample;

FIGURE 6 is a schematic pictorial view depicting examples of mirror motion that can be implemented in an embodiment of an optical imager;

FIGURE 7 is a schematic pictorial diagram illustrating an embodiment of an optical imager which can generate a phase shifted interference pattern by adding a phase shifter to the reference beam;

FIGURE 8 is a pictorial view depicting an embodiment of an optical imager in which a difference image is generated using an interferometric microscope objective;

FIGURE 9 is a combined pictorial and block diagram depicting a high-resolution imager with the microscope objective outside the interferometer;

FIGURE 10 shows pictorial views respectively depicting an example of an image produced by a standard microscope and an embodiment of an illustrative high-resolution optical imager;

FIGUREs 11A through **11I**, several pictorial diagrams illustrate examples of light source optic configurations that can be implemented in various embodiments of an optical imager;

FIGURE 12 is a schematic pictorial and block diagram that depicts an embodiment of a high-resolution optical imager for a fully or partially transparent sample;

FIGURE 13 is a schematic pictorial and block diagram showing another embodiment of a high-resolution optical imager for a fully or partially transparent sample;

FIGUREs 14A through **14G** are multiple pictorial diagrams depicting various phase delay methods to shift the fringes which can be used for embodiments of optical imagers such as those shown in **FIGURE 12** and **FIGURE 13**;

FIGURE 15 is a schematic pictorial and block diagram illustrating an embodiment of a speckle reduction device and associated speckle reduction method using a rotating diffuser via a rotating motor;

FIGURE 16 is a schematic pictorial and block diagram depicting an embodiment of a speckle reduction device and associated speckle reduction method using a scattering medium embedded between two transparent or semitransparent electrodes;

FIGURE 17 is a schematic pictorial and block diagram showing an embodiment of a speckle reduction device and associated speckle reduction method using a flowing scattering medium;

FIGURE 18 is a schematic pictorial and block diagram illustrating an embodiment of a speckle reduction device and associated speckle reduction method using a linearly moving diffuser;

FIGURE 19 is a pictorial view showing an embodiment of a speckle reduction device and associated speckle reduction method using a partially coherent light source; and

FIGURE 20 is a schematic pictorial and block diagram illustrating an embodiment of a coherent or partially coherent light source coupled to an optical fiber via a lens or combination of lenses that can be used in an optical imager.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0006] Structures and methods are disclosed to detect microscopic images at resolution much higher than what is possible to achieve using standard optical microscopes.

[0007] Illustrative structures and methods can include and use an interferometer coupled to microscopic optics, image processing apparatus and phase shift control electronics to produce high resolution images of a sample surface. The illustrative optical imagers and associated methods can be non-contact, relatively fast, and image the sample at resolution much higher than is possible to achieve using standard microscopes. The structures and methods also increase the depth of focus and image contrast.

[0008] The embodiments, configurations, and associated techniques disclosed hereinafter overcome the optical resolution of the microscope by utilizes interference, phase shifting and image capture and computation methods, and produce images that are higher resolution than limited by the optical wavelength of the light source and the numerical aperture of the optical system. Additionally, the images have higher contrast than a conventional microscope image, and have much longer depth of focus than using a microscope with a similar objective lens.

[0009] The fringe shift in an interference image of a sample obtained with an interferometric microscope is mainly due to time delay of light, for instance the optical path length difference, between one point and another on the sample. For a sample with topographic variations, the interference image contains shifted fringes wherever a variation in height exists. The wavelength and NA of the optical system limit the in-plane (x,y direction) resolution of the image, which is limited by the diffraction of light at edges of the topographic variation in the sample. Edges that have much smaller dimension than the optical wavelength look rounded due to the diffraction limit. Fringe shift at various points on the topographic pattern however is due to time delay between one point of the sample and the other, which is an out-of-plane (z direction) phenomenon. Illustrative optical imagers and associated methods make use of the key difference between the in-plane and out-of plane phenomenon to overcome the optical limit.

[0010] The same considerations are applicable for a sample with a pattern other than topographic variations, such as a sample with embedded phase objects with features smaller than the optical wavelength.

[0011] Referring to **FIGURE 1**, a schematic pictorial and block diagram illustrates an embodiment of an optical imager **100** that enables high-resolution imaging. The illustrative optical imager **100** comprises an interferometer **120**, microscopic optics **122** operative in combination with the interferometer **120** to generate a reference image **107** and an object image **108**, and an image capture device **110** configured to capture an interferometric image with a phase difference between the reference image **107** and the object image **108**. The optical imager **100** further comprises a phase shifter operative to selectively control the phase difference and a controller **116** operative to capture a plurality of interferometric images at a selected plurality of phase differences and combine the plurality of interferometric images into a processed image with in-plane resolution that is increased over optical wavelength and numerical aperture characteristics.

[0012] **FIGURE 1** depicts the apparatus **100** used to generate high-resolution images. The apparatus **100** is an interferometer **120** coupled to microscopic objective **106** and eyepiece lenses **111**. The image of the sample is captured by a camera **110**. The image displayed on a video screen **112** contains the microscopic image, and overlapping interference fringes **114** and **115**. If the reference beam **107** is blocked, the image will be a standard optical image, with resolution limited by the wavelength of light and microscope objective numerical aperture. To increase resolution, the phase difference between the reference beam **107** and the object beam **108** are changed by various methods described throughout the description, and the image is captured at various phase shifts shown in equation (1):

$$I(x,y,\phi_o),\ I(x,y,\phi_o+\phi_1),\ \ldots,\ I(x,y,\ \phi_o+\phi_i),\ \ldots,\qquad (1)$$

where $I(x,y,\ \phi_o)$ is the interferometric image captured with a phase difference ϕ_o between the reference beam **107** and the object beam **108**. If phase is delayed by an additional ϕ_1 or ϕ_i, the interference image is denoted as $I(x,y,\phi_o+\phi_1)$ or $I(x,y,\ \phi_o+\phi_i)$, respectively. The interferometric images with reference to object phase difference $\phi_o+\phi_i$ and $\phi_o+\phi_{i+1}$ are shown in **FIGURE 3**. **FIGURE 3** depicts changes in the interference pattern, where fringes **314**, **315** shift in the direction of the arrows **319** if phase is induced either by using a phase shifter in the reference beam path **107**, by moving the reference mirror **104** or by moving the sample **105** using the sample translation stage **109** and **209**, as depicted in **FIGURES 1** and **2**, to form resulting shifted fringes **320** and **321**.

[0013] The illustrative optical imager **100** can perform a method for generating an increased-resolution image comprising illuminating an object with at least partially coherent light, forming a reference image and an object image, and capturing an interferometric image with a phase difference between the reference image and the object image. The optical imager **100** selectively controls the phase difference and captures multiple interferometric images at selected phase differences. The multiple interferometric images are combined into a processed image with in-plane resolution that is increased over optical wavelength and numerical aperture characteristics.

[0014] The controller **116** can be operative to selectively control capture of an image at a first phase and a second phase and determine a difference interferometric image as a difference of interferometric images captured at the first and second phases.

[0015] After capturing one interference image $I(x,y,\phi_o)$, one of the beams is phase delayed further by ϕ_1, resulting in a new image $I(x,y,\phi_o+\phi_1)$, in which fringes are shifted due to the additional phase delay. After capturing the two images, the difference of the two images is computed, as depicted in equation (2):

$$\Delta I = I(x,y,\phi_o+\phi_1) - I(x,y,\phi_o). \qquad (2)$$

[0016] The sequence is repeated for each consecutive measurement, as shown in equation (3):

$$\Delta I_i = I(x,y,\phi_o+\phi_{i+1}) - I(x,y,\phi_o+\phi_i). \qquad (3)$$

[0017] Thus, the optical imager **100** can operate by capturing an image at a first phase and a second phase and determining a difference interferometric image as a difference of interferometric images captured at the first and second phases.

[0018] The controller **116** is operative to acquire interferometric images at multiple of the first and second phases and summing multiple of the difference interferometric images.

[0019] Each image ΔI_i carries spatial information higher than achievable using standard microscope, since the spatial information is obtained interferometrically. The new image ΔI_i is added to the non-interferometric image obtained by blocking the reference beam **107** to enhance the resolution of the image, or a number of the images ΔI_i can be added to produce an average image which results in an image that is higher resolution than a standard microscope image, according to equation (4):

$$\Delta I_{avg} = \sum_i \Delta I_i . \qquad (4)$$

[0020] Thus in some embodiments, the optical imager **100** can acquire non-interferometric images and average the non-interferometric image with a sum of the plurality of difference interferometric images.

[0021] In some embodiments, the controller **116** can be operative to acquire interferometric images at a plurality of first and second phases, multiplying a plurality of difference interferometric images by a factor smaller than one that is selected to avoid over-saturation, and summing the plurality of difference interferometric images.

[0022] To avoid over-saturation of the image, each difference image ΔI_i in equation (4) can be multiplied by a factor smaller than 1.

[0023] The controller **116** can be configured to be operative to acquire a non-interferometric image and average the non-interferometric image with a sum of the plurality of difference interferometric images.

[0024] When phase difference is varied through many cycles, to assure best averaging, ΔI_i in equation (4) may be replaced by a corresponding absolute value, as depicted in equation (5):

$$\Delta I_{avg} = \sum_i |\Delta I_i| . \qquad (5)$$

[0025] In some implementations, the controller **116** can be operative to select phase change increments between successive images to produce a fraction of fringe movement and summing multiple successive images to cover a full fringe cycle.

[0026] For example, to enhance the resolution of the processed image the phase change between each consecutive image can be selected to produce a fraction of fringe movement. For example, if each phase-shift moves the fringes by one-tenth of fringe, ten shifts produce a complete set that covers one full fringe cycle. Repeating the process using multiple fringe cycles results in a better averaged image than using one fringe cycle only.

[0027] In some implementations or in some conditions, the controller **116** can be operative to selectively control capture an image at a first phase and a second phase and determine a ratio interferometric image as a ratio of interferometric images captured at the first and second phases. The controller **116** can be operative to acquire interferometric images at a plurality of first and second phases and summing a plurality of ratio interferometric images.

[0028] Taking the absolute value of the difference in equation (3) can also reveal fine features of the sample. Dividing one image with the next, for example replacing difference operation in equation (3) with division operation also reveals fine features of the sample, as is described in more detail hereinafter.

[0029] For example, instead of subtracting each phase shifted interference image, the image can be divided. Specifically, instead of the operation of equation (2) can be replaced by the operation given in equation (6) as follows:

$$I_i = I(x,y,\phi_o + \phi_{i+1}) / I(x,y, \phi_o + \phi_i), \qquad (6)$$

and the actions in equations (4) and (5) repeated. Care can be exercised to ensure that the images do not contain zero pixels, which result in divide-by-zero errors in computation which can be overcome by adding a constant value to the overall interference image, thus avoiding zero valued pixels.

[0030] Thus in some embodiments, the optical imager **100** can capture an image at a first phase and a second phase, and determine a ratio interferometric image as a ratio of interferometric images captured at the first and second phases. Interferometric images can be acquired at multiple first and second phases and multiple ratio interferometric images can be summed.

[0031] In an example embodiment, the optical imager **100** can further comprise a light source **101** that is operative to generate at least partially coherent light, a reference mirror **104**, an objective lens **106**, and a beam splitter **103** that is configured to direct the at least partially coherent light to the reference mirror **104** for reflecting the light onto a reference beam path **107** and to an object **105** through the objective lens **106** for reflecting the light onto an object beam path **108**. The illustrative optical imager **100** further comprises an imaging lens **111** arranged to pass reflected light along the reference beam path **107** and the object beam path **108** to the image capture device **110**.

[0032] **FIGURE 1** depicts a high-resolution optical imager **100**, an apparatus that contains coherent light source **101** such as a laser, a laser diode, or a partially coherent light source. The light source **101** is expanded **102** either via a non-collimated laser diode, from a cleaved fiber end, or is expanded using a refractive or a diffractive optical component placed in the beam path of a collimated laser. Light passes through a beam splitter **103**. Part of the light is directed toward a reference mirror **104**, and the other part is directed towards the sample **105** after passing through an objective lens **106**. The reference beam path is depicted in dashed lines **107**, and the object beam path is depicted in solid lines **108**. Sample is mounted on a translation stage **109** which provides x, y, z control as well as rotation and tilt of the sample with respect to the object beam path **108**. Reflected light from reference mirror **104** and the sample **105** are directed toward a camera **110** after passing through an imaging lens **111**. The raw image is displayed on a video screen **112** containing the optical image of the sample pattern **113** and overlapping fringes **114**. Due to topographic variations of the sample pattern, the fringes are shifted **115**. The image **113** is limited by the optical resolution, and at very high magnifications, sharp edges are rounded. After image is captured and processed through processing software and processing and control electronics **116**, the resulting image is displayed on a second video screen **117**, and the sample pattern is revealed **118** at much higher resolution than the unprocessed image **113**. Phase shifting either via a phase shifting or moving the fringes is achieved by moving the sample as illustrated in **FIGURE 5**, by moving the reference mirror, or by incorporating a phase shifter in the reference beam path **107**. An optional lens **162** can be used to better match the reference **107** and object **108** beam divergence, or to adjust the fringes from circular to linear or vise versa. Phase shifting can be controlled by the processing and control electronics **116**.

[0033] For example, since laser light produces speckles to obtain a very high-resolution clean image without speckle noise, the light source **101** in **FIGURE 1** may be switched to a non-coherent source, or a second beam splitter may be replaced between the light source **101** and the beam splitter **103**, which directs light towards the sample. An image can be taken using the noncoherent illumination I_{NI} which does not contain any speckles. The averaged interferometric image ΔI_{avg} and the non-interferometric image I_{NI} can be added or multiplied together to produce a high-resolution, yet clean image with low-noise and speckle-free.

