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(54) Title: SCANNING INTERFEROMETRIC NEAR-FIELD CONFOCAL MICROSCOPY WITH BACKGROUND AMPLITUDE REDUCTION AND COMPENSATION

(57) Abstract: The invention features systems and methods for near-field, interferometric microscopy in which one or more phase retardation plates are positioned in the measurement and/or reference arms to reduce the contribution to the interference signal of background sources including, e.g., a beam component scattered from a near-field aperture used to couple a probe beam to a sample. The systems may operate in either reflective or transmissive modes.

SCANNING INTERFEROMETRIC NEAR-FIELD CONFOCAL MICROSCOPY WITH BACKGROUND AMPLITUDE REDUCTION AND COMPENSATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from provisional application Serial No. 60,221,086 filed July 27, 2000 by Henry A. Hill entitled "Scanning Interferometric Near-Field Confocal Microscopy with Background Amplitude Reduction and Compensation," the contents of which is incorporated herein by reference.

BACKGROUND

Scanning microscopy techniques, including near-field and confocal scanning microscopy, conventionally employ a single spatially localized detection or excitation element, sometimes known as the scanning probe ["Near-field Optics: Theory, Instrumentation, and Applications," M. A. Paesler and P. J. Moyer, (Wiley-New York) (1996); "Confocal Laser Scanning Microscopy," C. Sheppard, *BIOS* (Scientific-Oxford and Springer-New York) (1997).] The near-field scanning probe is typically a sub-wavelength aperture positioned in close proximity to a sample; in this way, sub-wavelength spatial resolution in the object-plane is obtained. An aperture smaller than a free space optical wavelength of an optical beam used in a near-field microscopy application is hereinafter referred to as a sub-wavelength aperture. The confocal scanning probe employs diffraction-limited optics to achieve resolution of the order of the optical wavelength. Spatially extended images are acquired by driving the scanning probe in a raster pattern.

Effects of background beams in certain near-field microscopy systems generally are a significant source of systematic and statistical errors.

SUMMARY OF THE INVENTION

The invention features systems and methods for near-field, interferometric microscopy in which one or more phase retardation plates are positioned in the measurement and/or reference arms to reduce the contribution to the interference signal of background sources including, e.g., a beam component scattered from a near-field aperture used to couple a probe beam to a sample. The systems may operate in either reflective or transmissive modes. Furthermore, the microscopy systems using the

aperture may be designed to investigate the profile of a sample, to read optical date from a sample, and/or write optical date to a sample.

In general, in one aspect, the invention features an interferometric optical microscopy system for imaging an object. The system includes: (i) a beam splitter positioned to separate an input beam into a measurement beam and a reference beam; (ii) a measurement beam source array positioned to receive the measurement beam, the measurement beam source array including a mask having an array of measurement apertures each configured to radiate a portion of the measurement beam to the object, the object interacting with the radiated measurement beam portions to direct signal radiation back through the apertures to define a measurement return beam; (iii) a reference beam source array positioned to receive the reference beam, the reference beam source array including an array of elements each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam; (iv) a multi-element photo-detector; (v) imaging optics positioned to direct the measurement and reference return beams to the photo-detector and configured to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector, wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and (vi) at least one phase mask positioned to contact the return measurement beam and the return reference beam, wherein the at least one phase mask causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

Embodiments of the microscopy system may include any of the following features.

The at least one phase mask may include a first phase mask and a second phase mask, wherein the first phase mask is positioned to contact the return measurement beam and not the return reference beam, and wherein the second phase mask is positioned to contact the return reference beam and not the return measurement beam. For example, the first phase mask may be positioned in a pupil plane of the imaging optics for the return measurement beam and the second phase mask may be positioned in a pupil plane of the imaging optics for the return reference beam.

Alternatively, the at least one phase mask may include a first phase mask positioned to contact both of the return measurement beam and the return reference beam. For example, that first phase mask is positioned in a pupil plane of the imaging optics for both the return measurement beam and the return reference beam.

The at least one phase mask may divide the transverse profile of the return measurement beam and the return reference beam into multiple sections along the first dimension and imparts a relative phase shift equal to $\pi+2\pi n$, where is n is an integer, to half of the multiple sections.

The phase mask may further cause the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension. For example, the at least one phase mask may divide the transverse profile of the return measurement beam and the return reference beam along the first dimension into multiple sections and impart a relative phase shift equal to $\pi+2\pi n_1$, where is n_1 is an integer, to half of the multiple sections corresponding to the first dimension, and the at least one phase mask may further divide the transverse profile of the return measurement beam and the return reference beam along a second dimension orthogonal to the first dimension into multiple sections and impart a relative phase shift equal to $\pi+2\pi n_2$, where is n_2 is an integer, to half of the multiple sections corresponding to the second dimension.

The system may further include a second, at least one phase mask positioned to contact the return measurement beam and the return reference beams, wherein the second, at least one phase mask causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension.

The system may further include a pinhole array positioned adjacent the photo-detector, wherein each pinhole is aligned with a separate set of one or more detector elements, and wherein the imaging system causes the conjugate image for each measurement aperture to align with a corresponding pinhole of the pinhole array.

The mask in the measurement beam source array may further include an array of measurement scattering elements, wherein each measurement scattering element is adjacent a corresponding one of the measurement apertures and has transverse dimensions comparable to the corresponding measurement aperture. Each

measurement scattering element scatters a portion of the measurement beam, and the measurement return beam further includes the portions of the measurement beam scattered by the measurement scattering elements. In such cases, the imaging optics are further configured to produce a conjugate image of the array of measurement scattering elements that overlaps with the conjugate image of the array of reference elements, wherein the conjugate image for each measurement scattering element overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal that provides an estimate of scattering from the adjacent measurement aperture.

For embodiments including the scattering elements, the system may further include a pinhole array positioned adjacent the photo-detector, wherein each pinhole is aligned with a separate set of one or more detector elements, and wherein the imaging system causes the conjugate image for each measurement aperture and each measurement scattering element to align with a corresponding pinhole of the pinhole array.

Each reference element may include a reflective element.

Each reference element may include a transmissive aperture.

In general, in another aspect, the invention features an interferometric optical microscopy system for imaging an object, the system including: (i) a beam splitter positioned to separate an input beam into a measurement beam and a reference beam; (ii) a measurement beam source array positioned to receive the measurement beam, the measurement beam source array including a mask having an array of source apertures each configured to radiate a portion of the measurement beam to the object; (iii) a measurement beam detector array including a mask having an array of measurement apertures, wherein the object interacts with the radiated measurement beam portions and directs the resulting signal radiation through the measurement apertures to define a measurement return beam; (iv) a reference beam source array positioned to receive the reference beam, the reference beam source array including an array of elements each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam; (v) a multi-element photo-detector; (vi) imaging optics positioned to direct the measurement and reference return beams to the photo-detector and configured to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector,

wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and (vii) at least one phase mask positioned to contact the return measurement beam and the return reference beams, wherein the at least one phase mask causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

Embodiments of the microscopy system may include any of the following features.

The at least one phase mask may include a first phase mask and a second phase mask, wherein the first phase mask is positioned to contact the return measurement beam and not the return reference beam, and wherein the second phase mask is positioned to contact the return reference beam and not the return measurement beam. For example, the first phase mask may be positioned in a pupil plane of the imaging optics for the return measurement beam and the second phase mask may be positioned in a pupil plane of the imaging optics for the return reference beam.

Alternatively, the at least one phase mask may include a first phase mask positioned to contact both of the return measurement beam and the return reference beam. For example, that first phase mask is positioned in a pupil plane of the imaging optics for both the return measurement beam and the return reference beam.

The at least one phase mask may divide the transverse profile of the return measurement beam and the return reference beam into multiple sections along the first dimension and imparts a relative phase shift equal to $\pi+2\pi n$, where is n is an integer, to half of the multiple sections.

The phase mask may further cause the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension. For example, the at least one phase mask may divide the transverse profile of the return measurement beam and the return reference beam along the first dimension into multiple sections and impart a relative phase shift equal to $\pi+2\pi n_1$, where is n_1 is an integer, to half of the multiple sections corresponding to the first dimension, and the at least one phase mask may further divide the transverse profile of the return measurement beam and the return reference beam along a second dimension orthogonal to the first dimension into multiple sections

and impart a relative phase shift equal to $\pi+2\pi n_2$, where is n_2 is an integer, to half of the multiple sections corresponding to the second dimension.

The system may further include a second, at least one phase mask positioned to contact the return measurement beam and the return reference beams, wherein the second, at least one phase mask causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension.

The system may further include a pinhole array positioned adjacent the photo-detector, wherein each pinhole is aligned with a separate set of one or more detector elements, and wherein the imaging system causes the conjugate image for each measurement aperture to align with a corresponding pinhole of the pinhole array.

Each reference element may include a reflective element.

Each reference element may include a transmissive aperture.

In general, in another aspect, the invention features an interferometric, microscopy method for imaging an object, the method including: (i) separating an input beam into a measurement beam and a reference beam; (ii) directing the measurement beam to an array of measurement apertures to cause a portion of the measurement beam to couple through each of the measurement apertures and radiate the object; (iii) receiving signal radiation from the object back through the apertures in response to the radiated measurement beam portions, wherein the signal radiation defines a measurement return beam; (iv) directing the reference beam to array of reference elements to cause each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam; (v) imaging the measurement and reference return beams onto a photo-detector to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector, wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and (vi) imparting a phase pattern onto each of the return measurement beam and the return reference beams that causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

In general, in another aspect, the invention features an interferometric, microscopy method for imaging an object, the method including: (i) separating an

input beam into a measurement beam and a reference beam; (ii) directing the measurement beam to an array of source apertures to cause a portion of the measurement beam to couple through each of the measurement apertures and radiate the object; (iii) receiving signal radiation from the object through an array of measurement apertures in response to the radiated measurement beam portions, wherein the signal radiation defines a measurement return beam; (iv) directing the reference beam to array of reference elements to cause each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam; (v) imaging the measurement and reference return beams onto a photo-detector to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector, wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and (vi) imparting a phase pattern onto each of the return measurement beam and the return reference beams that causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

Embodiments of either of the above methods may further include features corresponding to any of the features described above in connection with the microscopy systems.