[0034] The operations produce an image of the sample at much higher resolution than is possible using a standard microscope, as shown in **FIGURE 4**. **FIGURE 4** depicts a standard microscope pattern **422** of the sample which is limited by the optical resolution. The processed image **418** of the high-resolution imaging apparatus reveals more detail than the microscope image, and edges of the image appear sharper than standard microscope image.

[0035] Accordingly, in various embodiments an optical isolator increases image resolution.

[0036] **FIGURE 1** shows a sample **205** that is placed at normal incidence to the optical axis and the object beam **108**. In other arrangements, the sample **205** can be placed at an angle as illustrated in **FIGURE 2**. Accordingly, the illustrative optical imagers and associated techniques can be implemented to enable sampling the object at normal incidence or a selected angle of incidence. **FIGURE 2** depicts a sample **205** mounted at an angle with respect to the object beam **208** on a translation stage **209** which holds the sample **205**. The stage is placed in the apparatus **100** shown in **FIGURE 1**.

[0037] In some embodiments or in selected operation, the phase shifter can comprise a device that controllably moves the object. The phase shifter can move the object in selected space increments or other suitable technique. In particular embodiments, implementations, or in selected operation, a difference image can be generated by moving the sample. One possible method to produce high-resolution images is to move, tilt or rotate the sample as shown in **FIGURE 5**, record the images, and subtract the images as described in equation (2) and (3). In this case, when averaging multiple difference images as described in equation (3), each difference image should be reset by shifting or rotating, ΔI_i to the original image location (i.e. x_o, y_o) before performing the averaging operation described in equation (4).

[0038] Referring to **FIGURE 5**, a schematic pictorial view shows an embodiment of an optical imager that can generate a phase shifted interference pattern by changing the physical position of the sample at small increments. The original position of the sample **505** is shifted to a new location **523**, for example by either a linear movement **524, 525, 526**, tilt **527**, rotation **528**, or combination of motions of the sample **505**. Phase shifting by movement of the sample holder is controlled by the processing and control electronics **116** which controls the mechanical movement of the sample holder stage **509**. Set **501**, **502**, **503**, **504**, **506**, **507**, **508**, **510**, **511**, and **562**, are similar or equivalent to set **101**, **102**, **103**, **104**, **106**, **107**, **108**, **110**, **111**, and **162**.

[0039] In some embodiments or in selected operation, the phase shifter can comprise a device that controllably moves the reference mirror. The reference mirror can be moved in selected space increments or other suitable arrangement. In particular embodiments, implementations, or in selected operation, a difference image can be generated by moving the reference mirror. The phase difference between the reference beam **107**, **607** and object beam **108, 608** can be achieved by moving the reference mirror **104**, **604** as shown in **FIGURE 6**. Two methods of movement produce a phase shift, specifically by moving **630** the reference mirror **604** to a new location **629**, or by tilting **632** the mirror to a new location **631**. Tilting can be in the vertical or horizontal direction, or at any selected direction.

[0040] Referring to **FIGURE 6**, a schematic pictorial view depicting examples of mirror motion that can be implemented in an embodiment of an optical imager. **FIGURE 6** depicts a method for shifting the phase in the interferometer illustrated in **FIGURE 1** by changing the physical position of the reference mirror **604** at small increments. The original position of the mirror **604** is shifted to a new location **629** by linear movement **630**, tilting **632** the reference mirror **604** to a new position **631**, or a combination of motions. Phase shifting by moving the reference mirror can be controlled by the processing and control electronics **116**.

[0041] In some embodiments or in selected operation, the phase shifter can be positioned in the reference beam path. Suitable types of phase shifters can be selected including a liquid crystal device that changes the optical path length (OPL) of the reference beam with phase shift controlled by an external voltage controller, a retro-reflecting prism in an optical beam path comprising a plurality of mirrors or a mirror-coated prism that changes OPL when translated linearly, an optical flat glass that is tilted to change OPL, an optical wedge that changes OPL when translated linearly, an optical phase shifter device, an electro-optic phase shifter, a polarization phase shifter, and a fiber optic phase shifter.

[0042] In particular embodiments, implementations, or in selected operation, a difference image can be generated using a phase shifter. The phase difference between the reference beam **107, 707** and object beam **108**, **708** can be varied by adding a phase shifter **733** to the reference beam path as shown in **FIGURE 7**. The phase shifter **733** changes the optical path length of the reference beam **707**, thus changing the phase difference between the reference beam **707** and the object beam **708**. The phase shifter **733** can be a liquid crystal device that changes the optical path length (OPL) of the reference beam **707**, where phase shift is controlled by an external voltage controller **734**, which in turn is controlled by the processing and control electronics **116**. The phase shifter **734** can be an optical wedge which can changes the OPL when translated linearly or rotated, can be an optical flat glass which is titled to change the OPL, or can be any suitable selected type of optical phase shifting device, such as an electro-optic phase shifter, a polarization phase shifter, or a fiber optic phase shifter. Additional phase shifting methods are depicted in **FIGUREs 14A** through **14G**.

[0043] Referring to **FIGURE 7**, a schematic pictorial diagram illustrates an embodiment of an optical imager **700** which can generate a phase shifted interference pattern by adding a phase shifter **733** to the reference beam **707**. The phase shifter **733** can be a liquid crystal device that changes the optical path length (OPL) of the reference beam **707**, where phase shift is controlled by an external voltage controller **734**. The phase shifter **733** can also be an optical prism which can changes the OPL when translated linearly as illustrated in **FIGURE 14(A)**, can be an optical flat glass which is titled to change the OPL as illustrated in **FIGURE 14(B)**, a translated optical wedge as illustrated in **FIGURE 14(D)**, or can be an arbitrary type of optical phase shifter device, such as an electro-optic phase shifter, or a polarization phase shifter, or a fiber optic phase shifter. Detailed description of the interferometer components is described in association with **FIGURE 1**. The output signals from the camera **710** are sent to a screen and processing and control electronics, as illustrated in **FIGURE 1**. Phase shifting is controlled by the processing and control electronics **116**. Element set **701**, **702**, **703**, **704**, **705**, **706**, **707**, **708**, **709**, **710**, **711**, and **762**, are similar or equivalent to set **101**, **102**, **103**, **104**, **105**, **106**, **107**, **108**, **109**, **110**, **111**, and **162**.

[0044] In some embodiments, the optical imager can comprise an interferometric objective which is operative to generate an interference pattern and shift phase by moving, tilting or rotating in a selected direction. Referring to **FIGURE 8**, a pictorial view illustrates an embodiment of an optical imager **800** in which a difference image is generated using an interferometric microscope objective. In the architecture shown in **FIGURE 1**, interference fringes are generating by using a beam splitter **103** that directs light to a reference mirror **104**, which reflects light toward the camera **110**, and the reference **107** and object **108** beams are added coherently at the camera **110**. Another approach can use an interferometric microscope objective **835** is shown in **FIGURE 8**, where partially reflective mirrors **836** and **837** produce a reference beam, which interferes with the object beam. Phase shift can be achieved either by moving the interferometric objective **835** or by moving **824**, **825**, **826**, tilting **827**, or rotating **828** the sample, as shown in **FIGURE 8**, or by a combination of motions. The calculations according to the illustrative equations herein can be performed to produce difference interference images and result in a high-resolution image.

[0045] **FIGURE 8** depicts an apparatus using interferometric objective **835**, which contains partially reflective mirrors **836** and **837**. Mirror **836** is the reference mirror, which is either partially reflective, or is transparent optical flat glass with the center region coated with a high reflective coating. The interferometric objective **835** is used to generate the interference pattern. The interference pattern shown in **FIGURE 3** is shifted either by moving the sample as described in **FIGURE 5**, or by moving, tilting or rotating the interferometric objective **835** in an arbitrary direction **838**. The apparatus contains a coherent or a partially coherent light source **801**, a beam splitter **803**, an imaging lens **811**, and a camera **810**. The output of the camera **810** is sent to a screen and processing and control electronics, as illustrated in **FIGURE 1**. Phase shifting by moving the interferometric objective can be controlled by the processing and control electronics **116**. Element set **802**, **805**, and **809** can be similar or equivalent to set **102**, **105**, and **109**. Element set **823**, **824**, **825**, **826**, **827**, **828**, and **838** can be similar or equivalent to set **523**, **524**, **525**, **526**, **527**, **528**, and **538**.

[0046] In various embodiments, an optical imager can be implemented to increase or enhance depth of focus.

[0047] In addition to producing high-resolution images, the structures and methods described herein can also produce longer depth of focus. In a standard microscope, the best focus is achieved at a specific distance z_0 between the objective lens and the sample. As distance deviates from z_0, the image becomes blurred. Increasing depth of focus is particularly useful when viewing samples at an angle. The structures and methods described herein can operate by determining the difference between interference patterns to sharpen the image. Even in areas of the sample that fall away from z_0, the blurred image interference pattern can be compared with a shifted-phase version of the sample, resulting in a self-referencing image. After performing the calculations according to the illustrative equations, a sharper image is obtained than using a standard microscope. Therefore image blur is reduced by the resolution enhancement method. Since the image is still sharpened at various distances z away from z_0, depth of focus is enhanced.

[0048] High-resolution reflection imaging can be performed with a microscope objective positioned outside the interferometer. Thus in some embodiments, the beam splitter and the reference mirror can be positioned between the objective lens and the object. In other embodiments, a mirror configured whereby the object is positioned between the objective lens and the mirror.

[0049] **FIGURE 9** is a combined pictorial and block diagram depicting a high-resolution imager **900** with the microscope objective **906** outside the interferometer, an apparatus is similar to that shown in **FIGURE 1** with some differences. An advantage of the imager **900** in comparison to the optical imager **100** shown in **FIGURE 1** in some conditions and applications is easier accommodation of a partially coherent source, such as a light emitting diode (LED). A partially coherent source has coherence length much shorter than a coherent source such as a laser. To produce interference fringes, the optical-path-length (OPL) difference of the reference arm **107**, **907**, and the object arm **108**, **908** must be less than the coherence length. The closer the OPL of the reference and object arms are matched, the higher contrast fringes obtained, thus increasing the difference calculation accuracy. For a partially coherence source, the shorter is the OPL of each arm and the more easily OPL of the reference and object beams are matched, a further advantage of the optical imager **900** over the imager **100**. An associated disadvantage of the optical imager **900** is that since the beam splitter is placed between the objective lens **906** and the sample **905**, the working distance of the objective lens must be sufficiently long to accommodate the beam splitter **903**. Therefore either a low-power objective lens or a long working distance objective lens is to be used.

[0050] **FIGURE 9** depicts a high-resolution imager with beam splitter **907** and reference mirror **904** placed between the microscope objective **906** and the sample **905**. A coherent or partially coherent light source **901** and collimating, focusing or expanding optics **941** direct light toward the sample **905** and the reference mirror **904**, thus producing interference fringes. The interference fringes **914** and **915**, also shown in **FIGURE 3**, are shifted either by moving the sample **905** as described in association with **FIGURE 5**, by moving, tilting or rotating the reference mirror **904**, or by using a phase shifter **934** in the reference beam path **907**. The phase shift is controlled by the processing and control electronics **916**. The apparatus contains a coherent an imaging lens **911**, and a camera **910**. The output image of the camera **910** is sent to a screen and processing and control electronics, as illustrated in **FIGURE 1**. Element set **912**, **913**, **914**, **915**, **916**, **917** and **918** are similar or equivalent to set **112**, **113**, **114**, **115**, **116**, **117**.

[0051] An optical imager can be implemented to determine line edge shape. Referring to **FIGURE 10**, pictorial views respectively show an example of an image produced by a standard microscope and an embodiment of an illustrative high-resolution optical imager. **FIGURE 10** depicts a standard microscope image **1039** of a sample viewed at an angle. The image is limited by the optical resolution. The processed image **1040** of the high-resolution imaging apparatus reveals more detail than the microscope image, revealing edge structure.

[0052] Due to limited resolution, for very fine patterns such as patterns found in semiconductor integrated circuits (IC), standard microscopy is not capable of directly estimating the exact shape of the pattern. For example, an IC line edge is not easily determined using a standard microscope because of the resolution limit. Using the methods described herein, if the sample is placed at an angle, the shape of the line edge is determined as shown in **FIGURE 10**. As a comparison, the standard microscope image **1039** of a sample viewed at an angle is limited by the resolution and depth of focus and does not show line edge details. The image **1040** resulting using the high-resolution imaging scheme described here reveals more detail of the line edge.

[0053] In particular embodiments, an optical imager can comprise one or more beam shaping elements configured for shaping a beam from a coherent or partially coherent light source, the beam shaping element comprising a positive lens that collimates, diverges, converges a beam, or the like.

[0054] In various embodiments, the optical source **101** can be coherent, noncoherent, or partially coherent. Furthermore, the optical source **114** can be selected to generate illumination at a selected wavelength in a range of visible, infrared, ultraviolet, a selected part of light spectra, and X-ray.

[0055] Various schemes discussed herein throughout utilize coherent or partially coherent light sources. The schemes are not limited to a single optical wavelength and can accommodate variety of wavelength as appropriate for different applications. For example, ultraviolet (UV), visible or infrared (IR) light sources can be used with the choice of the optics. Furthermore, the scheme can be expanded to other parts of the electromagnetic spectrum, by modifying the detectors and optical components. For example, if an x-ray source is to be used, the refractive optical components can be replaced with diffractive or reflective optical components, and standard mirrors can be replaced by grazing incident mirrors. In addition, the detector array of the camera can be chosen to match the appropriate wavelength.