Confocal and near-field confocal, microscopy systems are also described in the following, commonly-owed provisional applications: Serial No. 09/631,230 filed August 2, 2000 by Henry A. Hill entitled "Scanning Interferometric Near-Field Confocal Microscopy," and the corresponding PCT Publication WO 01/09662 A2 published February 8, 2001; Provisional Application Serial No. 60/221,019 filed July 27, 2000 by Henry A. Hill and Kyle B. Ferrio entitled "Multiple-Source Arrays For Confocal And Near-Field Microscopy" and the corresponding Utility Application Serial No. _____ having the same title filed on July 27, 2001; Provisional Application Serial No. 60/221,287 by Henry A. Hill filed July 27, 2000 entitled "Control of Position and Orientation of Sub-Wavelength Aperture Array in Near-field Scanning Microscopy and the corresponding Utility Application Serial No. _____ having the same title filed on July 27, 2001; Provisional Application Serial No. 60/221,091 filed July 27, 2000 by Henry A. Hill entitled "Multiple-Source Arrays with Optical Transmission

Enhanced by Resonant Cavities and the corresponding Utility Application Serial No. _____ having the same title filed on July 27, 2001; and Provisional Application Serial No. 60/221,295 by Henry A. Hill filed July 27, 2000 entitled "Differential Interferometric Confocal Near-Field Microscopy" and the corresponding Utility Application Serial No. _____ having the same title filed on July 27, 2001; the contents of each of the preceding applications being incorporated herein by reference. Aspects and features disclosed in the preceding provisional applications may be incorporated into the embodiments described in the present application.

Embodiments of the invention may include any of the following advantages.

One advantage is a tomographic complex amplitude imaging technique that conveniently reduces or eliminates the statistical error effects of light from out-of-focus image points.

Another advantage is an improved technique for tomographic complex amplitude imaging wherein systematic error effects of out-of-focus light images are greatly reduced or eliminated.

Another advantage is a tomographic complex amplitude imaging technique which allows substantially simultaneous imaging of an object at multiple image points.

Another advantage is a convenient technique for tomographic complex amplitude imaging in with the means to obtain a signal-to-noise ratio for the images that is achievable with an interferometric system.

Another advantage is a tomographic complex amplitude imaging system and technique which avoids the computation difficulties of solving nonlinear differential equations.

Another advantage is an interferometric profiler based on interferometry of near-field beams.

Another advantage is an interferometric profiler based on interferometric confocal microscopy of near-field beams.

Another advantage is a scanning interferometric near-field confocal microscope operating in a continuous scan mode with a pulsed input optical beam.

Another advantage is a scanning interferometric near-field confocal microscope with enhanced signal-to-noise ratios for measured complex amplitudes of scattered/reflected near-field beams by an object material.

Another advantage is a simpler inversion type of calculation for properties of object being profiled and/or imaged.

Another advantage is that the directions of propagation of components of a near-field probe beam at a given volume section of an object being profiled/imaged are substantially the same for a given measured amplitude and phase of a reflected/scattered near-field probe beam from the volume section wherein the dimensions of the volume section are much less than the dimensions of the source of the near-field probe beam.

Another advantage is that amplitudes and phases of reflected/scattered near-field probe beams by an object being profiled/imaged are measured for substantially low order electric and magnetic multipole near-field sources wherein the dominant multipole sources are three different near-field probe beam sources comprising an electric dipole and two different orthogonal orientations of a magnetic dipole.

Another advantage is that effects of an interference term between a back-ground beam produced by scattering and/or reflections of an antecedent beam of a beam generating a near-field probe beam and a reflected/scattered portion of the near-field probe beam by an object being profiled/imaged are compensated.

Another advantage is that effects of an interference term between a back-ground beam produced by scattering and/or reflections of an antecedent beam of a beam generating a near-field probe beam and a reference beam are compensated.

Another advantage is that statistical errors in measured amplitudes and phases of reflected/scattered near-field probe beams by an object being profiled/imaged can be substantially the same as statistical errors based on Poisson statistics of the reflected/scattered near-field probe beams, *i.e.* not significantly degraded by the presence of background signals.

Another advantage is that a wavelength dependence of amplitudes and phases of reflected/scattered near-field probe beams for near-field probe beams generated by different near-field probe beam sources substantially comprising an electric dipole and two different orthogonal orientations of a magnetic dipole is measured.

Another advantage is that a radial dependence of amplitudes and phases of reflected/scattered near-field probe beams for near-field probe beams generated by different near-field probe beam sources substantially comprising an electric dipole and two different orthogonal orientations of a magnetic dipole is measured.

Another advantage is that an angular dependence of amplitudes and phases of reflected/scattered near-field probe beams for near-field probe beams generated by different near-field probe beam sources substantially comprising an electric dipole and two different orthogonal orientations of a magnetic dipole is measured.

Another advantage is that a resolution of the invention is only weakly dependent on optical resolution of an optical system imaging spatially filtered reflected/scattered near-field probe beams from an object being profiled/imaged onto pixels of a detector wherein the spatially filtering is achieved by an array of wavelength and/or sub-wavelength apertures.

Another advantage is that a source of a near-field probe beam may be a pulsed source.

Another advantage is that scanning of an object being profiled/imaged may be implemented in a "step and repeat" mode or in a continuous scan mode.

Another advantage is that measured interference terms between spatially filtered reflected/scattered near-field probe beams and reference beams can be obtained substantially simultaneously for a one-dimensional or a two-dimensional array of locations on an object being profiled/imaged.

Another advantage is that a rotation in a plane of polarization of a reflected/scattered near-field probe beam by an object being profiled/imaged due to a given state of magnetization of the object at a point in or on the object is measured.

Another advantage is that statistical errors in the measured values of intensity for each point in an one-dimensional or two-dimensional arrays of measured intensity values are the same as the statistical error acquired in a measured intensity value for a single pinhole interferometric confocal near-field microscope.

Another advantage is that a rotation in a state of polarization of a reflected/scattered near-field probe beam by an object being profiled/imaged, due for example to a state of magnetization or a changes in a state of magnetization of the object at a point in or on the object is measured.

Another advantage is that the invention may be used to write to an optical data storage medium such as a magneto-optical material.

Another advantage is that the invention profiles a surface and internal layers near the surface of an object being profiled/imaged without contacting the object.

Another advantage is that a wavelength of a source of a near-field probe beam may be in the ultraviolet, visible, or the infrared. For example,the source may comprise two or more different wavelengths.

Another advantage is that either optical heterodyne or homodyne techniques may be used to measure amplitudes and phases of interference terms between a reference beam and a reflected/scattered near-field probe beam from an object being profiled/imaged.

Another advantage is that an effective spatial resolution of the invention may be improved over the resolution obtained with non-interferometric near-field microscopy by the combination of information obtained from measured amplitudes and phases of reflected/scattered near-field probe beams for different types of near-field probe beam sources, *i.e.* substantially an electric dipole and two different orientations of a magnetic dipole.

Another advantage is that a complex value of an index of refraction for an object being profiled/imaged can be determined from measured arrays of amplitudes and phases of reflected/scattered near-field probe beams produced by reflection/scattering by the object, wherein the dimensionality of the arrays may comprise one or two dimensions corresponding to one and two dimensions of space, a dimension for the spatial separation of the source of the near-field probe beam and the object, a dimension for each of wavelength of components of the near-field probe beam source, and a dimension for the multipole characterization of the source of the near-field probe beam.

Another advantage is that multiple layers of optical data stored on and/or in an optical storage medium can be read substantially simultaneously.

Another advantage is that a source of near-field probe beams can be sub-wavelength apertures in a sub-wavelength thick conducting layer.

Another advantage is that a source of a near-field probe beam(s) may comprise wavelength and sub-wavelength Fresnel zone plate(s).

Another advantage is that microlenses may be added to a source(s) of near-field probe beam(s) to alter properties of the near-field probe beam(s) at an object being profiled/imaged.

Another advantage is that gratings may be added to an array of wavelength or sub-wavelength apertures operating as spatial filters of reflected/scattered or

transmitted near-field probe beam(s) to alter properties of the reflected/scattered or transmitted near-field probe beam(s).

Another advantage is that an optical system imaging onto pixels of a detector spatially filtered reflected/scattered near-field probe beam from an object being profiled/imaged has a depth resolution of a pinhole confocal microscope.

Another advantage is that microlenses may be added to a source(s) of near-field probe beam(s) to alter properties of the near-field probe beam(s) at an object being profiled/imaged.

Another advantage is that gratings may be added to a source(s) of near-field probe beam(s) to alter properties of the near-field probe beam(s) at an object being profiled/imaged.

Another advantage is that gratings may be added to an array of wavelength/sub-wavelength apertures operating as spatial filters of reflected/scattered or transmitted near-field probe beam(s) to alter properties of the reflected/scattered or transmitted near-field probe beam(s).

Another advantage is that a change in temperature of a site in or on an object being profiled/imaged can be detected as a change in the complex value of the index of refraction of the object at the site.

Another advantage is that an angular distribution of a reflected/scattered near-field probe beam from an object being profiled/imaged is measured to obtain information about a multipole nature of the reflected/scattered near-field probe beam.

Another advantage is that an angular distribution of a reflected/scattered near-field probe beam from a wavelength or sub-wavelength size structure in/or on an object being imaged or profiled is measured.

Another advantage is that if it is necessary to correct for out-of-focus images which are already greatly reduced in the apparatus, the computer processing required to achieve a given level of correction with the apparatus is significantly reduced compared to the computer processing required in prior art scanning single-pinhole and scanning slit confocal and scanning single-pinhole and scanning slit confocal interferometric microscopy.

Other features, aspects, and advantages follow.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, wherein like reference characters denote similar elements throughout the several views:

FIG. **1** illustrates, in schematic form, the first embodiment of the present invention;

FIG. **2a** illustrates, in schematic form, the lens assembly comprising Amici type objective lens **26** and lens **24**, as used in the first embodiment, and the lens assembly comprising Amici type objective lens **26** and lens **124**, as used in the second embodiment;

FIG. **2b** illustrates, in schematic form, conducting element **28** in relation to object material **112** being profiled/imaged and angular distribution functions of electric far field components associated with an electric dipole and a magnetic dipole located at a sub-wavelength aperture **30**;

FIG. **2c** illustrates, in schematic form, the reference object **20R** comprising Amici type objective lens **26R** and lens **24R**, as used in the first embodiment;

FIG. **2d** illustrates, in schematic form, element **28** comprising reflecting elements **30R** and **32R** used in reference object **20R**; and

FIG. **3** illustrates, in schematic form, image plane **114** and amplitude distribution functions for images of a sub-wavelength aperture **30** and a sub-wavelength scattering site **32** at respective pinholes in image plane **114**.

FIG. **4** illustrates, in schematic form, an embodiment of the invention operating in a transmission mode.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention comprise scanning interferometric near-field confocal microscopes operating in either a reflection or transmission mode with a reduction of effects of background beams and a corresponding reduction in statistical errors. The embodiments further comprise transmission of an optical beam through one or more wavelength and sub-wavelength apertures, e.g., arrays of wavelength and sub-wavelength apertures, which employs apertures smaller than a free space optical wavelength of an optical beam used in the near-field microscopy. The sub-wavelength apertures are hereinafter referred to as sub-wavelength apertures.

Embodiments of the present invention can permit the separation of the complex amplitude of reflected and/or scattered light by a wavelength or sub-wavelength scattering site or aperture in a line section or a plane section from the complex amplitude of background light produced by superimposed out-of-focus images of structures before and to the side of the wavelength or sub-wavelength scattering site or aperture under examination. The wavelength or sub-wavelength scattering site or aperture under examination are located in either a line section or a two-dimensional section. The described tomographic technique can separate a desired complex amplitude signal of an line section or a plane section from "background" complex amplitude signals generated by various mechanisms. Such background complex amplitude signals may be (1) out-of-focus images of sections of apparatus of an interferometric near-field confocal microscope other than the line section or two-dimensional section being imaged, (2) scattering of a desired amplitude signal, (3) scattering of signals originating from sources other than the line section or two-dimensional section being imaged, and/or (4) thermal radiation. Scattering sites and thermal radiation sources may be located in the space before and to the side of the line section or two-dimensional section under examination.

The technique for separation of background beams is implemented with either of two different levels of discrimination against out-of-focus images. In the first level (Level 1), the impulse response functions of imaging subsystems of the apparatus of the present invention are manipulated in either of two orthogonal planes by introducing one-dimensional patterns of phase changes, respectively, at pupils of the respective imaging subsystems. In the second level (Level 2), the impulse response functions of imaging subsections of the apparatus of the present invention are manipulated in both of two orthogonal planes by introducing two-dimensional patterns of phase changes at pupils of the respective imaging subsystems. A Level 2 discrimination leads to a more effective discrimination of out-of-focus images from in-focus images, with respect to both systematic and statistical errors, than a Level 1 discrimination. Level 1 and Level 2 discriminations may be implemented for any of the embodiments that are described.

In the description that follows, embodiments are described with a Level 1 discrimination. Further embodiments of the invention can include Level 2 discrimination, which follow in a straightforward manner from the embodiments that follow. The Level 1 discrimination is based on a particular orientation of an orthogonal

plane in which the impulse response functions of imaging subsystems are manipulated. The choice of the orientation of the orthogonal plane in which the impulse response functions of imaging subsystems are manipulated impacts on the degree of reduction of the effects of background beams on statistical errors achieved in apparatus of the present invention.

While the apparatus of the present invention has application for a wide range of radiation sources, the following description is taken, by way of example, with respect to an optical measuring system in which the incident beam is a beam of electromagnetic radiation, e.g., an optical beam. In further embodiments, for example, the beam incident on the aperture or arrays of apertures can include an acoustic radiation beam, an electron beam, and an atomic beam.

The source of optical beams used by embodiments of the present invention include CW and pulsed sources in different combinations with single and multiple wavelength sources.

Also, while the apparatus of the present invention has application for a wide range of imaging systems, the following description is taken, by way of example, with respect to interferometric confocal near-field microscopy measuring systems. Optical cavities as used herein includes, but is not limited to, use in scanning and step-and-repeat interferometric near-field confocal microscopy systems and scanning and step-and-repeat confocal and interferometric confocal microscopy systems.

Referring to the drawings in detail, FIG. **1** depicts in schematic form the first embodiment of the present invention. As shown in FIG. **1**, the first embodiment comprises an interferometer, a source **10**, object material **112**, object material chuck **160**, chuck stage **162**, translator **164**, reference object **20R**, and detector **116**. The configuration of the interferometer is known in the art as a Michelson interferometer, and is shown as a simple illustration. Other forms of interferometer known in the art such as a polarized Michelson interferometer and as described in an article entitled "Differential Interferometer Arrangements for Distance and Angle Measurements: Principles, Advantages, and Applications," by C. Zanoni (VDI Berichte NR. **749**, pp. 93-106, 1989) may be incorporated into the apparatus of FIG. **1** without departing from the spirit and scope of the present invention.

For the first embodiment, light source **10** is preferably a point source or a source of radiation spatially incoherent across the surface of the source, preferably a laser or

like source of coherent or partially coherent radiation, and preferably linearly polarized. Light source **10** emits input beam **12**. As shown in FIG. **1**, input beam **12** enters collimating lens **14** to form input beam **16**. Input beam **16** is transmitted by a phase retardation plate **18** as input beam **20**. The plane of polarization of input beam **20** is rotated by phase retardation plate **18** to be either parallel or orthogonal to the plane of FIG. **1**. However, other orientations of the plane of polarization of input beam **20** may be beneficially used in certain end use applications. The function of phase retardation plate **18** is controlled by signal **128** from electronic controller, signal processor, and computer **200**.

Input beam **20** is incident on a non-polarizing beam splitter **100** and a first portion thereof is transmitted as a measurement beam **22**. A second portion of input beam **20** incident on beam splitter **100** is reflected as reference beam **50**. Measurement beam **22** is transmitted through an aperture in lens **60** and incident on a lens assembly comprising lenses **24** and **26**.

The propagation of measurement beam **22** through the lens assembly is shown schematically in an expanded form in FIG. **2a**. Lens **26** is an Amici type objective lens. Measurement beam **22** is focused by the lens assembly to a beam diameter at element **28** that encompasses an array of at least one sub-wavelength aperture and at least one sub-wavelength scattering site in element **28**. Element **28** shown schematically in FIG. **2b** in an expanded form is a conducting layer on a surface of Amici type objective lens **26**.

The sub-wavelength apertures and the sub-wavelength scattering sites are elements **30** and **32**, respectively, as indicated in FIG. **2b**. Sub-wavelength scattering sites **32** are preferably non-transmitting conducting elements with a complex index of refraction different from the complex index of refraction of the conducting material of element **28**. The complex indices of refraction are different so that elements **32** effectively serve as sub-wavelength scattering sites. The diameter of elements **30** and **32** is a with $a < \lambda$, preferably $a \ll \lambda$, where λ is the wavelength of measurement beam **22**. The separation of elements **30** and **32** is b with $b > a$, preferably $b \gg a$. The thickness of conducting material of element **28** is of the order of 20 nm and chosen so that the fraction of the probe beam transmitted by sections of element **28** not containing sub-wavelengths **30** is $\ll 1$.

The relative spacing of elements **30** in element **28** is further selected to minimize the effect of one sub-wavelength aperture on the transmission properties a second sub-wavelength aperture. A coupling leading to either an enhancement or a reduction of transmission by an array of sub-wavelength apertures will complicate interpretation of results obtained with the apparatus of the first embodiment.

The diameters of sub-wavelength apertures **30** need not be restricted to a single diameter as shown schematically in **FIG. 2b** but may beneficially comprise two or more diameters for an end use application. Further, the shapes of sub-wavelength apertures **30** may comprise shapes other than circular, *e.g.*, squares or rectangles without departing from the spirit and scope of the present invention.

The spacing of sub-wavelength apertures **30** need not be restricted to a single value as shown schematically in **FIG. 2b** but may beneficially comprise two or more different spacings for an end-use application without departing from the spirit and scope of the present invention.

Further, the arrangement of sub-wavelength apertures **30** may be arranged in various geometric patterns or a random pattern without departing from the spirit and scope of the present invention.

The apertures **30** in element **28** can be formed as holes in a mask or as transmissive dielectric regions in an otherwise non-transmissive mask, e.g., transmissive vias in an otherwise reflective element. Moreover, the dielectric material in element **28** defining the apertures **30** can form a waveguide or optical cavity that enhances the transmission of the near-field probe beam to the sample. See, e.g., the previously cited application "Multiple-Source Arrays For Confocal And Near-Field Microscopy." Furthermore, in the presently described embodiment, the mask portion of element **28** is described as conducting to indicate that it is reflective. In other embodiments, element **28** is not necessarily conductive, but is, generally, not transmissive, with the coupling of the near-field probe beams to the sample being accomplished by the apertures **30** in element **28**.