[0056] For the high-resolution imaging schemes depicted herein throughout, to optimize the light throughput to the optical system, the input angle can be closely matched to the acceptance angle of the optical system. Referring to **FIGUREs 11A** through **11I**, several pictorial diagrams illustrate examples of light source optic configurations that can be implemented in various embodiments of an optical imager. Since the schemes are implemented using a general coherent or partially coherent light source, optical components can be used to generate collimated **11-42**, diverging **11-43** or converging **11-44** light input to the optical system by implementing one or more refractive components, reflective components such as concave or convex mirrors, or diffractive components such as diffractive optical elements or holographic optical elements. Light shaping for an expanding beam such as from an LED or a laser diode is depicted in **FIGUREs 11A** through **11C**. Light shaping for a pre-collimated beam such as a laser beam is shown in **FIGUREs 11D** through **11I**. In other arrangements, a combination of circular and cylindrical optical components can be used to shape non-circular beams, such as from laser diodes.

[0057] **FIGUREs 11A** through **11I** depict various configurations for shaping the beam from a coherent or partially coherent light source **1101** such that light throughput through the interferometer can be optimized. **FIGUREs 11A, 11B**, and **11C** illustrate configurations with a coherent or a partially coherent light source **1101** with a diverging beam **1102** and can be shaped by a positive lens **1141** so that the final output light is collimated **1142**, diverging at a different angle than **1143** than the beam before going through the lens **1102**, or converging beam **1144**. Beam shaping is achieved by the lens focal length and position from the light origin. In **FIGUREs 11D, 11E**, and **11F**, configurations include examples in which the light source is pre-collimated such as in a laser beam, and a combination of two or more positive lenses **1141** and

1146 are used to generate an expanded collimated beam **1142**, a diverging **1143** or converging beam **1144**. In **FIGURE 11G**, **11H**, and **11I** configurations include example of a pre-collimated light source such as a laser beam, and a combination of a positive lens **1141** and negative lens **1147** to generate an expanded collimated beam **1142**, a diverging beam **1143**, or a converging beam **1144**.

[0058] In a particular embodiment, the optical imager can comprise a modified Mach-Zehnder interferometer arranged with the object positioned in one arm of the interferometer through the object beam path and a phase shifter positioned in the reference beam path.

[0059] In some embodiments, the optical imager can have the objective lens positioned inside the interferometer.

[0060] Some configurations can be adapted for high-resolution imaging through transparent or semi-transparent samples.

[0061] The high-resolution imaging structures and method described in association with **FIGURE 1** are suitable for reflective samples. When the sample is transparent or semi-transparent, topographic variations as well as variations in refractive index of the material can be imaged. Variations in material refractive index include density variations in the material, or image transparent biological materials. The technique can also be used to obtain high-resolution images.

[0062] Methods for imaging through transparent or semi-transparent samples can be performed using the techniques illustrated in association with **FIGUREs 1**, **5**, **7**, **8**, or **9** with a reflective object placed in back of the sample.

[0063] Methods for imaging through transparent or semi-transparent samples can also be performed using a transmission interferometer scheme depicted in **FIGUREs 12** and **13**, according to phase shifting and image difference computation described herein throughout.

[0064] **FIGURE 12** is a schematic pictorial and block diagram that depicts a high-resolution optical imager **1200** for a fully or partially transparent sample and includes a coherent light source **1201** such as a laser, a laser diode, or a partially coherent light source. The light expansion is controlled using either a single lens **1241**, or a combination of lenses as depicted in **FIGUREs 11A** through **11I**. The apparatus is a modified Mach-Zehnder interferometer with the sample **1205** placed in one arm of the interferometer through the object beam path **1208**, and a phase shifter **1233** placed in the reference beam path **1207**. A set of imaging optics **1206** and **1211** are used to image the sample onto the camera **1210**. An optional lens **1249** can be used to control the interference fringes (circular, elliptical or linear) by matching the beam expansion of the reference and object beams. The apparatus contains beam splitters **1203** and mirrors **1204**. The raw image is displayed on a video screen **1212** contains the optical image of the sample pattern **1213** and overlapping fringes **1214**. Due to topographic variations of the sample pattern, the fringes are shifted **1215**. The image **1213** is limited by the optical resolution, and at very high magnifications, sharp edges are rounded. After an image is captured and processed by the processing and control electronics **1216**, the resulting image is displayed on a second video screen **1217**, and the sample pattern is revealed **1218** at much higher resolution than the unprocessed image **1213**. Phase shifting is achieved by moving one of the mirrors **1204**, by a phase shifter **1233**, or by moving or tilting the sample **1205**, forming imaging ray paths **1248**. Phase shifting is controlled by processing and control electronics **1216**. In the illustrative scheme, the objective lens **1206** is placed inside the interferometer.

[0065] In other embodiments, the objective lens can be positioned outside the interferometer.

[0066] Referring to **FIGURE 13**, a schematic pictorial and block diagram depicts a high-resolution optical imager **1300** for a fully or partially transparent sample similar to the imager shown in **FIGURE 12**, with the main difference that the objective lens **1306** is placed outside the interferometer. Element set **1301**, **1303**, **1304**, **1305**, **1306**, **1307**, **1308**, **1309**, **1310**, **1311**, **1312**, **1313**, **1314**, **1315**, **1316**, **1317**, **1318** , **1333**, **1341**, and **1348** are similar or equivalent to set **1201**, **1203**, **1204**, **1205**, **1206**, **1207**, **1208**, **1209**, **1210**, **1211**, **1212**, **1213**, **1214**, **1215**, **1216**, **1217**, **1218**, **1233**, **1241**, and **1248**.

[0067] The difference between architectures shown in **FIGURE 12** and **13** is that in **FIGURE 12** the objective lens **1206** is placed inside the reference arm of the interferometer. In **FIGURE 13**, the objective lens **1306** is placed outside the interferometer. In **FIGURE 12**, an additional lens **1249** may be used to match the reference and object beams and can be omitted in the **FIGURE 13** scheme. In addition, due to a smaller number of optical components in the reference beam path in **FIGURE 13** than in **FIGURE 12** schemes, the **FIGURE 13** method may be more suitable for light sources **1301** with very small coherence distance, facilitating matching of the optical path length (OPL) of the reference **1307** and object **1308** arms. A disadvantage of the **FIGURE 13** configuration is that the objective lens **1306** has a longer working distance than the **FIGURE 12** setup due to the beam splitter **1303** between the objective lens **1306** and the sample **1305**, either limiting the objective to low magnification, or calling for a relatively expensive long working distance objective lens.

[0068] Fringe movement in **FIGURE 12** and **13** schemes is achieved either using a phase shifter **1233** and **1333** which is detailed in **FIGUREs 14A** through **14D**, or by moving shifting or moving one of the mirrors **1302**, **1304**, as depicted in **FIGUREs 14E** and **14F**.

[0069] In various embodiments, an optical imager can comprise a lens configured to control circular, elliptical, or linear interference fringes by matching beam expansion of reference and object beams.

[0070] In some implementations, the phase shifter can comprise a retro-reflecting prism placed in an optical beam path comprising a set of two mirrors or a mirror-coated prism, and a linear translator that moves the retro-reflecting prism.

[0071] In other examples, the phase shifter can comprise an optical flat, and a rotating device that rotates angle of incidence of the optical flat.

[0072] Otherwise, the phase shifter can comprise a liquid crystal light valve including transparent or semitransparent electrodes and a liquid crystal material, driven by an electrical source.

[0073] Some implements may include a phase shifter comprising an optical wedge and a linear translator for translating the optical wedge.

[0074] Any other suitable phase shifter can be implemented.

[0075] Referring to **FIGUREs 14A** through **14F**, multiple pictorial diagrams depict various phase delay methods to shift the fringes which can be used for the optical imagers such as those shown in **FIGURE 12** and **FIGURE 13**. Arrangements in **FIGUREs 14A** through **14D** can also be used in place of the phase shifters **733** and **933** shown in **FIGUREs** 7 and **9**, respectively, when placed in the reference beam paths **1407**. **FIGURE 14A** shows phase delay by linear translation **1430** of a retro-reflecting prism **1450** placed in the optical beam path **1407** by using a set of two mirrors **1404** or a mirror-coated prism, which is not shown to promote clarity. **FIGURE 14B** depicts phase delay by rotating **1427** the angle of incidence of an optical flat **1451**. **FIGURE 14C** illustrates phase delay using a liquid crystal light valve, including transparent or semitransparent electrodes **1452**, and a liquid crystal material **1433** driven by an electrical source **1434**. **FIGURE 14D** shows phase delay by linearly translating **1430** an optical wedge **1452**. **FIGURE 14E** depicts phase delay by linearly shifting **1430** one of the mirrors **1404** in the apparatus of **FIGURE 12** or **13**, shown as mirrors **1204** and **1304** in the corresponding figures, to a new position is **1429**. **FIGURE 14F** shows phase delay by tilting **1432** one of the mirrors **1404** in the apparatus of **FIGURE 12** or **13** shown as mirrors **1204** and **1304** in the corresponding figures, to a new position is **1431**. The phase delay is controlled by the processing and control electronics **116**, **916**, **1216** and **1316** in the respective figures.

[0076] In various configurations, an optical imager may implement a suitable speckle reduction method, if desired.

[0077] If a coherent source such as a laser is used as the input light source to the high-resolution imaging schemes described herein throughout, the interference pattern can contain a speckle. The speckle pattern can be a source of noise. To reduce or eliminate the speckle noise, yet still be able to use a highly coherent source, various speckle reduction methods can be used. One method involves passing light through a moving random media, such as a rotating diffuser as depicted in **FIGURE 15**, a linearly moving diffuser as depicted in **FIGURE 18**, a moving random media such as a liquid crystal type material mixed with a scattering medium as depicted in **FIGURE 16**, or a flowing scattering medium circulated with a pump as depicted in **FIGURE 17**. Using a suitable technique, speckle is reduced by moving the random media such that speckles move at higher rate than the camera image capture speed, and the interference pattern is smoothed. A randomizing apparatus is generally placed at the input terminal of the interferometer but may also be placed throughout the optical path of the optical system. When used at the input terminal of the optical system, at least two lenses or equivalent optical components, one before the random media and one after, may be desired. One lens controls the spot size of the light incident on the random media, thus controlling the speckle sizes, and controls the desired image smoothness without losing the interference pattern. Another lens or a set of lenses as depicted in **FIGUREs 11A** through **11I** can be used following the random medium to control light divergence, convergence or collimation, to improve or optimize light throughput to the optical system.

[0078] An optical imager can include a speckle reduction device configured for usage with a coherent source comprising first and second lenses configured to receive and pass illumination from the coherent source, a rotating diffuser positioned between the first and second lenses, and a rotating motor. The rotating motor is operative to rotate the rotating diffuser whereby a captured image is a time average of moving speckle patterns, an interference image is smoothed, and speckle noise is reduced or eliminated. Referring to **FIGURE 15**, a schematic pictorial and block diagram illustrates an embodiment of a speckle reduction device **1500** and associated speckle reduction method using a rotating diffuser **1553** via a rotating motor **1554** when using a coherent source **1501** as the light source to the high-resolution imaging apparatus described herein throughout. When the diffuser **1553** rotates, the speckle pattern generated by the coherent source **1501** also moves. When the speckles move much faster than the image capture rate of the camera **110**, the captured image is a time-averaged image of the moving speckle patterns, thus the interference image is smoothed and speckle noise is greatly reduces or eliminated. The spatial coherence is directly proportional to the speckle size. To control the speckle size, a lens **1555** is used to adjust the spot size incident on the rotating diffuser **1553**, thus controlling the spatial coherence of light. Another lens **1541** or combination of lenses as depicted in **FIGUREs 11A** through **11I** is used to control the light divergence/convergence or collimation. An optional stationary diffuser **1563** may be placed after the moving diffuser **1553** such that speckle movement is in random orientation rather than in directional of the diffuser movement.

[0079] In other examples, an optical imager can include a speckle reduction device configured for usage with a coherent source comprising first and second lenses configured to receive and pass illumination from the coherent source, and an electrically-motile scattering medium embedded between two transparent or semitransparent electrodes positioned between the first and second lenses whereby a captured image is a time average of speckle patterns moved by application of voltage across the electrodes, an interference image is smoothed, and speckle noise is reduced or eliminated. Referring to **FIGURE 16**, a schematic pictorial and block diagram depicts an embodiment of a speckle reduction device **1600** and associated speckle reduction method using a scattering medium **1653** embedded between two transparent or semitransparent electrodes **1652** when using a coherent source **1601** as the light source to the high-resolution imaging apparatus described herein throughout. The medium can be a liquid crystal type material mixed with a scattering medium, or any type of medium that can be moved electrically. By applying a voltage **1634** across the electrodes **1652**, the random medium is moved, thus moving the speckles generated by the coherent source **1601**. The interference images captured by the apparatus discussed herein throughout contain speckle noise if a highly coherent light source is used. When the speckles move much faster than the image capture rate of the camera **110**, the captured image is a time averaged image of the moving speckle patterns, thus the interference image is smoothed and speckle noise is greatly reduces or eliminated. The spatial coherence is directly proportional to the speckle size. To control the speckle size, a lens **1655** is used to adjust the spot size incident on the random medium **1653**, thus controlling the spatial coherence of light. Another lens **1641** or a combination of lenses as depicted in **FIGUREs 11A** through **11I** is used to control the light divergence/convergence or collimation.