The sub-wavelength apertures may further comprise a Fresnel zone plate or a microlens to alter beneficially in certain end use applications the transmission through an array of sub-wavelength apertures without departing from the spirit and scope of the present invention. In certain other end use applications, gratings may be added to an array of wavelength/sub-wavelength apertures operating as spatial filters of

reflected/scattered or transmitted near-field probe beam(s) to alter properties of the reflected/scattered or transmitted near-field probe beam(s) without departing from the spirit and scope of the present invention.

A first portion of the measurement beam incident on sub-wavelength apertures **30** is transmitted as a near-field probe beam. A portion of the near-field probe beam is incident on object material **112** and a portion thereof is reflected and/or scattered back to the sub-wavelength apertures **30**, and a portion thereof is transmitted as a near-field return probe beam. The spatial separation of adjacent surfaces of object material **112** and conducting element **28** is h as indicated in FIG. **2b**. The value of h is preferably of the order of $2a$. A second portion of the measurement beam incident on sub-wavelength apertures **30** is reflected and/or scattered as a first background return beam. A portion of the measurement beam incident on sub-wavelength scattering sites **32** is reflected and/or scattered as a second background return beam. The near-field return probe beam, the first background return beam, and the second background return beam exit Amici type objective lens **26** as return beam **34** shown as rays **34A** and **34B** in FIGS. **1a** and **4a** wherein return beam **34** comprises rays between rays **34A** and **34B.** Return beam **34** is collimated by lens **60** as return beam **36** shown as rays **36A** and **36B** in FIG. **1**, wherein beam **36** comprise rays between rays **36A** and **36B.**

A portion of the measurement beam not incident on sub-wavelength apertures **30** and scattering sites **32** is reflected as a return measurement beam. The return measurement beam exits lens **24** as a beam substantially parallel to measurement beam **22** and a portion thereof is reflected as a return measurement beam component of beam **42**. Beam **42** is incident on and substantially occulted by stop **70**.

Reference beam **50** is transmitted by a phase shifter **64**, transmitted by an aperture in lens **66**, incident on reference object **20R**, and reflected as reflected reference beam **54** shown as rays **54A** and **54B** in FIG. **1** wherein beam **54** comprises rays between rays **54A** and **54B.** Beam **54** is collimated by lens **66** and transmitted by phase shifter **64** as a reflected reference beam **56** shown as rays **56A** and **56B** in FIG. **1**, wherein beam **56** comprises rays in between rays **56A** and **56B**. Phase shifter **64** introduces a relative phase shift χ in the reflected reference beam **56** as a result of the two transits of reference beam **50** through phase shifter **64**. The magnitude of phase shift χ is controlled by control signal **132** from electronic controller, signal processor, and computer **200**.

The propagation of reference beam **52** through reference object **20R** is shown schematically in an expanded form in FIG. **2c**. Reference object **20R** is an Amici type objective lens. Reference beam **52** is focused by reference object **20R** to a beam diameter at element **28R** that encompasses an array of at least two wavelength or sub-wavelength reflecting spots on element **28R**. Element **28R** is shown schematically in FIG. **2d** in an expanded form as an array of reflecting spots **30R** and **32R** on a surface of Amici type objective lens **26R**. Reflecting spots **30R** and **32R** generate reflected reference beam components of beam **54** that correspond to elements **30** and **32**, respectively, of element **28**. The spacing of the reflective spots **30R** and **32R** and the focal length of lens **66** are chosen such that reflective spots **30R** and **32R** and elements **30** and **32**, respectively, are conjugates as seen by a subsequent imaging onto a detector. The diameter a'' of the reflective spots **30R** and **32R** is chosen to efficiently generate reflected reference beam **56** with a diameter substantially the same as the diameter of return beam **36**. The relative reflectivities of reflecting spots **30R** and **32R** may be the same or beneficially different depending on an end use application.

It will be evident to those skilled in the art that the path of the reference beam could be configured such that the reference beam is transmitted by a reference object **20R** having an element which is complimentary to element **28R** of the first embodiment without departing from the spirit and the scope of the present invention. Examples of the generation of a reference beam by transmitting beams through wavelength and/or sub-wavelength apertures is described in cited U.S. Provisional Application by Hill entitled "Multiple-Source Arrays With Optical Transmission Enhanced By Resonant Cavities."

A portion of return beam **36** is transmitted by half-wave phase retardation plate **44** (see FIG. **1**) and incident on beam splitter **100** wherein a portion thereof is reflected as a return beam component of phase shifted beam **38A**. Phase-shifted beam **38A** comprises rays between ray **38A** and the corresponding optical axis. A second portion of return beam **36** is incident on beam-splitter **100** wherein a portion thereof is reflected as a return beam component of non-phase-shifted beam **38B**. Non-phase-shifted beam **38B** comprises rays between ray **38B** and the corresponding optical axis.

A portion of reflected reference beam **56** is transmitted by half-wave phase retardation plate **44R** (see FIG. **1**) and incident on beam splitter **100** wherein a portion thereof is transmitted as a reflected reference beam component of phase-shifted beam

38A. A second portion of return beam **36** is incident on beam splitter **100** wherein a portion thereof is transmitted as a reflected reference beam component of non-phase-shifted beam **38B**. Phase-shifted beam **38A** and non-phase-shifted beam **38B** are mixed with respect to polarization by polarizer **68**, then incident on lens **62**, and focused as mixed phase-shifted beam **40A** and beam non-phase-shifted beam **40B**. Phase-shifted beam **40A** comprises rays between ray **40A** and the corresponding optical axis and non-phase-shifted beam **40B** comprises rays between rays **40B** and the corresponding optical axis. Mixed beams **40A** and **40B** are focused onto a pinhole plane **114** such that a pinhole in image plane **114** is a conjugate image of either one of the sub-wavelength apertures **30** or one of sub-wavelength scattering points **32**.

Pinhole plane **114** is shown schematically in FIG. **3**. The diameter of the pinholes is c and the spacing between the pinholes is d. The spacing d is equal to the separation b of sub-wavelength apertures **30** and sub-wavelength scattering sites **32** times the magnification of the imaging system imaging the sub-wavelength apertures **30** and sub-wavelength scattering points **32** onto corresponding pinholes in pinhole plane **114**. Diameter c is selected to be approximately twice the size of a diffraction limited image of a point object by the imaging system and the spacing d is selected to be larger than c, preferably $\geq$ to approximately four times the size of a diffraction limited image of a point object by the imaging system. Typical amplitude functions of diffraction limited images of wavelength or sub-wavelength apertures **30** and wavelength or sub-wavelength scattering sites **32** and corresponding to combined components of phase-shifted and non-phase-shifted beams **40A** and **40B** are shown in FIG. **3**. Also shown in FIG. **3** are amplitude functions of diffraction limited images of wavelength or sub-wavelength apertures **30R** and wavelength or sub-wavelength scattering sites **32R** and corresponding to combined components of phase-shifted and non-phase-shifted beams **40A** and **40B**.

A portion of mixed beams **40A** and **40B** are transmitted by the pinholes in pinhole plane **114** and detected by a detector **116**, preferably by a quantum photon detector. Detector **116** comprises an array of pixels, comprising either a pair of pixels, a one dimensional array of pixels, or a two dimensional array of pixels according to the requirements of an end-use application, with a one-to-one mapping of pinholes in pinhole plane **114** to the pixels of detector **116**. Detector **116** generates an electrical interference signal comprising an array of signal values $[S_n]$ corresponding to the array

of pixels. Subscript n is an index indicating an element in the array of signal values $[S_n]$. The array of signal values $[S_n]$ may comprise a pair of elements, a one-dimensional array comprising at least three elements, or a two-dimensional array depending on an end-use application.

The array of signal values $[S_n]$ may be written to a good approximation as

$$[S_n] = [(S_D + S_I)_n] \quad (1)$$

where term $(S_D)_n$ represents terms either associated with sub-wavelength apertures **30** or associated with sub-wavelength apertures **32** and term $(S_I)_n$ represents interference cross terms either associated with sub-wavelength apertures **30** or associated with sub-wavelength apertures **32**.

A $(S_D)_n$ term associated with sub-wavelength apertures **30** is proportional to the sum of the squares of the amplitudes of the corresponding portions of the near-field return probe beam, of the first background return beam, and of the reflected reference beam and interference cross terms between complex amplitudes of the near-field return probe beam and of the first background return beam. A $(S_D)_n$ term associated with sub-wavelength apertures **32** is proportional to the sum of the squares of the amplitudes of the corresponding portions of the second background return beam and of the reflected reference beam. A $(S_I)_n$ term associated with wavelength or sub-wavelength apertures **30** is proportional to the sum of the interference cross terms between complex amplitudes of the near-field return probe beam and of the reflected reference beam and between complex amplitudes of the first background return beam and of the reflected reference beam. A $(S_I)_n$ term associated with sub-wavelength apertures **32** is proportional to the interference cross term between complex amplitudes of the second background return beam and of the reflected reference beam.

Term $(S_D)_n$ is independent of phase shift χ. Term $(S_I)_n$ is a sinusoidal function of phase shift χ and may be written as

$$(S_I)_n = \left(|S_I|\cos(\varphi+\chi)\right)_n \quad (2)$$

where $\left(|S_I|\right)_n$ and φ are an amplitude and phase, respectively, related to the complex amplitudes contributing to $(S_I)_n$.

Operation of the apparatus of the first embodiment of the present invention depicted in FIGS. **1a**, **4a**, and **4b** is based on the acquisition of a sequence of four measurements of arrays of signal values. The sequence of the four arrays of signal values $[S_n]_1$, $[S_n]_2$, $[S_n]_3$, and $[S_n]_4$ is obtained by detector **116** with phase shifter **64** introducing a sequence of phase shifts χ_0, $\chi_0+\pi$, $\chi_0+\pi/2$, and $\chi_0+3\pi/2$ radians, respectively, where χ_0 is some fixed value of phase shift χ. The four arrays of signal values $[S_n]_1$, $[S_n]_2$, $[S_n]_3$, and $[S_n]_4$ are sent to electronic controller, signal processor, and computer **200** as signal **131**, in either digital or analog format, for subsequent processing.

Conventional conversion circuitry, i.e., analog-to-digital converters, is included in either detector **116** or electronic controller, signal processor, and computer **200** for converting the four arrays $[S_n]_1$, $[S_n]_2$, $[S_n]_3$, and $[S_n]_4$ to a digital format. Phase shift χ introduced by phase shifter **64** is controlled by signal **132** where signal **132** is generated and subsequently transmitted by electronic controller, signal processor, and computer **200**. Phase shifter **64** can be of an electro-optical type.

Next, two arrays of signal value differences $[S_n]_1-[S_n]_2=\left[(S_I)_n\right]_1-\left[(S_I)_n\right]_2$ and $[S_n]_3-[S_n]_4=\left[(S_I)_n\right]_3-\left[(S_I)_n\right]_4$ are computed by electronic controller, signal processor, and computer **200**.

Elements of the arrays of signal value differences corresponding to pixels that are associated with wavelength or sub-wavelength apertures **30** contain substantially and with relatively high efficiency only two interference cross terms, a first interference cross term between the complex amplitude of the near-field return probe beam and of the complex amplitude of the reflected reference beam and a second interference cross term between the complex amplitude of the first background return beam and of the complex amplitude of the reflected reference beam.

Elements of the arrays of signal value differences corresponding to pixels that are associated with wavelength or sub-wavelength scattering sites **32** contain substantially and with relatively high efficiency only the interference cross term between the complex amplitude of the second background return beam and of the complex amplitude of the reflected reference beam.

The relatively high efficiency for isolation of effects of amplitudes of beams associated with wavelength or sub-wavelength apertures **30** and wavelength or sub-wavelength scattering sites **32** in the measured intensity values is due in part to the properties of the amplitude functions shown in FIG. **3** and in part controlled by the choice of parameters c and d. The combined amplitude function of return beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B** is an anti-symmetric function about the center line of a corresponding aperture. The combined amplitude function of reflected reference beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B** is an anti-symmetric function about the center line of a corresponding aperture. Thus the interference cross term between the combined amplitude function of return beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B** and the combined amplitude function of reflected reference beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B** is a symmetric function about the center line of the corresponding aperture. The integral of a symmetric function across the corresponding aperture is non-zero and the interference cross term detected with high efficiency.

The complex amplitude of the near-field return probe beam is computed by electronic controller, signal processor, and computer **200** from the amplitude of the first interference term between the complex amplitude of the near-field return probe beam and the amplitude of the reflected reference beam. The computation comprises using measured values of the interference cross terms between components of the complex amplitude of the second background return beam and components of the complex amplitude of the reflected reference beam to compensate the measured values of elements of signal value differences associated with wavelength or sub-wavelength apertures **30** for the contribution of the second interference cross terms between components of the complex amplitude of the first background return beam and components of the complex amplitude of the reflected reference beam. The computation further comprises using measured values for the square of the amplitudes

of the portions of the reflected reference beam transmitted by the pinholes of pinhole plane **114** and detected by detector **116**.

Object material **112** is mounted on an object chuck **160**. The angular orientation and height of object chuck **160** is controlled by three transducers, two of which are shown as **161A** and **161B**, that are attached to chuck stage **162**. The angular orientation and height of object material **112** relative to the surface of conducting element **28** are detected and used to generate error signals. The detection and generation of error signals may be by known techniques in the art such as capacitive or "cap" gauges, precision distance measuring interferometry including wave domain reflectometry [see, e.g., commonly owned U.S Patent Application with Serial No. 09/089,105 and entitled "Methods And Apparatus For Confocal Interference Microscopy Using Wavenumber Domain Reflectometry And Backgroung Amplitude Reduction And Compensation" by Henry A. Hill, the contents of which is incorporated herein by reference] and scanning interferometric near-field microscopy [see, e.g., previously mentioned U.S. Patent Application entitled "Control of Position and Orientation of Sub-Wavelength Aperture Array in Near-field Scanning Microscopy;" by Henry A. Hill.] The error signals are transmitted as a component of signal **166** to electronic controller, signal processor, and computer **200**. Servo control signals are generated by electronic controller, signal processor, and computer **200** from the error signals and transmitted as a servo control signal component of signal **166** to chuck stage **162**. Transducers **161A, 161B**, and the third transducer (not shown) alter the orientation and/or height of object material **112** according to the servo control signal component of signal **166**.

The location of chuck stage **162** in a plane substantially parallel to the surface of element **28** is controlled by translator **164**. The location of chuck stage **162** is detected by known techniques in the art such as precision distance measuring interferometry and error signals transmitted as an error signal component of signal **168** to electronic controller, signal processor, and computer **200**. [See U.S. Patent Application with Serial No. 09/252,266 entitled "Interferometer And Method For Measuring The Refractive Index And Optical Path Length Effects Air" by Peter de Groot, Henry A. Hill, and Frank C. Demarest filed Feb. 18, 1999 and U.S. Patent Application with Serial No. 09/252,266 entitled "Apparatus And Method For Measuring The Refractive Index And Optical Path Length Effects Of Air Using Multiple-Pass Interferometry" by Henry

A. Hill, Peter de Groot, and Frank C. Demarest filed Feb. 18, 1999. The contents of both applications are incorporated herein by reference.] Servo control signals are generated by electronic controller, signal processor, and computer **200** from the error signal component of signal **168** and transmitted as a servo signal component of signal **168** to translator **164**. Translator **164** controls the location and orientation of chuck stage **162** in one or two orthogonal directions and in one or two orthogonal planes of orientation, according to the requirements of an end use application, in response to the servo signal component of signal **168**.

Next, the object material **112** is scanned in a combination of one or two orthogonal directions substantially parallel to the surface of object material **112** and in the spatial separation of the element **28** from the adjacent surface of object material **112** according to the requirements of an end-use application. Measured arrays of signal values $[S_n]_1$, $[S_n]_2$, $[S_n]_3$, and $[S_n]_4$ are obtained as a function of the scanned parameters and the amplitudes and phases of the respective interference cross terms between the complex amplitude of the respective near field return probe beam and of the respective complex amplitude of the reflected reference beam computed by electronic controller, signal processor, and computer **200**.

Information with apparatus of the first embodiment about object material **112** is acquired in the presence of a significantly reduced background signal. Sources of contributions to the background signal comprise the first background return beam, a portion of the return measurement beam not occulted by stop **70**, a background produced by reflection and/or scattering of other beams associated with the measurement beam in the apparatus of the first embodiment, and corresponding beams associated with the reflected reference beam. The background signal is significantly reduced first because the apparatus of the first embodiment comprises a confocal optical imaging/detecting system, second because of effects of halfwave phase retardation plates **44** and **44R**, and third because of the background compensation procedure based on measurement of the second background return beam.

It is well known to those in the art that confocal optical imaging/detecting systems have significantly improved depth discrimination in relation to non-confocal optical imaging/detecting systems and therefore significantly improved discrimination against scattered/reflected beams generated in plane sections displaced from the plane

section being imaged. The effects of halfwave phase retardation plates **44** and **44R** produces a further reduction of systematic effects and of statistical effects of background beams, However, confocal optical imaging/detecting systems and the effects of halfwave phase retardation plates **44** and **44R** do not discriminate against the first background return beam. The background compensation procedure based on measurement of the second background return beam compensates for the first background return beam that is not discriminated against by the confocal imaging/detecting properties of the apparatus of the first embodiment. It should be noted that The background compensation procedure based on measurement of the second background return beam further compensates for the scattered/reflected beams generated in plane sections displaced from the plane section being imaged not discriminated against by the confocal imaging/detecting properties and the effects of halfwave phase retardation plates **44** and **44R** of the apparatus of the first embodiment.

The effects of halfwave phase retardation plates **44** and **44R** produces a further reduction of systematic effects and of statistical effects of background beams. The further reduction of the interference cross term between the reflected reference beam and a component of a background beam follows in part from the fact that the amplitude of a beam decreases as the distance to the image plane is increased. This property is the basis of the reduced background in prior-art confocal interference microscopy. However, in the apparatus of the present invention, the reduction in magnitude of the interference cross term between an out-of-focus scattered beam and the combined reflected reference beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B** is enhanced in relation to that achieved in prior-art confocal interference microscopy.

The enhanced reduction referred to in the preceding paragraph is realized by the presence of phase shifters **44** and **44R**. The part of the out-of-focus scattered beam that interferes with the complex in-focus combined reflected reference beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B** generally displays only small relative changes across the space of the in-focus combined reflected reference beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B**. Thus the spatial distribution of the interference cross term between the out-of-focus scattered beam and the in-focus combined reflected reference beam components of phase-shifted beam **40A** and non-phase-shifted beam **40B** is comprised primarily of a antisymmetric

distribution about the center line of a corresponding aperture in aperture array **114**. The integral of a antisymmetric distribution about an interval centered on the center line of the corresponding aperture is zero. Thus the net contribution of the interference cross term between the complex amplitude of an out-of-focus scattered beam and the reflected reference beam comprising a phase shifted and a non-phase shifted components is significantly reduced beyond that achieved in prior-art confocal interference microscopy.

The scanning of object material **112** in a combination of one or two orthogonal directions substantially parallel to the surface of object material **112** and in the spatial separation of the element **28** from the adjacent surface of object material **112** is implemented for the first embodiment as a "step and repeat" mode.