[0080] In still other configurations, an optical imager can include a speckle reduction device configured for usage with a coherent source comprising first and second lenses configured to receive and pass illumination from the coherent source, a liquid pump, and a scattering medium circulated by the liquid pump. In the arrangement a captured image is a time average of moving speckle patterns, an interference image is smoothed, and speckle noise is reduced or eliminated. Referring to **FIGURE 17**, a schematic pictorial and block diagram illustrates an embodiment of a speckle reduction device **1700** and associated speckle reduction method using a flowing scattering medium **1753** when using a coherent source **1701** as the light source to the high-resolution imaging apparatus described herein throughout. The scattering liquid medium **1753** is circulated by a liquid pump **1754**, thus moving the scattering medium. Light from the source **1701** is incident on an optical window **1756** filled with the flowing scattering media, and speckles generated by the coherent source **1701** move due to the movement of the scattering medium **1753**.

When the speckles move much faster than the image capture rate of the camera **110**, the captured image is a time averaged image of the moving speckle patterns, thus the interference image is smoothed and speckle noise is greatly reduces or eliminated. To control the speckle size, a lens **1755** is used to adjust the spot size incident on the random medium **1753**, thus controlling the spatial coherence of light. Another lens **1741**, or a combination of lenses as shown in **FIGUREs 11A** through **11I** is used to control the light divergence/convergence or collimation.

[0081] In further arrangements, an optical imager can include a speckle reduction device configured for usage with a coherent source comprising first and second lenses configured to receive and pass illumination from the coherent source, a motion device, and a scattering medium moved by the motion device whereby a captured image is a time average of moving speckle patterns, an interference image is smoothed, and speckle noise is reduced or eliminated. In various embodiments, the motion device can be a translation stage, a motorized stage, a solenoid-based moving apparatus, a piezoelectric moving stage, and a linear translation driver. Referring to **FIGURE 18**, a schematic pictorial and block diagram illustrates an embodiment of a speckle reduction device **1800** and associated speckle reduction method using a linearly moving diffuser **1853** with a coherent source **1801** as the light source to the high-resolution imaging apparatus described herein throughout. Movement is achieved using moving apparatus **1857** such as a translation stage, a motorized stage, a solenoid based moving apparatus such as an audio speaker, a piezoelectric moving stage, or any other means of producing a linear translation. The moving apparatus **1857** is translated linearly back and forth **1840**, thus producing movement of the speckle pattern generated by the coherent source **1801**. The moving apparatus **1857** is either controlled by an electrical source **1834** or by the control electronics **116**. When the speckles move much faster than the image capture rate of the camera **110**, the captured image is a time averaged image of the moving speckle patterns, thus the interference image is smoothed and speckle noise is greatly reduces or eliminated. The spatial coherence is directly proportional to the speckle size. To control the speckle size, a lens **1855** is used to adjust the spot size incident on the rotating diffuser **1853**, thus controlling the spatial coherence of light. Another lens **1841** or a combination of lenses as depicted in **FIGUREs 11A** through **11I** is used to control the light divergence/convergence or collimation. An optional stationary diffuser **1863** may be placed after the moving diffuser **1853** such that speckle movement is in random orientation rather than in the direction of the diffuser movement.

[0082] Another approach to reduce speckles is to use a low-coherence optical source, such a light emitting diode (LED), a halogen light, or any available low-coherence light source, as depicted in **FIGURE 19**. A set of lenses can be used to optimize light throughput to the optical system, also as depicted in **FIGUREs 11A** through **11I**. Additionally, an iris **1958** or a spatial filter **1958** may be inserted between the lenses **1941** to filter out intensity variations of the source

1901. An optional wavelength filter **1959** may be used to tune a wide-band optical source to a desirable narrow-band wavelength range.

[0083] Referring to **FIGURE 19**, a pictorial view shows an embodiment of a speckle reduction device **1900** and associated speckle reduction method using a partially coherent light source **1901**, such a halogen lamp, any thermal lamp, light emitting diode, super luminescence source, or a low coherence laser. Lenses **1941** or a combination of lenses as depicted in **FIGUREs 11A** through **11I** is used to control the light divergence/convergence or collimation. An optional iris **1958** or a spatial filter **1958** may be inserted between the lenses **1941** to filter out intensity variations of the source **1901**. An optional wavelength filter **1959** may be used to tune a wide-band optical source to a desirable narrow-band wavelength range.

[0084] A further method to reduce speckles involves addition of an non-interference image (I_{NI}) with the processed imaged. Specifically, ΔI_{avg} of equation (4) or (5) can be added or multiplied with I_{NI} to produce a high-resolution, yet clean (low-noise, speckle-free) image. The non-interference image can be obtained either by blocking the reference beam paths depicted in the figures herein throughout, or to use an additional beam splitter in the apparatus and illuminate the sample with a non-coherent light source.

[0085] In various embodiments or implementations fiber-optic, spectroscopic, and/or polarimetric components can be added to an optical imager.

[0086] **FIGUREs 1**, **5**, **7**, **8**, **9**, **12**, and **13** depict architectures containing bulk optical components. However, the structures are not limited for usage with bulk optical components, which can be replaced by fiber-optic components. For example, a fiber-optic phase shifter can be implemented instead of the bulk optic phase-shifter shown in **FIGURE 7**, whereby fiber optic components such as fiber-couplers, fiber optic phase-shifter or a fiber-coupled electro-optic modulator can be placed in the path of the reference beam **707**. The mirror **704** can also be replaced by a fiber reflector. Fiber-optic components and bulk-optic components can be combined to utilize the advantage of both systems, namely the massive parallel detection capability of the bulk optic, and the high-speed phase modulation capability of the fiber optics.

[0087] To add spectroscopic functionality to an apparatus, the light source **101**, **701** can be a tunable laser, a multiple wavelength switching laser or a coherent light source of different wavelengths. Wavelength filters can be placed in front of the camera **110**, **710** to tune the detection wavelength. In addition, the camera **110**, **710** may replaced with a spectroscopic imaging camera, and the light source can be replaced by a broad-band partially-coherent light source. Combining the hybrid system with the computational capabilities described in equations (2) to (4) can result in high-resolution spectroscopic microscopic images.

[0088] In addition, further information can be obtained by using polarization optics, which are particularly useful for interrogation of patterned optical thin films and birefringent films. The devices shown in **FIGUREs 1**, **5**, **7**, **8**, **9**, **12**, and **13** can be combined with polarization optics, such as replacing the beam splitter with a polarization beam splitter, adding optical wave plates and polarizers in the paths of the reference and object beams, and using polarization controlling phase shifters in the reference beam path as shown in **FIGURE 7**. Combining the hybrid system with the computational capabilities described in equations (2) to (4), (5) or (6) result in high-resolution polarimetric microscopic images.

[0089] Bulk optical, fiber-optic, polarization-optic and spectroscopic and wavelength-tuning-optics can be partly or completely combined to form a robust, high-resolution microscopic, spectroscopic and polarimetric imaging system.

[0090] Accordingly in some embodiments, an optical imager can further comprise a fiber-coupled optical source. For example, input light can be delivered via a optical-fiber **2060** as depicted in **FIGURE 20** for a more flexibility, and to be able for a more remote operation.

[0091] Referring to **FIGURE 20**, a schematic pictorial and block diagram illustrates an embodiment of a coherent or partially coherent light source **2001** coupled to an optical fiber **2060** via a lens or combination of lenses **2061** that can be used in an optical imager. Light at the output end of the fiber is either left expanding while entering the high-resolution imaging apparatus described herein throughout, or diverged, converged or collimated using a lens **2041**, or a combination of lenses as depicted in **FIGUREs 11A** through **11I**.

[0092] In various embodiments and in selected implementations, conditions, and/or applications, the optical imager **100** can be configured to image an object such as surface structures, sub-surface structures and features in a transparent media, sub-surface structures and features in a semi-transparent media, phase objects, and other suitable objects or samples.

[0093] The illustrative optical imagers and techniques can increase image contrast.

[0094] In some implementations and applications, the optical imagers and techniques can facilitate imaging of edge structures.

[0095] While the present disclosure describes various embodiments, these embodiments are to be understood as illustrative and do not limit the claim scope. Many variations, modifications, additions and improvements of the described embodiments are possible. For example, those having ordinary skill in the art will readily implement the steps necessary to provide the structures and methods disclosed herein, and will understand that the process parameters, materials, and dimensions are given by way of example only. The parameters, materials, and dimensions can be varied to achieve the desired structure as well as modifications, which are within the scope of the claims.

WHAT IS CLAIMED IS:

1. An optical imager comprising:

an interferometer;

microscopic optics operative in combination with the interferometer to generate a reference image and an object image;

an image capture device configured to capture an interferometric image with a phase difference between the reference image and the object image;

a phase shifter operative to selectively control the phase difference; and

a controller operative to capture a plurality of interferometric images at a selected plurality of phase differences and combine the plurality of interferometric images into a processed image with in-plane resolution that is increased over optical wavelength and numerical aperture characteristics.

2. The optical imager according to Claim 1 further comprising:

the controller operative to selectively control capture an image at a first phase and a second phase and determine a difference interferometric image as a difference of interferometric images captured at the first and second phases.

3. The optical imager according to Claim 2 further comprising:

the controller operative to acquire interferometric images at a plurality of first and second phases and summing a plurality of difference interferometric images.

4. The optical imager according to Claim 3 further comprising:

the controller operative to acquire a non-interferometric image and average the non-interferometric image with a sum of the plurality of difference interferometric images.

5. The optical imager according to Claim 2 further comprising:

the controller operative to acquire interferometric images at a plurality of first and second phases, multiplying a plurality of difference interferometric images by a factor smaller than one that is selected to avoid over-saturation, and summing the plurality of difference interferometric images.

6. The optical imager according to Claim 5 further comprising:

the controller operative to acquire a non-interferometric image and average the non-interferometric image with a sum of the plurality of difference interferometric images.

7. The optical imager according to Claim 1 further comprising:
the controller operative to select phase change increments between successive images to produce a fraction of fringe movement and summing multiple successive images to cover a full fringe cycle.

8. The optical imager according to Claim 1 further comprising:
the controller operative to selectively control capture an image at a first phase and a second phase and determine a ratio interferometric image as a ratio of interferometric images captured at the first and second phases.

9. The optical imager according to Claim 8 further comprising:
the controller operative to acquire interferometric images at a plurality of first and second phases and summing a plurality of ratio interferometric images.

10. The optical imager according to Claim 1 further comprising:
a light source operative to generate at least partially coherent light;
a reference mirror;
an objective lens;
a beam splitter configured to direct the at least partially coherent light to the reference mirror for reflecting the light onto a reference beam path and to an object through the objective lens for reflecting the light onto an object beam path; and
an imaging lens arranged to pass reflected light along the reference beam path and the object beam path to the image capture device.

11. The optical imager according to Claim 10 further comprising:
the phase shifter comprising a device that controllably moves the object.

12. The optical imager according to Claim 10 further comprising:
the phase shifter comprising a device that controllably moves the object in selected space increments.

13. The optical imager according to Claim 10 further comprising:
the phase shifter comprising a device the controllably moves the reference mirror.

14. The optical imager according to Claim 10 further comprising:
the phase shifter comprising a device that controllably moves the reference mirror in selected space increments.

15. The optical imager according to Claim 10 further comprising:
the phase shifter positioned in the reference beam path and selected from a group of phase shifters consisting of a liquid crystal device that changes the optical path length (OPL) of the reference beam with phase shift controlled by an external voltage

controller, a retro-reflecting prism in an optical beam path comprising a plurality of mirrors or a mirror-coated prism that changes OPL when translated linearly, an optical flat glass that is tilted to change OPL, an optical wedge that changes OPL when translated linearly, an optical phase shifter device, an electro-optic phase shifter, a polarization phase shifter, and a fiber optic phase shifter.

16. The optical imager according to Claim 10 further comprising:
an interferometric objective operative to generate an interference pattern and shift phase by moving, tilting or rotating in a selected direction.

17. The optical imager according to Claim 10 further comprising:
the beam splitter and the reference mirror positioned between the objective lens and the object.

18. The optical imager according to Claim 10 further comprising:
a mirror configured whereby the object is positioned between the objective lens and the mirror.

19. The optical imager according to Claim 10 further comprising:
at least one beam shaping element configured for shaping a beam from a coherent or partially coherent light source, the beam shaping element comprising a positive lens that collimates, diverges, or converges a beam.

20. The optical imager according to Claim 10 further comprising:
a modified Mach-Zehnder interferometer arranged with the object positioned in one arm of the interferometer through the object beam path and a phase shifter positioned in the reference beam path.

21. The optical imager according to Claim 20 further comprising:
the objective lens positioned inside the interferometer.

22. The optical imager according to Claim 20 further comprising:
the objective lens positioned outside the interferometer.

23. The optical imager according to Claim 1 further comprising:
a lens configured to control circular, elliptical, or linear interference fringes by matching beam expansion of reference and object beams.

24. The optical imager according to Claim 1 further comprising:
a speckle reduction device configured for usage with a coherent source comprising:
first and second lenses configured to receive and pass illumination from the coherent source;
a rotating diffuser positioned between the first and second lenses; and

a rotating motor operative to rotate the rotating diffuser whereby a captured image is a time average of moving speckle patterns, an interference image is smoothed, and speckle noise is reduced or eliminated.

25. The optical imager according to Claim 1 further comprising:

a speckle reduction device configured for usage with a coherent source comprising:

first and second lenses configured to receive and pass illumination from the coherent source; and

an electrically-motile scattering medium embedded between two transparent or semitransparent electrodes positioned between the first and second lenses whereby a captured image is a time average of speckle patterns moved by application of voltage across the electrodes, an interference image is smoothed, and speckle noise is reduced or eliminated.

26. The optical imager according to Claim 1 further comprising:

a speckle reduction device configured for usage with a coherent source comprising:

first and second lenses configured to receive and pass illumination from the coherent source;

a liquid pump; and

a scattering medium circulated by the liquid pump whereby a captured image is a time average of moving speckle patterns, an interference image is smoothed, and speckle noise is reduced or eliminated.