Other forms of the techniques for reduction of effects of background beams in confocal microscopy systems as described in commonly owned U.S. Patent Application No. 5,760,901 issued June 2, 1998 and entitled "Method And Apparatus For Confocal Interference Microscopy With Background Amplitude Reduction And Compensation" by Henry A. Hill may be incorporated into the apparatus of FIG. **1** without departing from the spirit and scope of the present invention. The contents the cited U.S. Patent are herein incorporated by reference.

Further embodiments of the invention include adapting the systems described above to operate in a transmission mode. Once such embodiment is shown in FIG. **4.**

Many elements of the embodiment shown in FIG. **4** perform similar functions as elements of the earlier embodiment and are indicated in FIG. **4** with the same element numbers as corresponding elements of the first embodiment shown in FIG. **1**.

Beam **20** is incident on non-polarizing beam splitter **102**, and a first portion thereof is transmitted as measurement beam **22T**. Measurement beam **22T** is next reflected by mirror **92** and then focused to a spot on substrate **112T** after reflection by mirror **90**. Substrate **112T** comprises a transparent substrate at the wavelength of beam **20** and an array of wavelength and/or sub-wavelength apertures corresponding to apertures **30** of the first embodiment. A portion of measurement beam **22T** focused to the spot is transmitted by the sub-wavelength apertures **30** as an array of near-field probe beams. The description of the sub-wavelength apertures **30** is the same as the corresponding portion of the description given for the array of sub-wavelength

apertures **30** of the first embodiment. The diameter of the spot is large enough span the array of sub-wavelength apertures **30**.

Sample **25** to be examined by the array of near-field beams is placed on the flat surface of Amici type lens **26T**. The array of near-field probe beams is transmitted by sample **25** as a transmitted beam **34** corresponding to beam **34** of the first embodiment with respect to subsequent processing by the apparatus of the fifth embodiment.

A second portion of beam **20** is reflected by mirror **102** as reference beam **50T**, as shown in FIG. **4**. Reference beam **50T** is transmitted through an aperture in lens **60** as reference beam **52** after reflection by mirrors **94A**, **94B**, and **94C**. The description of reference beam **52** is the same as corresponding portions of the description given for beam **52** of the first embodiment.

In additional embodiments, the function of the phase retardation plates may be more generally imparted by the use of a phase mask, which may extend over some or all of the respective beam. Such a phase mask may impart a the same or different phase shifts to selected transverse regions of an incident beam. For example, to causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension, the phase masks in the return reference and measurement beams may impart a pi phase-shift to half of the respective beam. This may be accomplished by, e.g., bisecting the beam with the pi phase-shift, or, e.g., by impart the pi phase-shift to different regions of the respective beam comprising half its transverse area in the pupil plane. One such example for the latter case would be a periodic alternating pattern of pi phase-shifts. Such variable patterns may further extend along multiple transverse dimensions. Moreover, in some embodiments the phase mask may be a composite phase mask formed by a series of individual phase masks.

Furthermore, in additional embodiments, rather than placing a separate phase mask in the each of the return measurement and reference beams, one phase mask may be positioned in a pupil plane of the imaging system where the return measurement and reference beams are combined as a mixed beam.

Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is:

1. An interferometric optical microscopy system for imaging an object, the system comprising:

a beam splitter positioned to separate an input beam into a measurement beam and a reference beam;

a measurement beam source array positioned to receive the measurement beam, the measurement beam source array comprising a mask having an array of measurement apertures each configured to radiate a portion of the measurement beam to the object, the object interacting with the radiated measurement beam portions to direct signal radiation back through the apertures to define a measurement return beam;

a reference beam source array positioned to receive the reference beam, the reference beam source array comprising an array of elements each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam;

a multi-element photo-detector;

imaging optics positioned to direct the measurement and reference return beams to the photo-detector and configured to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector, wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and

at least one phase mask positioned to contact the return measurement beam and the return reference beam, wherein the at least one phase mask causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

2. The system of claim 1, wherein the at least one phase mask comprises a first phase mask and a second phase mask, wherein the first phase mask is positioned to contact the return measurement beam and not the return reference beam, and wherein the second phase mask is positioned to contact the return reference beam and not the return measurement beam.

3. The system of claim 1, wherein the at least one phase mask comprises a first phase mask positioned to contact both of the return measurement beam and the return reference beam.

4. The system of claim 1, wherein the at least one phase mask divides the transverse profile of the return measurement beam and the return reference beam into multiple sections along the first dimension and imparts a relative phase shift equal to $\pi+2\pi n$, where is n is an integer, to half of the multiple sections.

5. The system of claim 1, wherein the phase mask further causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension.

6. The system of claim 5, wherein the at least one phase mask divides the transverse profile of the return measurement beam and the return reference beam along the first dimension into multiple sections and imparts a relative phase shift equal to $\pi+2\pi n_1$, where is n_1 is an integer, to half of the multiple sections corresponding to the first dimension, and wherein the at least one phase mask further divides the transverse profile of the return measurement beam and the return reference beam along a second dimension orthogonal to the first dimension into multiple sections and imparts a relative phase shift equal to $\pi+2\pi n_2$, where is n_2 is an integer, to half of the multiple sections corresponding to the second dimension.

7. The system of claim 1, further comprising a second, at least one phase mask positioned to contact the return measurement beam and the return reference beams, wherein the second, at least one phase mask causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension.

8. The system of claim 2, wherein the first phase mask is positioned in a pupil plane of the imaging optics for the return measurement beam and the second phase mask is positioned in a pupil plane of the imaging optics for the return reference beam.

9. The system of claim 3, wherein the first phase mask is positioned in a pupil plane of the imaging optics for the return measurement beam and the return reference beam.

10. The system of claim 1, further comprising a pinhole array positioned adjacent the photo-detector, wherein each pinhole is aligned with a separate set of one or more detector elements, and wherein the imaging system causes the conjugate image for each measurement aperture to align with a corresponding pinhole of the pinhole array.

11. The system of claim 1,

wherein the mask in the measurement beam source array further comprises an array of measurement scattering elements, wherein each measurement scattering element is adjacent a corresponding one of the measurement apertures and has transverse dimensions comparable to the corresponding measurement aperture, and wherein each measurement scattering element scatters a portion of the measurement beam, the measurement return beam further comprising the portions of the measurement beam scattered by the measurement scattering elements, and

wherein the imaging optics are further configured to produce a conjugate image of the array of measurement scattering elements that overlaps with the conjugate image of the array of reference elements, wherein the conjugate image for each measurement scattering element overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal that provides an estimate of scattering from the adjacent measurement aperture.

12. The system of claim 11, further comprising a pinhole array positioned adjacent the photo-detector, wherein each pinhole is aligned with a separate set of one or more detector elements, and wherein the imaging system causes the conjugate image for each measurement aperture and each measurement scattering element to align with a corresponding pinhole of the pinhole array.

13. The system of claim 1, wherein each reference element comprises a reflective element.

14. The system of claim 1, wherein each reference element comprises a transmissive aperture.

15. An interferometric optical microscopy system for imaging an object, the system comprising:

a beam splitter positioned to separate an input beam into a measurement beam and a reference beam;

a measurement beam source array positioned to receive the measurement beam, the measurement beam source array comprising a mask having an array of source apertures each configured to radiate a portion of the measurement beam to the object;

a measurement beam detector array comprising a mask having an array of measurement apertures, wherein the object interacts with the radiated measurement beam portions and directs the resulting signal radiation through the measurement apertures to define a measurement return beam;

a reference beam source array positioned to receive the reference beam, the reference beam source array comprising an array of elements each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam;

a multi-element photo-detector;

imaging optics positioned to direct the measurement and reference return beams to the photo-detector and configured to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector, wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and

at least one phase mask positioned to contact the return measurement beam and the return reference beams, wherein the at least one phase mask causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

16. The system of claim 15, wherein the at least one phase mask comprises a first phase mask and a second phase mask, wherein the first phase mask is positioned to contact the return measurement beam and not the return reference beam, and wherein the second phase mask is positioned to contact the return reference beam and not the return measurement beam.

17. The system of claim 15, wherein the at least one phase mask comprises a first phase mask positioned to contact both of the return measurement beam and the return reference beam.

18. The system of claim 15, wherein the at least one phase mask divides the transverse profile of the return measurement beam and the return reference beam into multiple sections along the first dimension and imparts a relative phase shift equal to $\pi+2\pi n$, where is n is an integer, to half of the multiple sections.

19. The system of claim 15, wherein the phase mask further causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension.

20. The system of claim 19, wherein the at least one phase mask divides the transverse profile of the return measurement beam and the return reference beam along the first dimension into multiple sections and imparts a relative phase shift equal to $\pi+2\pi n_1$, where is n_1 is an integer, to half of the multiple sections corresponding to the first dimension, and wherein the at least one phase mask further divides the transverse profile of the return measurement beam and the return reference beam along a second dimension orthogonal to the first dimension into multiple sections and imparts a relative phase shift equal to $\pi+2\pi n_2$, where is n_2 is an integer, to half of the multiple sections corresponding to the second dimension.

21. The system of claim 15, further comprising a second, at least one phase mask positioned to contact the return measurement beam and the return reference beam, wherein the second, at least one phase mask has a phase mask pattern that causes

the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along a second dimension orthogonal to the first dimension.

22. The system of claim 16, wherein the first phase mask is positioned in a pupil plane of the imaging optics for the return measurement beam and the second phase mask is positioned in a pupil plane of the imaging optics for the return reference beam.

23. The system of claim 17, wherein the first phase mask is positioned in a pupil plane of the imaging optics for the return measurement beam and the return reference beam.

24. The system of claim 15, further comprising a pinhole array positioned adjacent the photo-detector, wherein each pinhole is aligned with a separate set of one or more detector elements, and wherein the imaging system causes the conjugate image for each measurement aperture to align with a corresponding pinhole of the pinhole array.

25. The system of claim 15, wherein each reference element comprises a reflective element.

26. The system of claim 15, wherein each reference element comprises a transmissive aperture.

27. An interferometric, microscopy method for imaging an object, the method comprising:

separating an input beam into a measurement beam and a reference beam;

directing the measurement beam to an array of measurement apertures to cause a portion of the measurement beam to couple through each of the measurement apertures and radiate the object;

receiving signal radiation from the object back through the apertures in response to the radiated measurement beam portions, wherein the signal radiation defines a measurement return beam;

directing the reference beam to array of reference elements to cause each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam;

imaging the measurement and reference return beams onto a photo-detector to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector, wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and

imparting a phase pattern onto each of the return measurement beam and the return reference beams that causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

28. An interferometric, microscopy method for imaging an object, the method comprising:

separating an input beam into a measurement beam and a reference beam;

directing the measurement beam to an array of source apertures to cause a portion of the measurement beam to couple through each of the measurement apertures and radiate the object;

receiving signal radiation from the object through an array of measurement apertures in response to the radiated measurement beam portions, wherein the signal radiation defines a measurement return beam;

directing the reference beam to array of reference elements to cause each configured to radiate a portion of the reference beam, the radiated reference beam portions defining a reference return beam;

imaging the measurement and reference return beams onto a photo-detector to produce overlapping conjugate images of the array of reference elements and the array of measurement apertures on the photo-detector, wherein the conjugate image for each measurement aperture overlaps with the conjugate image of a corresponding reference element to produce an optical interference signal indicative of a particular region of the object; and

imparting a phase pattern onto each of the return measurement beam and the return reference beams that causes the conjugate image for each reference element and each measurement aperture to have an asymmetric profile along at least a first dimension.

5

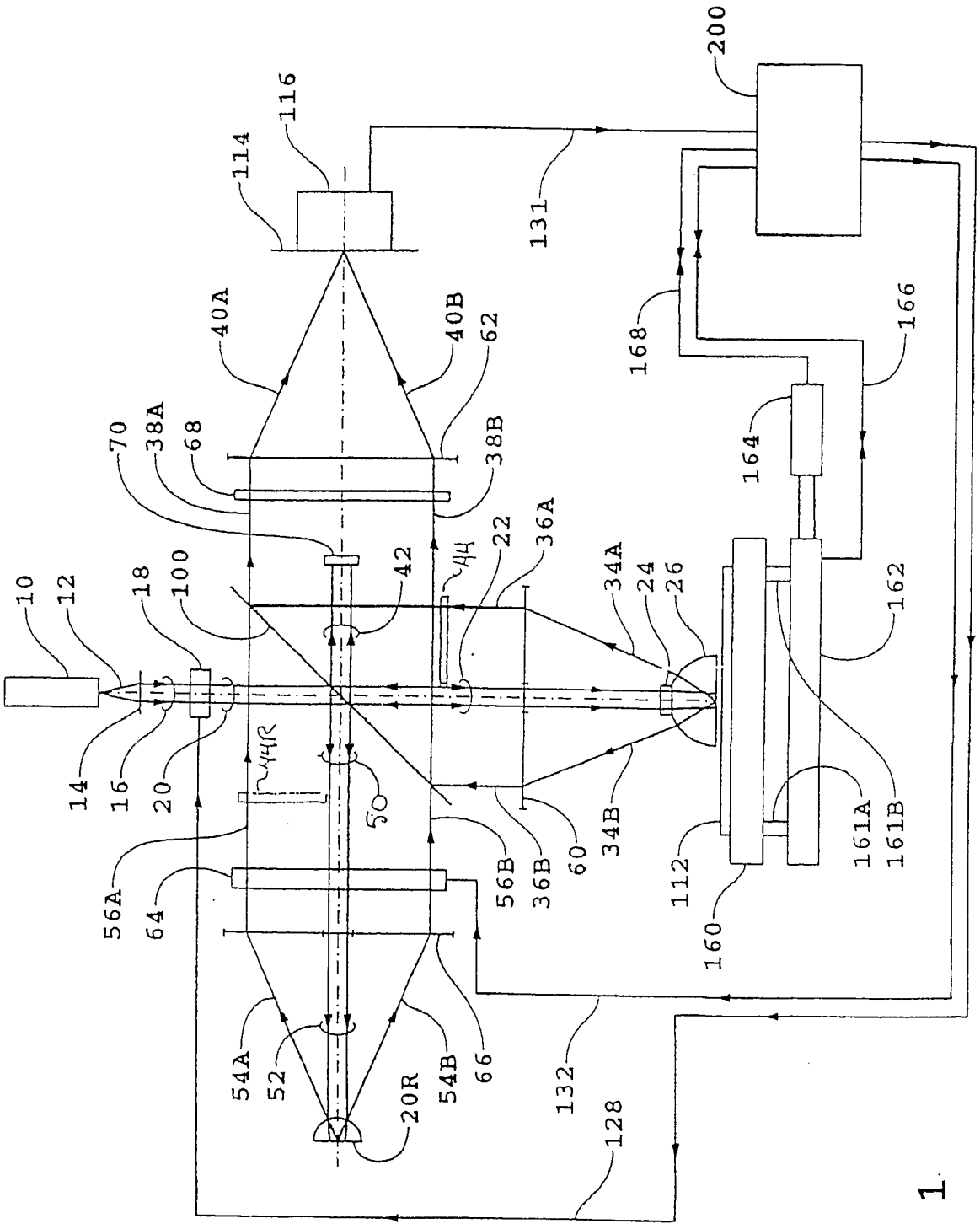

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38B
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100
162
14
16
20
44R
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FIG. 1

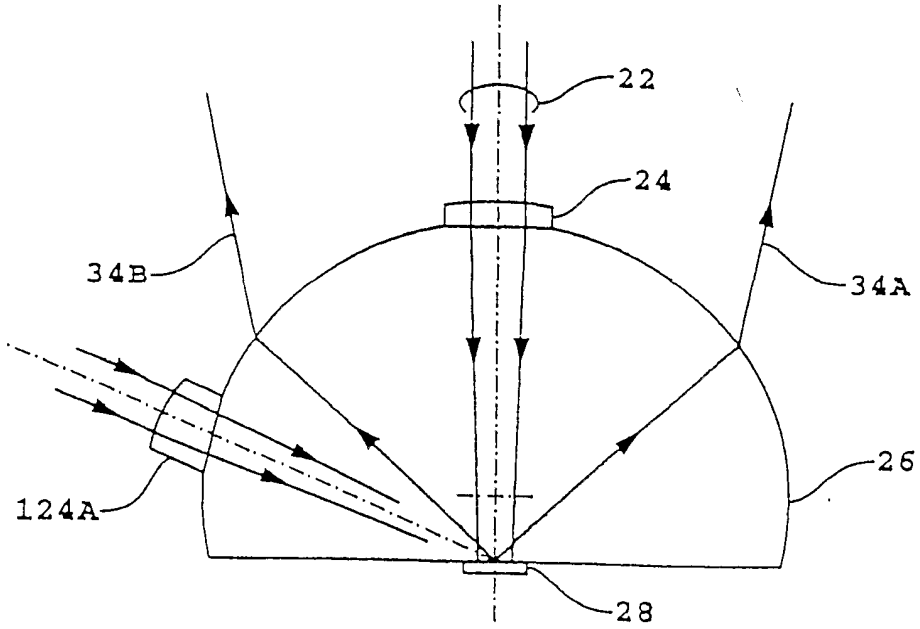

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124A
28

FIG. 2a

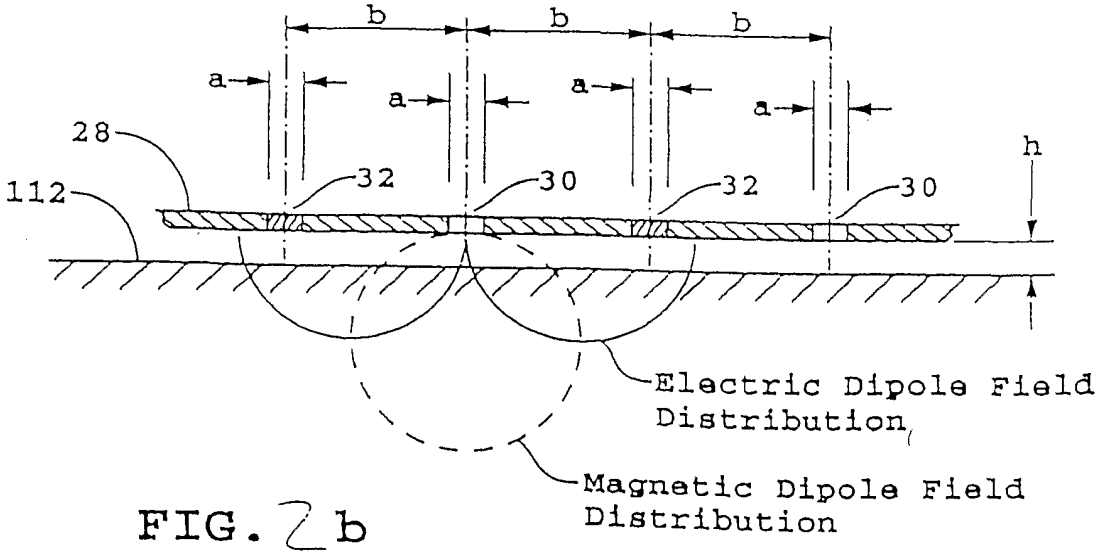

b
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30
h
Electric Dipole Field Distribution
Magnetic Dipole Field Distribution