27. The optical imager according to Claim 1 further comprising:

a speckle reduction device configured for usage with a coherent source comprising:

first and second lenses configured to receive and pass illumination from the coherent source;

a motion device; and

a scattering medium moved by the motion device whereby a captured image is a time average of moving speckle patterns, an interference image is smoothed, and speckle noise is reduced or eliminated.

28. The optical imager according to Claim 27 further comprising:

the motion device selected from a group consisting of a translation stage, a motorized stage, a solenoid-based moving apparatus, a piezoelectric moving stage, and a linear translation driver.

29. The optical imager according to Claim 1 further comprising:
the phase shifter comprising a retro-reflecting prism placed in an optical beam path comprising a set of two mirrors or a mirror-coated prism, and a linear translator that moves the retro-reflecting prism.

30. The optical imager according to Claim 1 further comprising:
the phase shifter comprising an optical flat, and a rotating device that rotates angle of incidence of the optical flat.

31. The optical imager according to Claim 1 further comprising:
the phase shifter comprising a liquid crystal light valve including transparent or semitransparent electrodes and a liquid crystal material, driven by an electrical source.

32. The optical imager according to Claim 1 further comprising:
the phase shifter comprising an optical wedge and a linear translator for translating the optical wedge.

33. The optical imager according to Claim 1 further comprising:
an optical source that is coherent, noncoherent, or partially coherent.

34. The optical imager according to Claim 1 further comprising:
an optical source that generates illumination at a selected wavelength in a range of visible, infrared, ultraviolet, a selected part of light spectra, and X-ray.

35. The optical imager according to Claim 1 further comprising:
a fiber-coupled optical source.

36. The optical imager according to Claim 1 wherein:
the optical imager is configured to image an object selected from a group consisting of surface structures, sub-surface structures and features in a transparent media, sub-surface structures and features in a semi-transparent media, and phase objects.

37. A method for generating an increased-resolution image comprising:
illuminating an object with at least partially coherent light;
forming a reference image and an object image;
capturing an interferometric image with a phase difference between the reference image and the object image;
selectively controlling the phase difference;
capturing a plurality of interferometric images at a selected plurality of phase differences; and

combining the plurality of interferometric images into a processed image with in-plane resolution that is increased over optical wavelength and numerical aperture characteristics.

38. The method according to Claim 37 further comprising:
capturing an image at a first phase and a second phase; and
determining a difference interferometric image as a difference of interferometric images captured at the first and second phases.

39. The method according to Claim 38 further comprising:
acquiring interferometric images at a plurality of first and second phases; and
summing a plurality of difference interferometric images.

40. The method according to Claim 39 further comprising:
acquiring a non-interferometric image; and
averaging the non-interferometric image with a sum of the plurality of difference interferometric images.

41. The method according to Claim 38 further comprising:
acquiring interferometric images at a plurality of first and second phases;
multiplying a plurality of difference interferometric images by a factor smaller than one that is selected to avoid over-saturation; and
summing the plurality of difference interferometric images.

42. The method according to Claim 41 further comprising:
acquiring a non-interferometric image; and
averaging the non-interferometric image with a sum of the plurality of difference interferometric images.

43. The method according to Claim 37 further comprising:
capturing an image at a first phase and a second phase; and
determining a ratio interferometric image as a ratio of interferometric images captured at the first and second phases.

44. The method according to Claim 43 further comprising:
acquiring interferometric images at a plurality of first and second phases; and
summing a plurality of ratio interferometric images.

45. The method according to Claim 37 further comprising:
increasing image resolution.

46. The method according to Claim 37 further comprising:
increasing depth of focus.

47. The method according to Claim 37 further comprising:
increasing image contrast.

48. The method according to Claim 37 further comprising:
imaging edge structures.

49. The method according to Claim 37 further comprising:
sampling the object at normal incidence or a selected angle of incidence.

50. The method according to Claim 37 further comprising:
imaging an object selected from a group consisting of surface structures, sub-surface structures and features in a transparent media, sub-surface structures and features in a semi-transparent media, and phase objects.

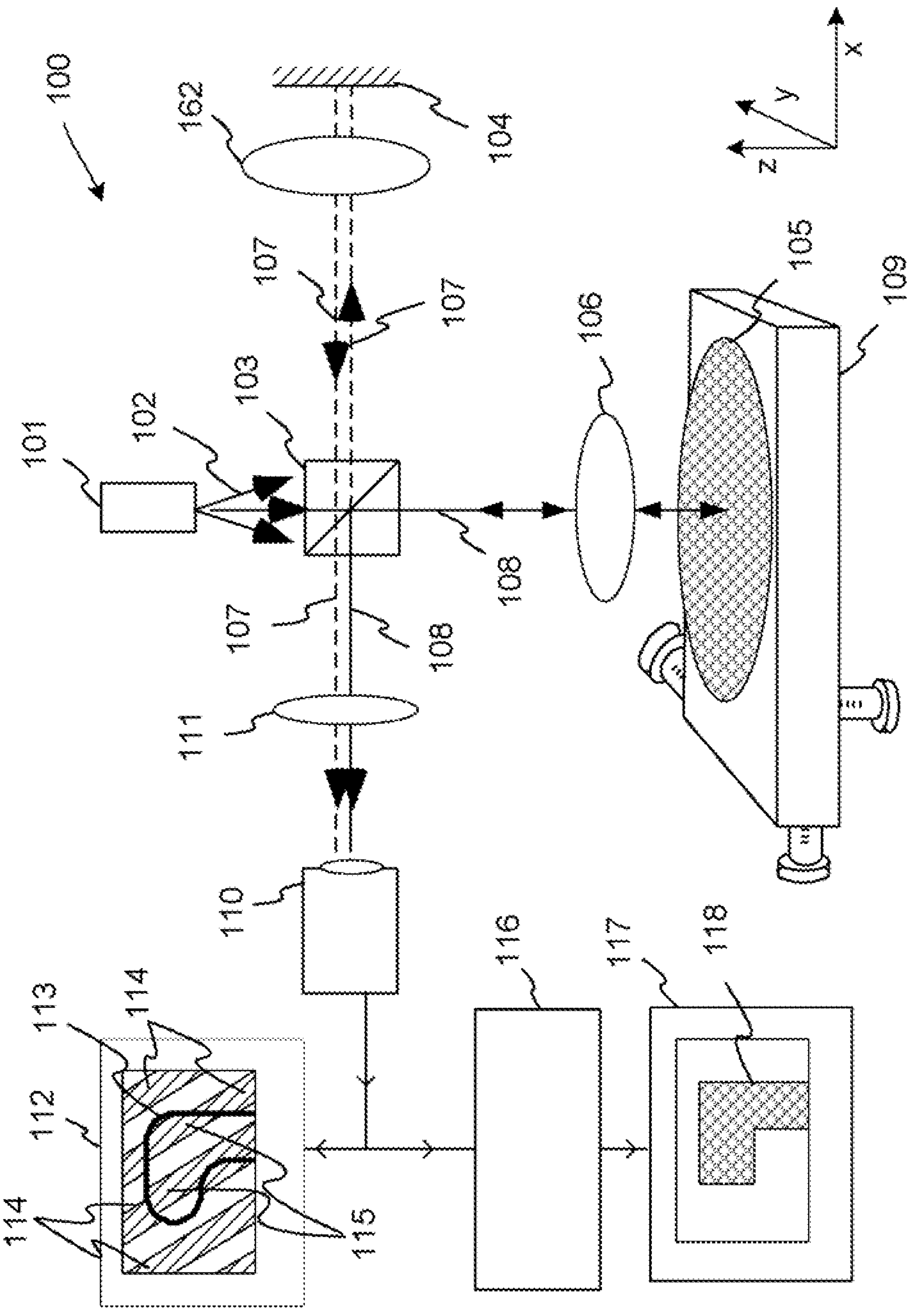
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FIG. 1

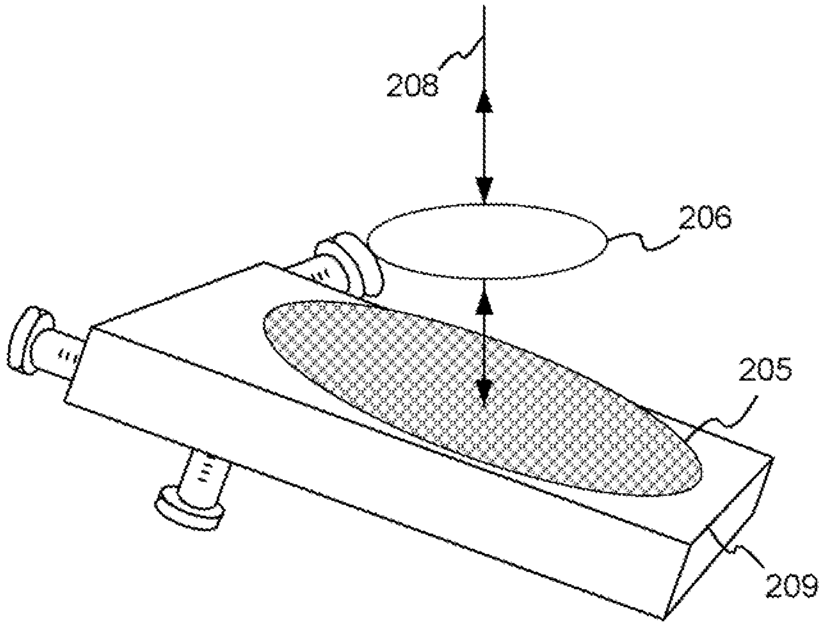

FIG. 2

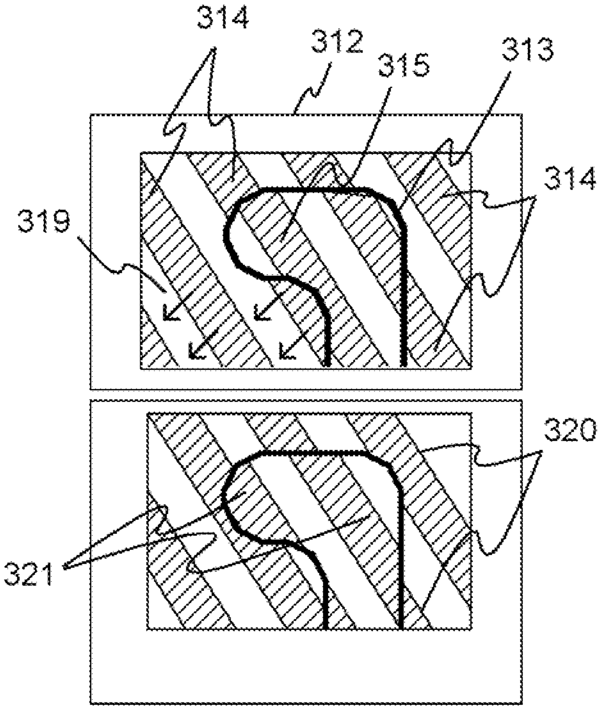

FIG. 3

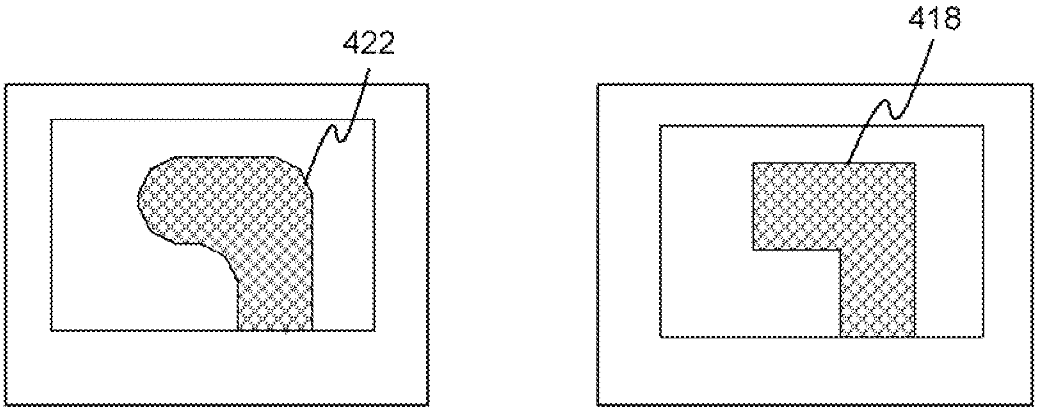

FIG. 4

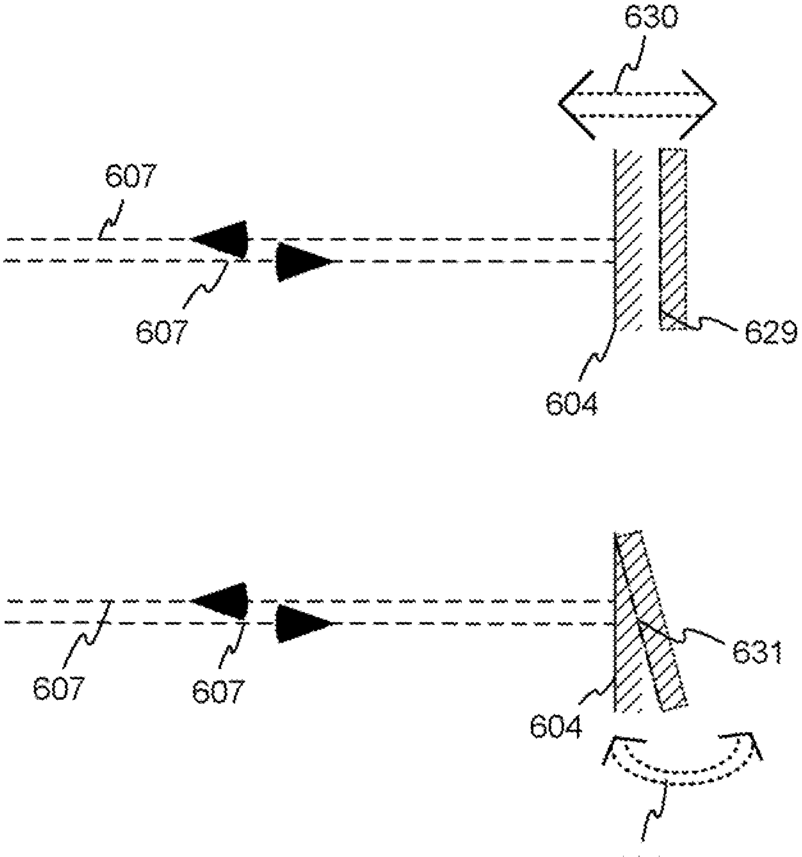

FIG. 6

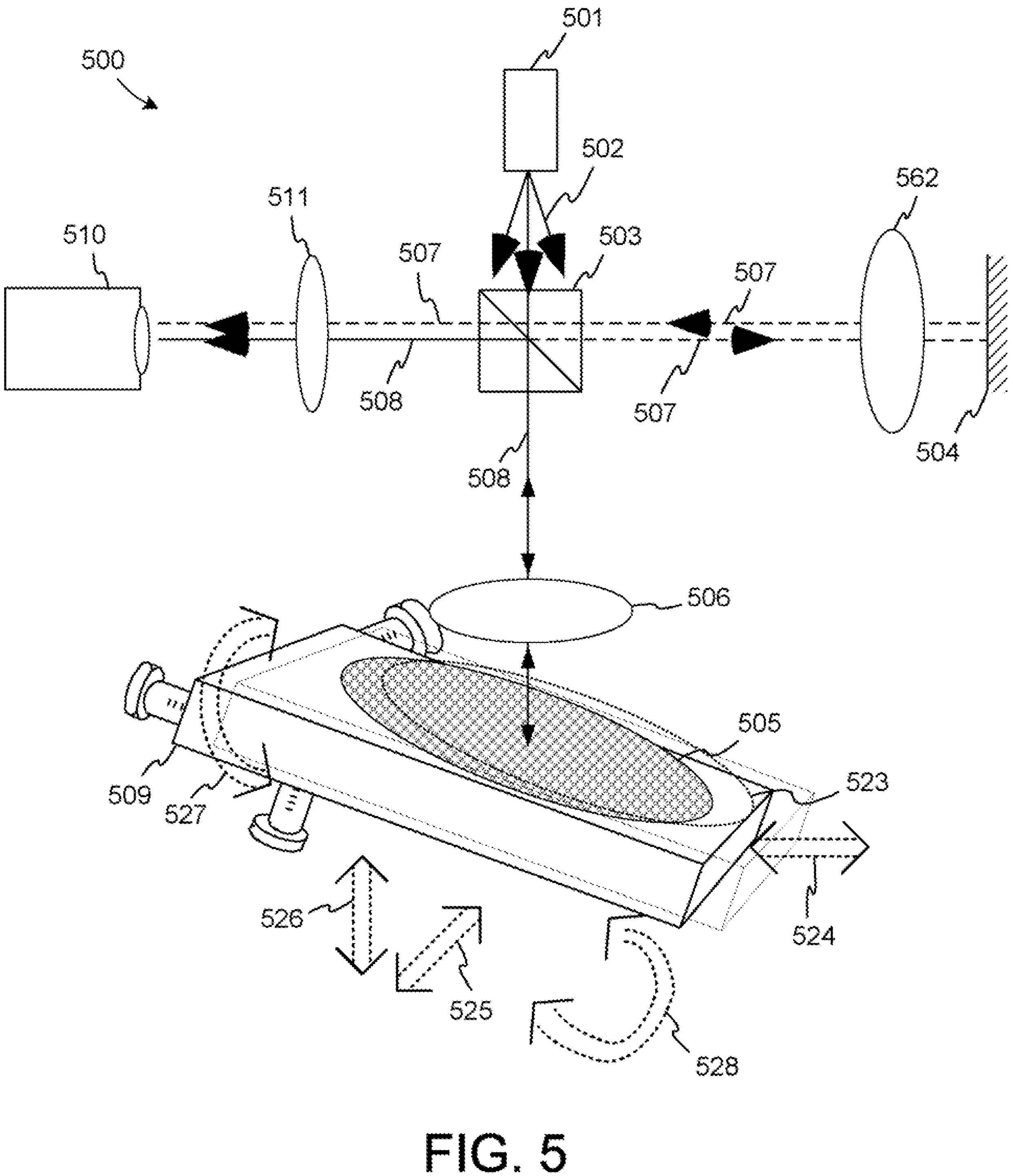
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FIG. 5

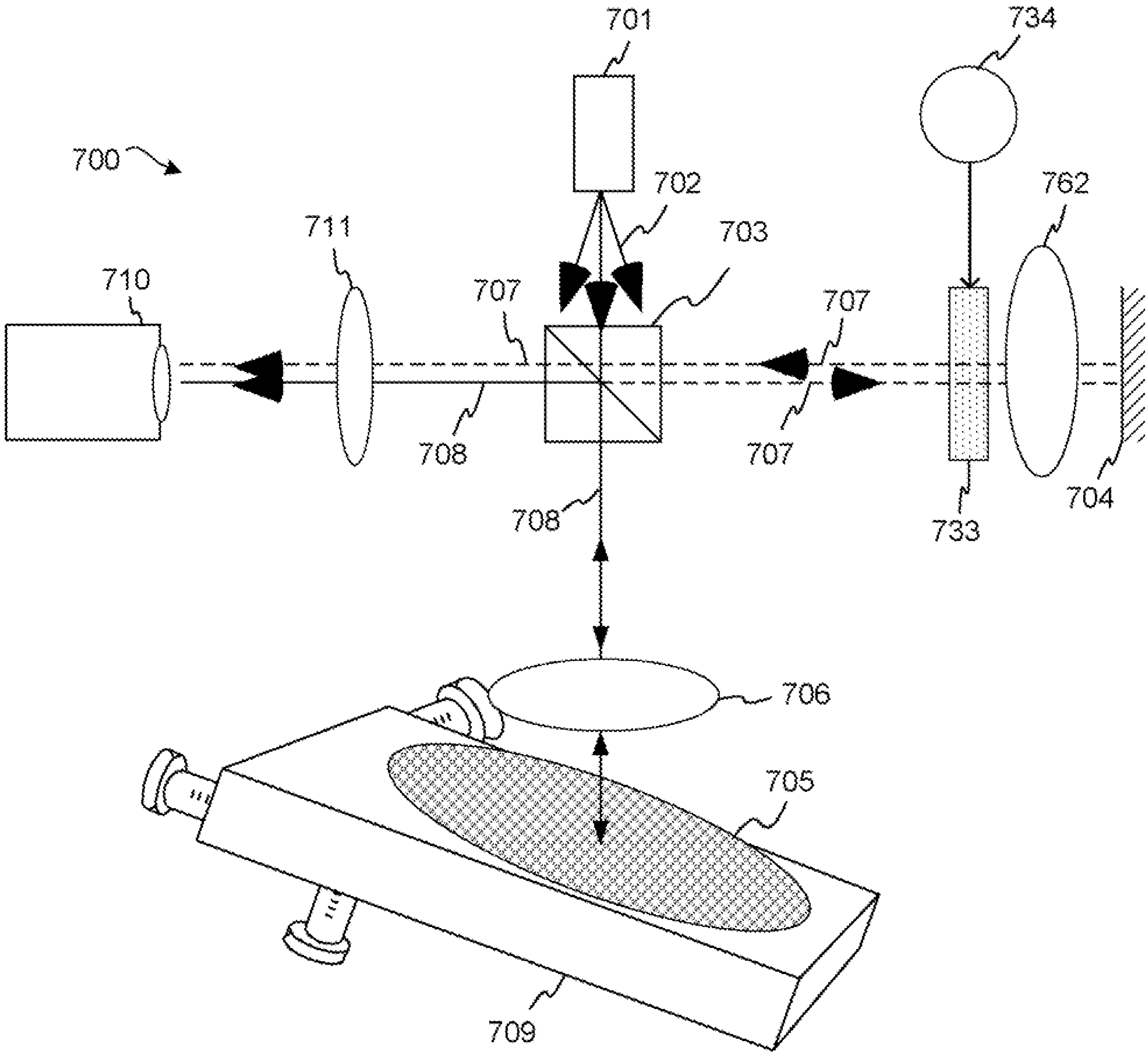
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FIG. 7

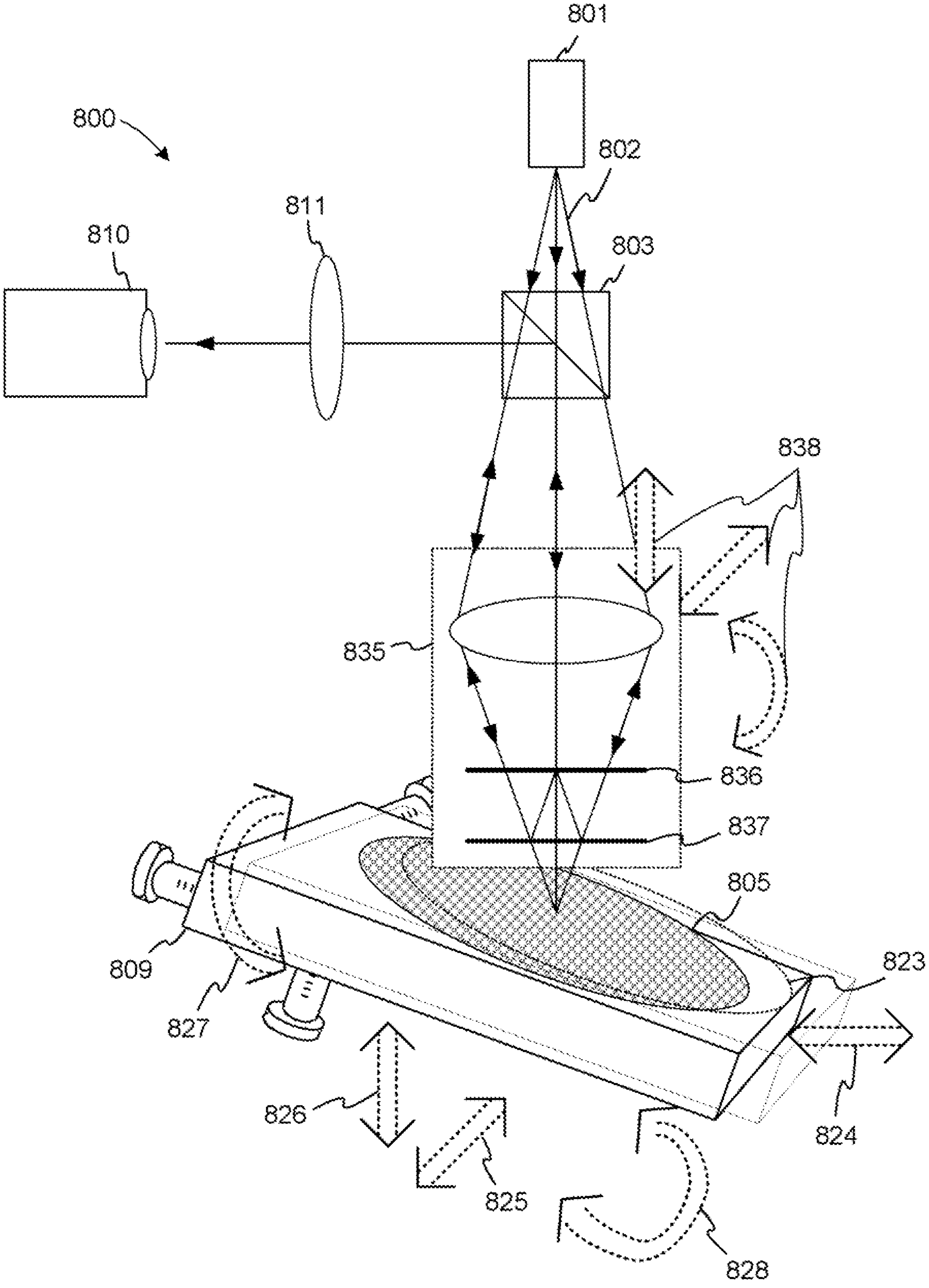
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FIG. 8