FIG. 2b

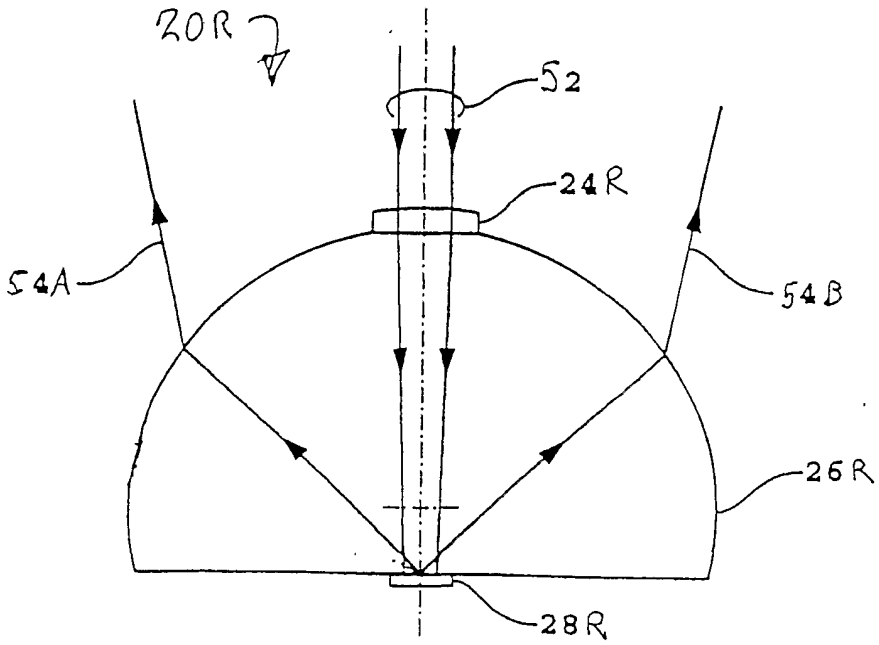


FIG. 2c

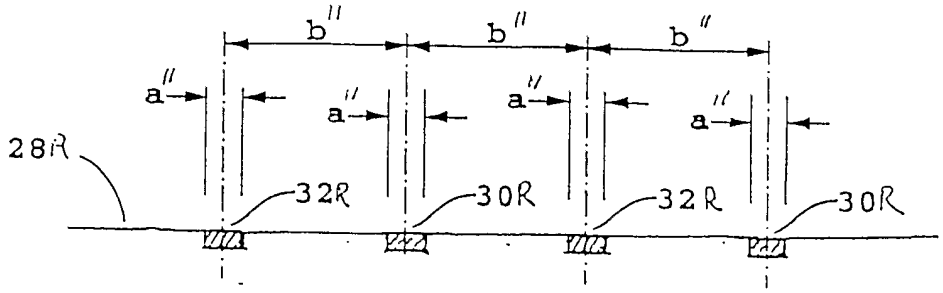


FIG. 2d

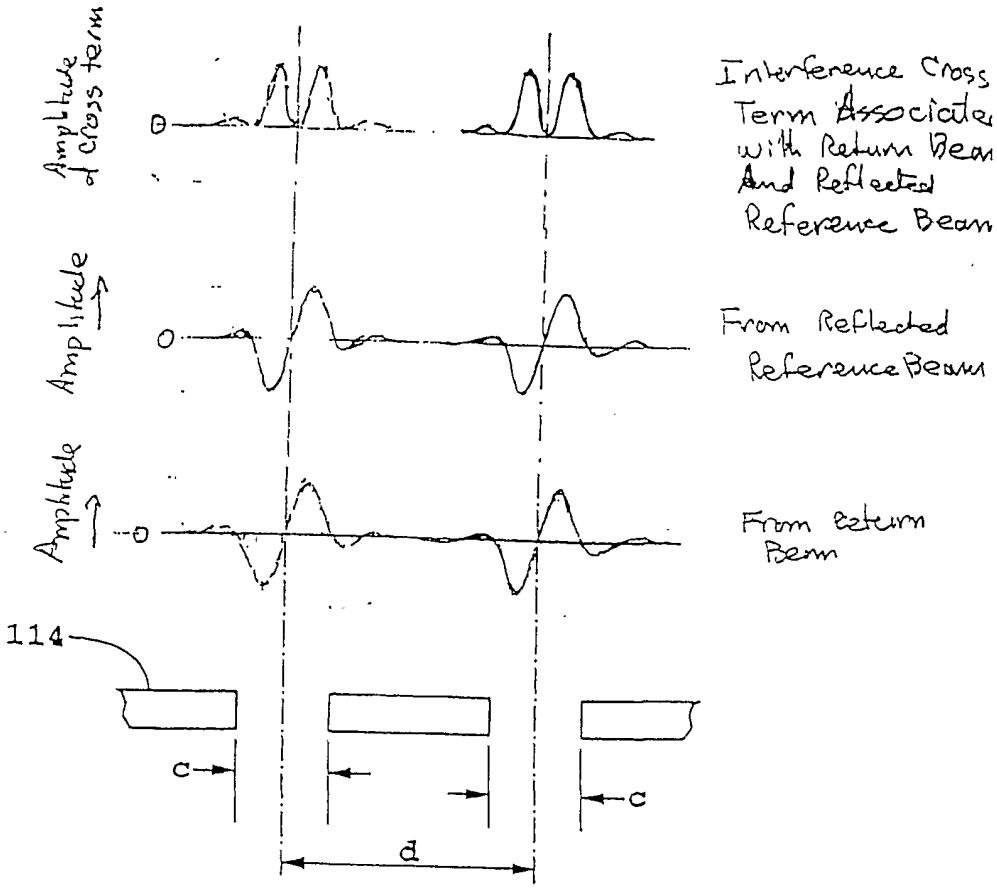

Amplitude of cross term
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Interference Cross Term Associated with Return Beam And Reflected Reference Beam
Amplitude
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From Reflected Reference Beam
Amplitude
0
From Return Beam
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c
c
d

FIG. 3

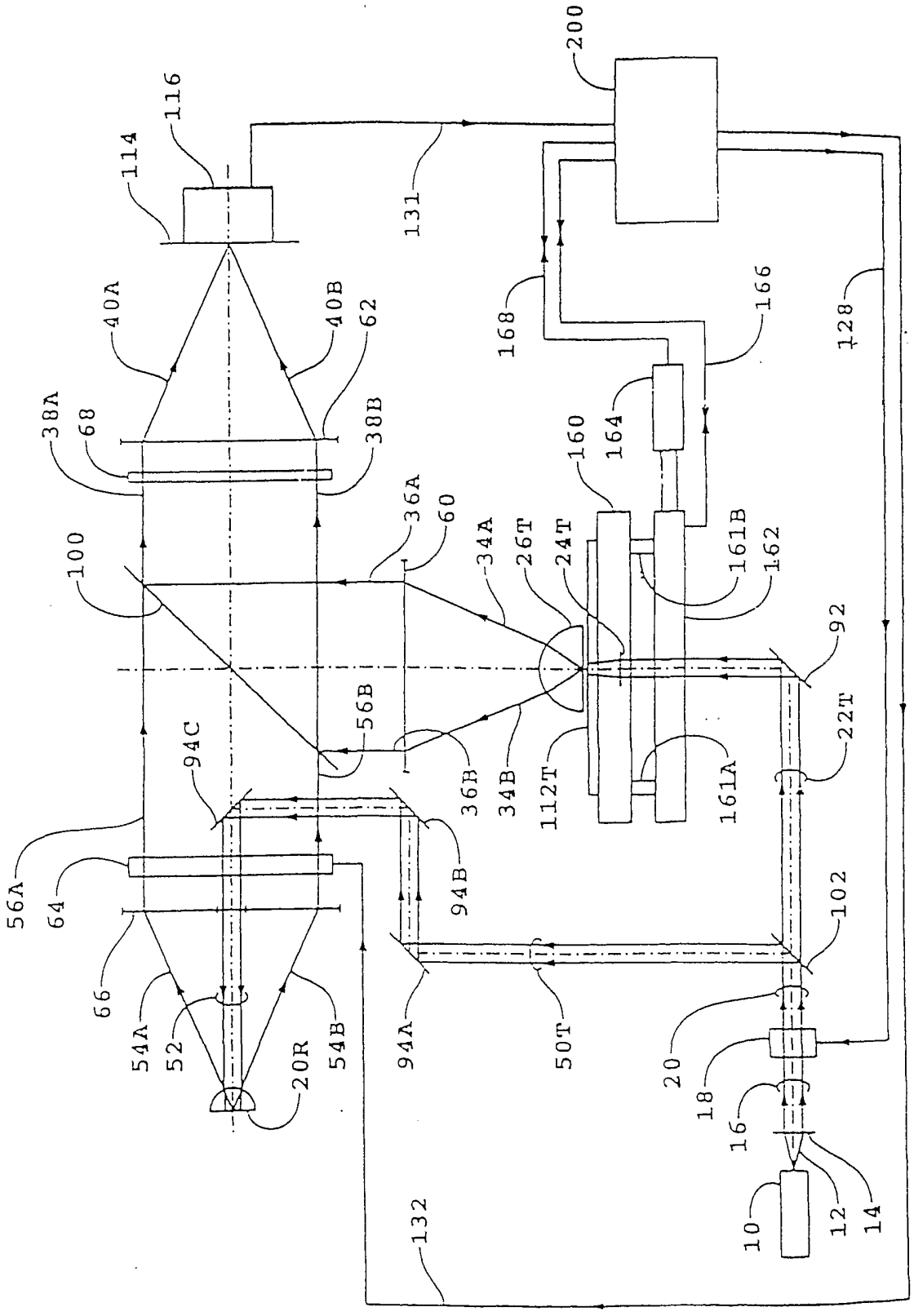

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162
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56B
22T
94C
36B
34B
112T
161A
56A
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94B
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50T
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18
16
10
12
14
132

FIG. 4