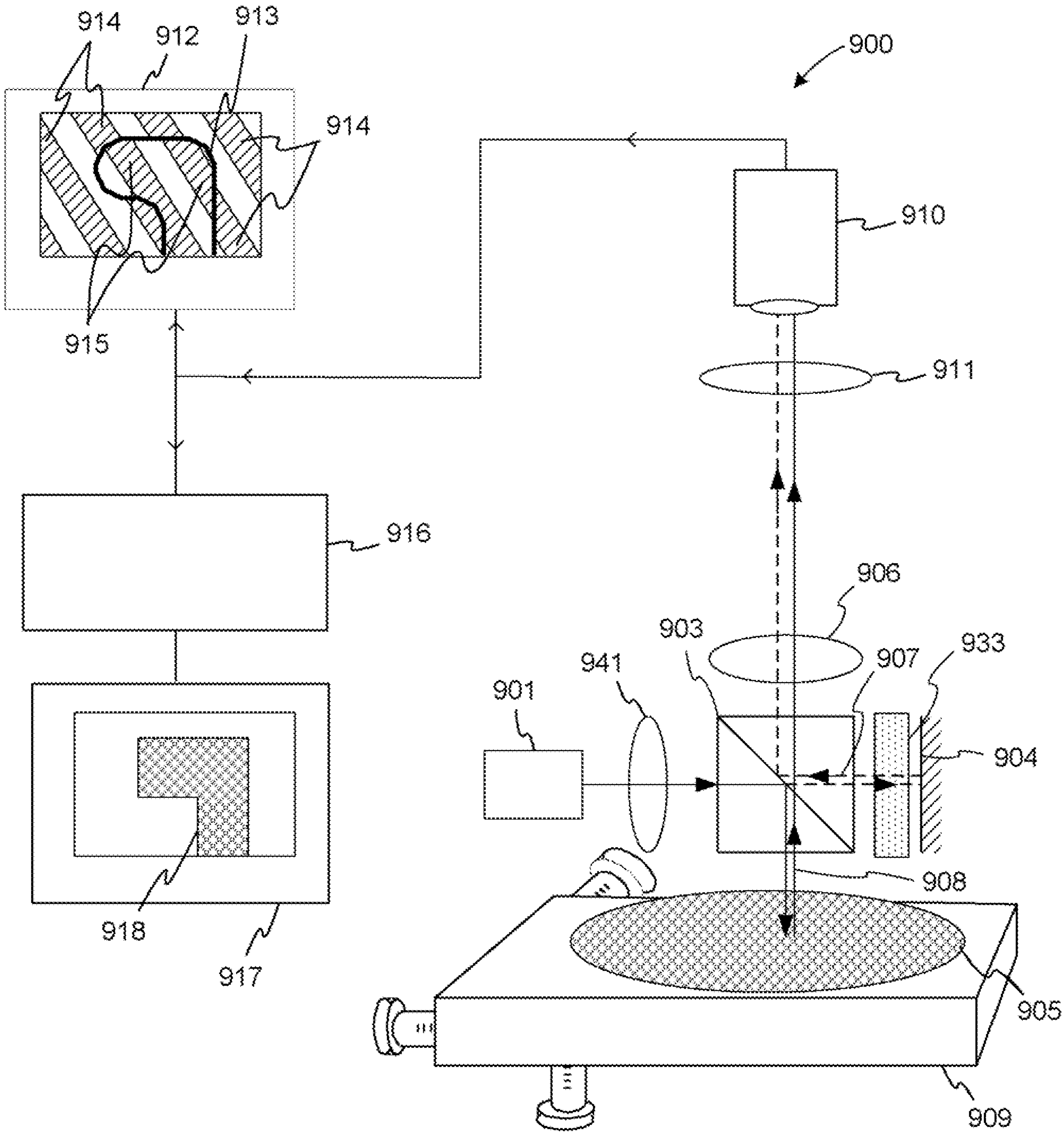
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FIG. 9

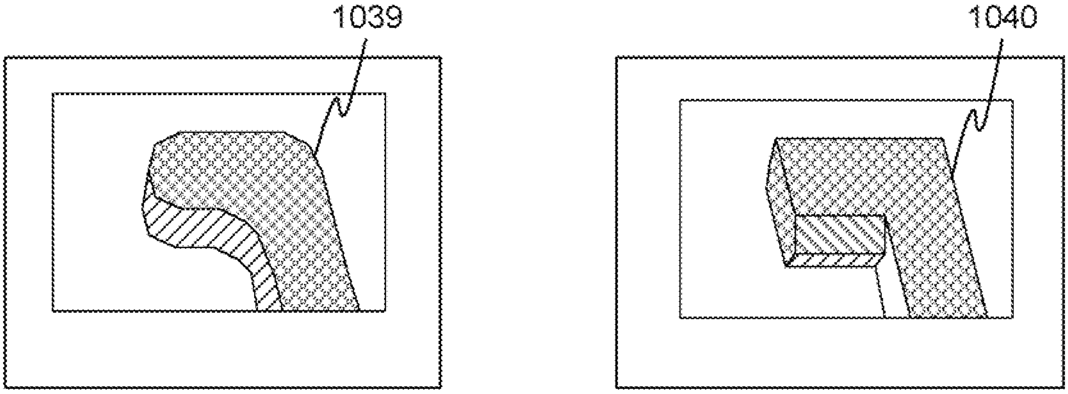

FIG. 10

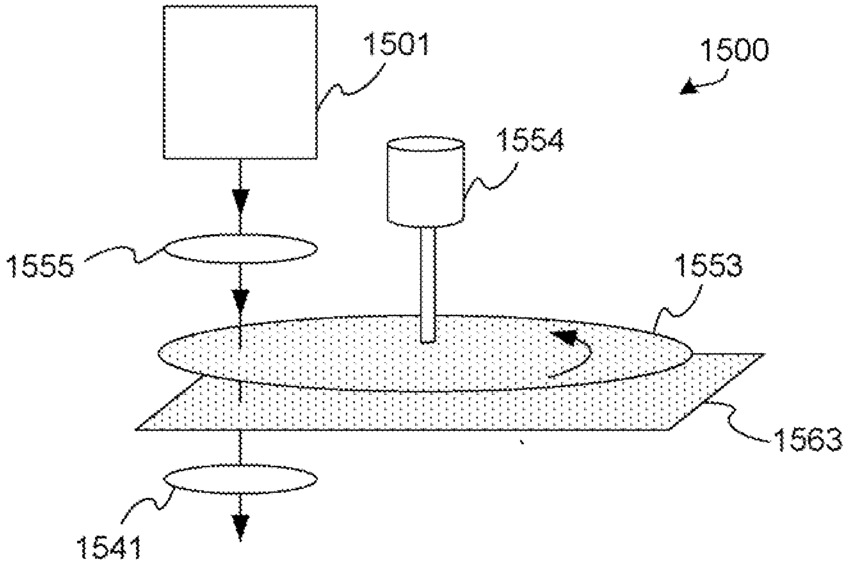

FIG. 15

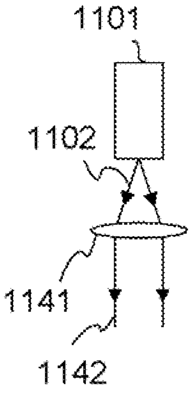

FIG. 11A

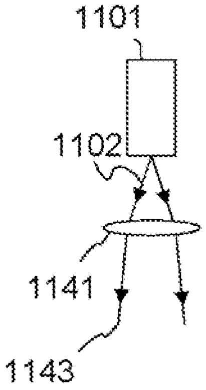

FIG. 11B

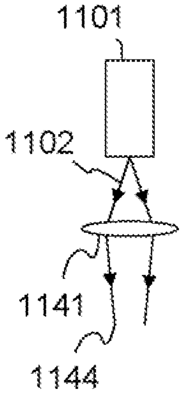

FIG. 11C

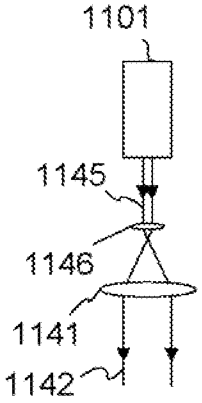

FIG. 11D

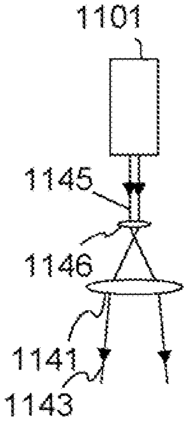

FIG. 11E

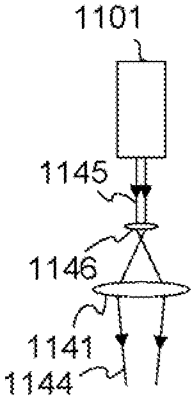

FIG. 11F

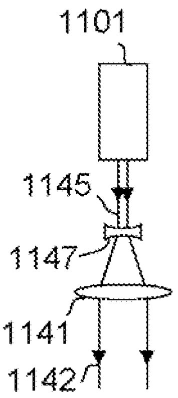

FIG. 11G

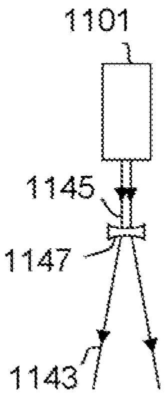

FIG. 11H

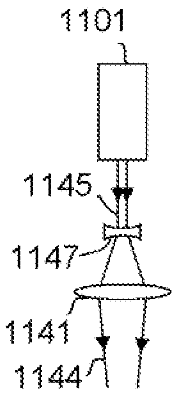

FIG. 11I

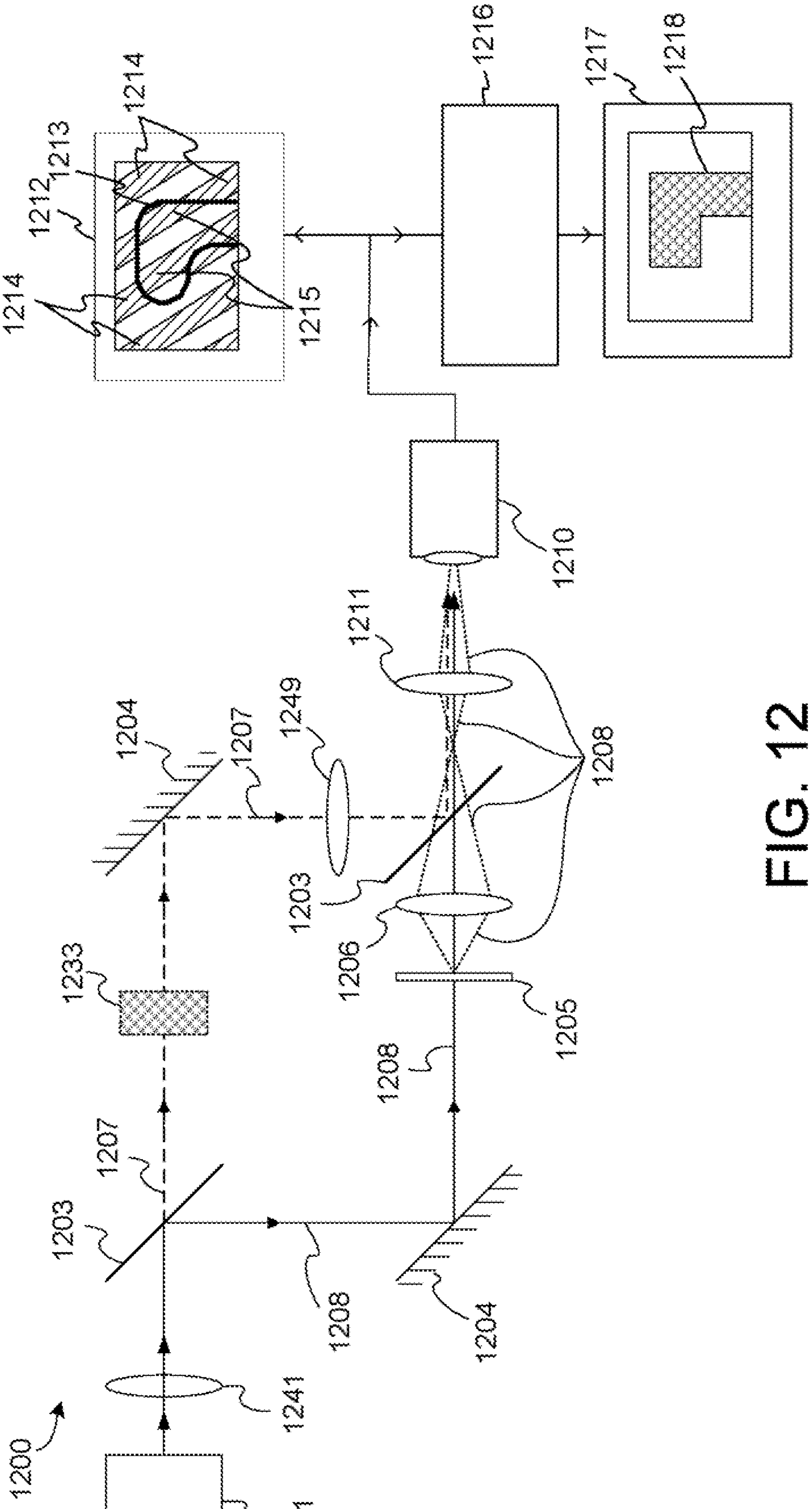
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FIG. 12

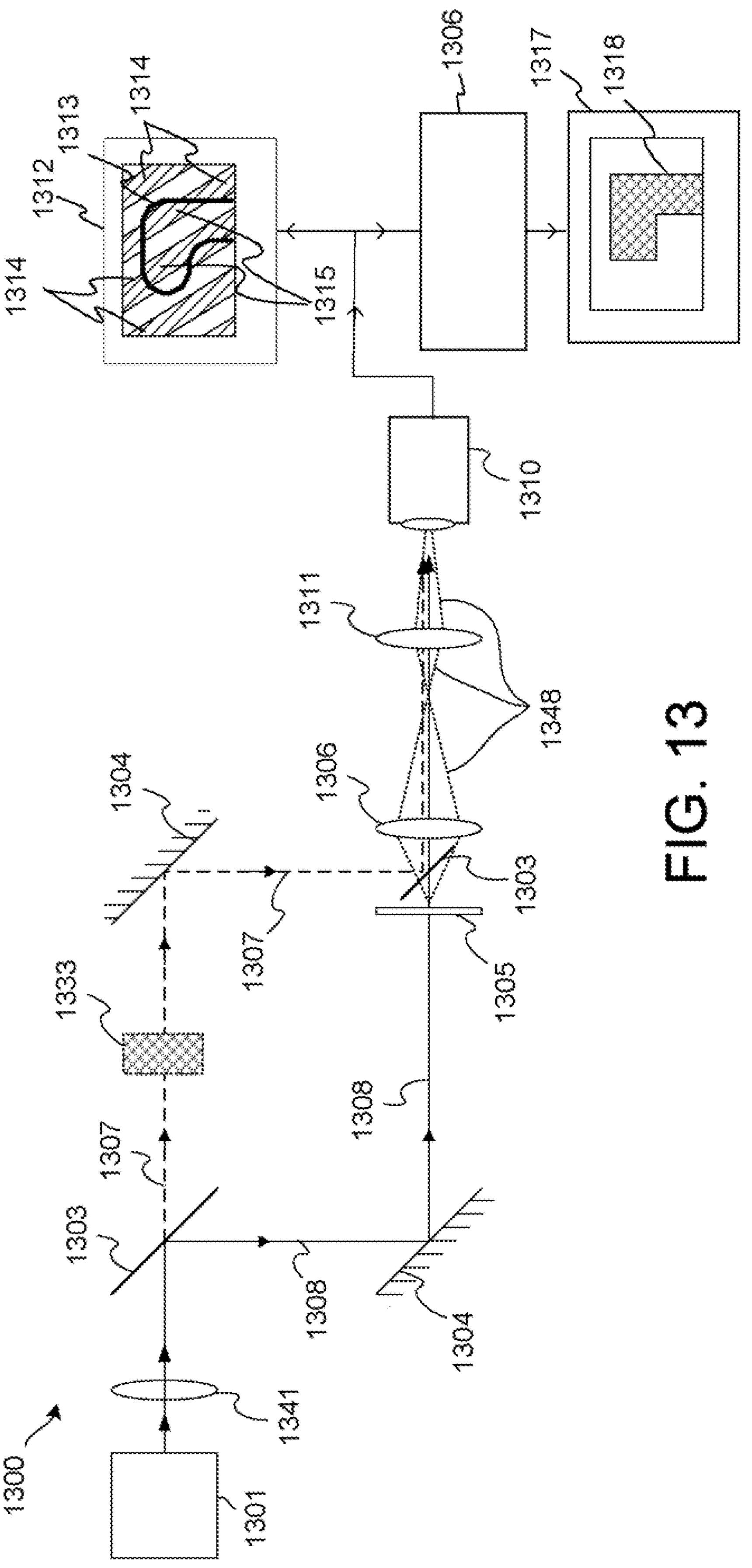
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FIG. 13

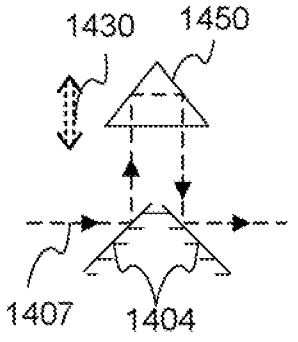

FIG. 14A

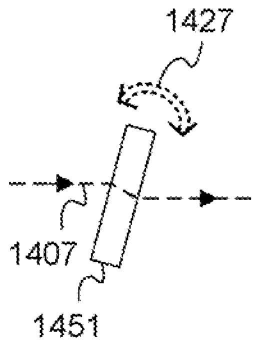

FIG. 14B

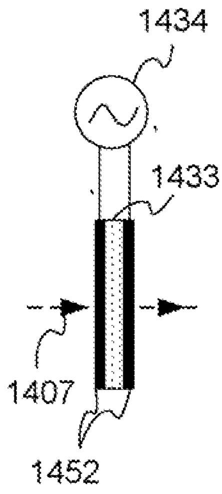

FIG. 14C

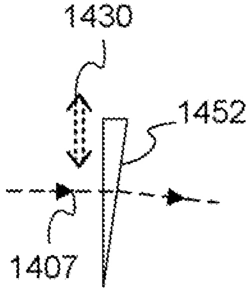

FIG. 14E

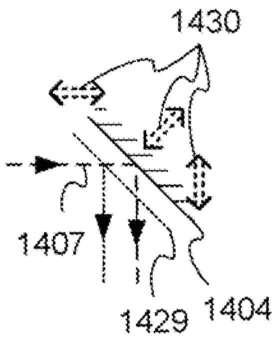

FIG. 14F

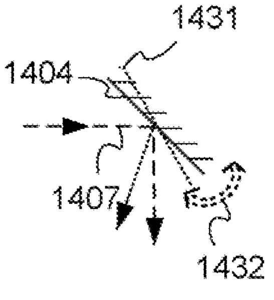

FIG. 14G

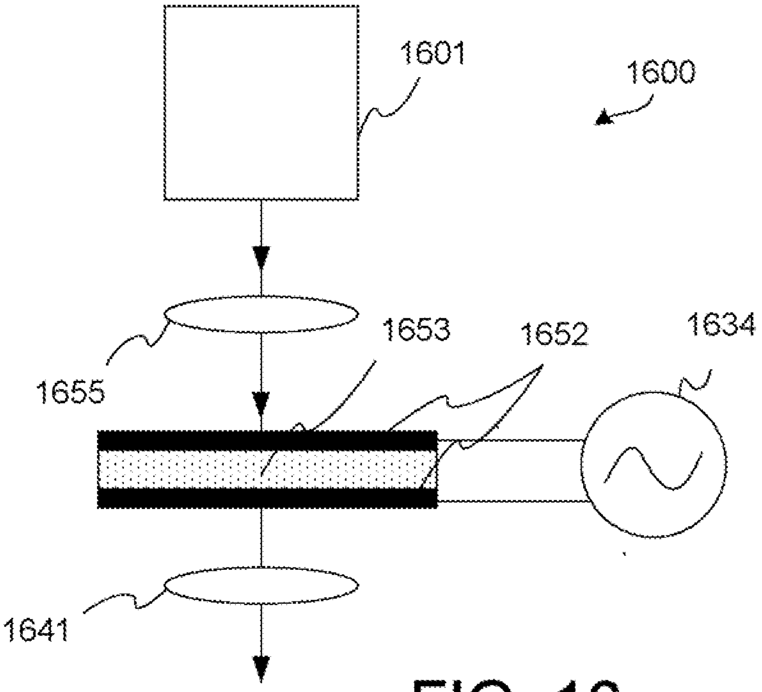
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FIG. 16

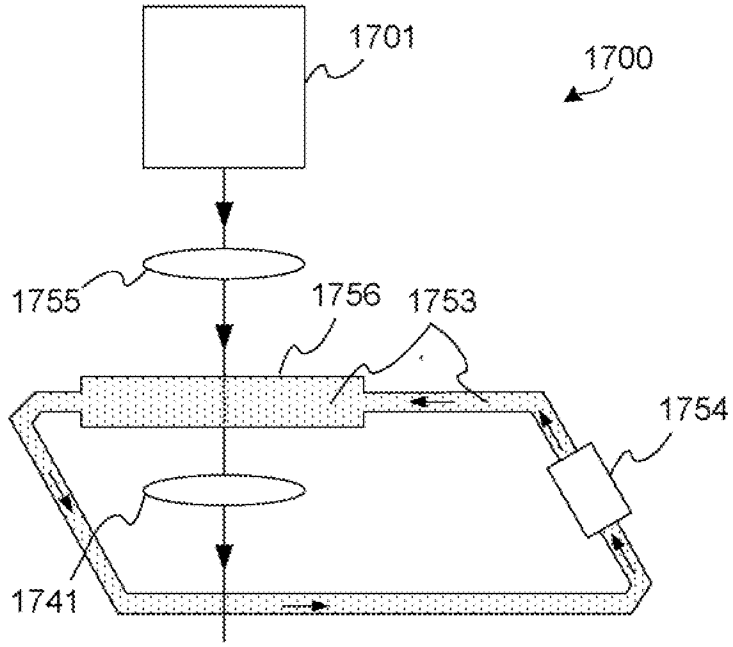
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FIG. 17

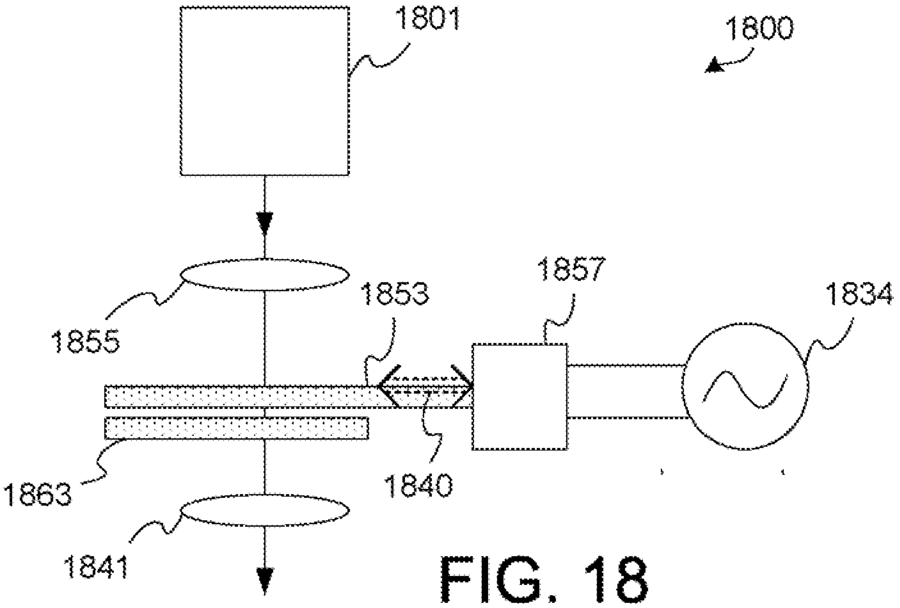
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FIG. 18

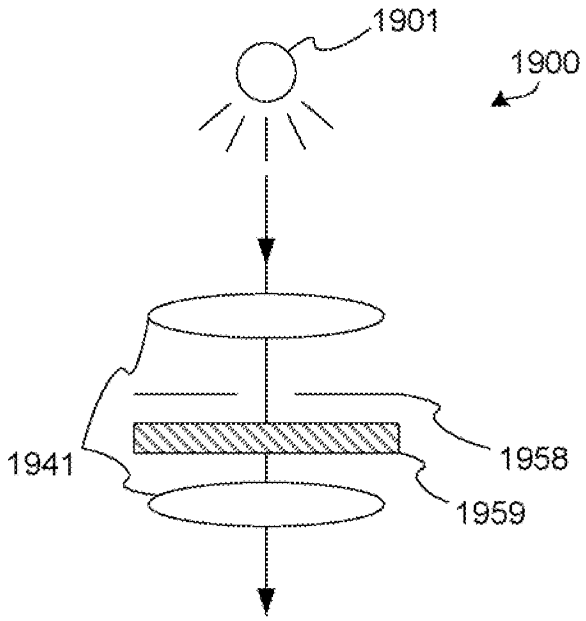
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FIG. 19

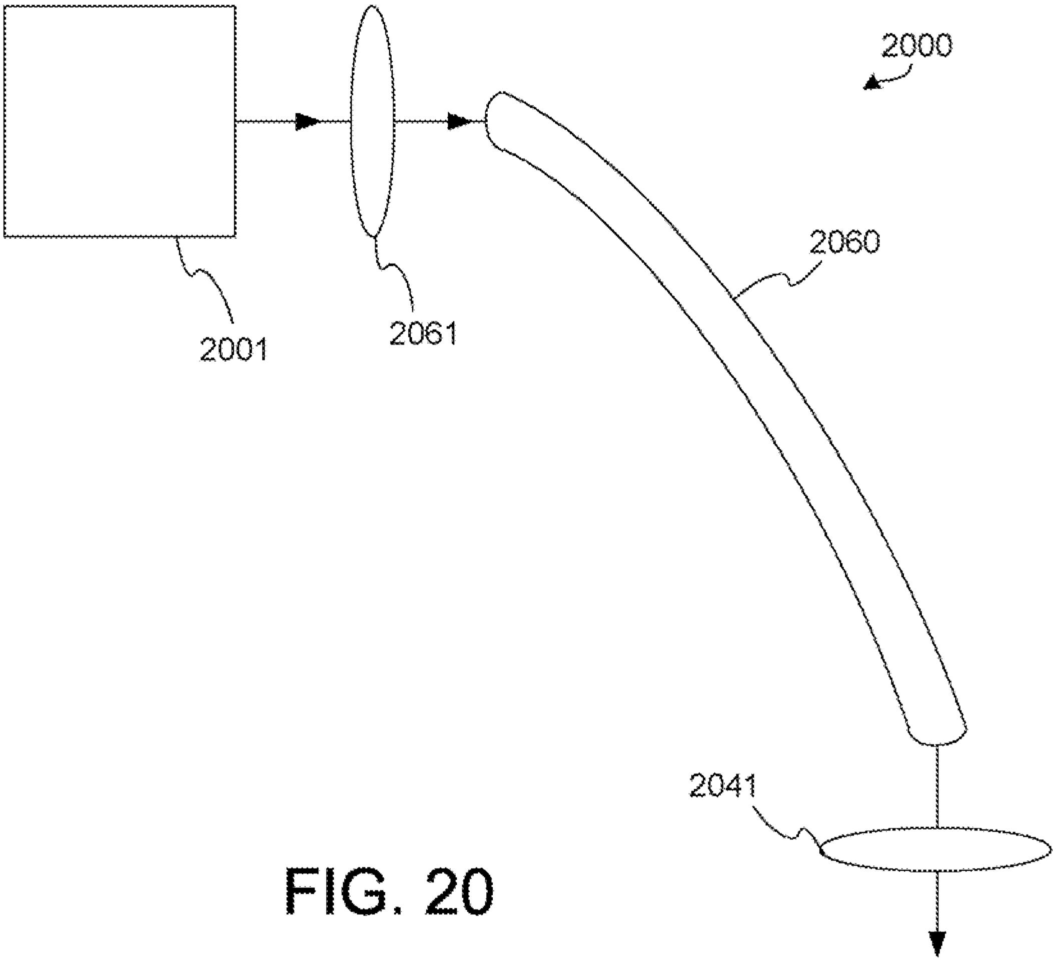

FIG. 20