(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 April 2008 (24.04.2008)

PCT

(10) International Publication Number
WO 2008/047245 A2

(51) International Patent Classification: Not classified

(21) International Application Number: PCT/IB2007/004201

(22) International Filing Date: 19 October 2007 (19.10.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/862,214 20 October 2006 (20.10.2006) US

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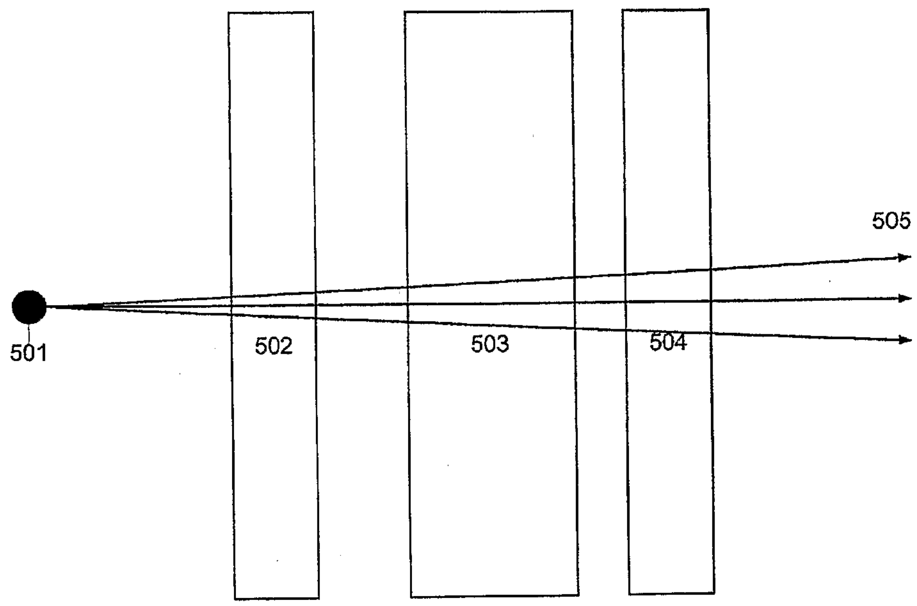
(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

(54) Title: OPTICAL DEVICES BASED ON INTERNAL CONICAL DIFFRACTION



(57) Abstract: Optical devices based on internal conical refraction for developing new set-ups, methods and applications based on the specific properties of internal conical diffraction. The devices include several set-ups, methods and applications consisting of biaxial crystal(s) - one or more polarization elements and optical elements. The biaxial crystal is an optical crystal which may belong to the trigonal, orthorhombic or trigonal crystal classes.

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OPTICAL DEVICES BASED ON INTERNAL CONICAL DIFFRACTION

FIELD OF THE INVENTION

The present invention relates generally to optical devices and methods using such devices, and more specifically it relates to optical devices based on internal conical refraction and methods using such devices in imaging.

DESCRIPTION OF THE BACKGROUND

Optical devices are used in numerous scientific, technological and industrial activities and in countless applications. For all these optical devices, only a very small number of basic concepts exist. The underlying physical mechanisms used as the foundation of these concepts resort to an even smaller number of generic physical mechanisms. A characteristics of most existing optical devices is that they are based either on the linear properties of geometrical optics, polarization or crystal optics or on the non-linear optical properties, due to material interaction. Only a few optical devices make use of the properties of singular optics.

SUMMARY OF THE INVENTION

In view of the disadvantages and limits inherent in the known types of optical devices now present in the prior systems, certain embodiments of the present invention provide new optical devices based on internal conical refraction construction wherein the same can be utilized for improving existing methods and applications and/or developing new optical systems, set-ups, methods and applications based on the specific properties of internal conical diffraction.

In these respects, the optical devices based on internal conical refraction according to certain embodiments of the present invention substantially depart from the conventional concepts and designs and in so doing provides an apparatus primarily developed for the purpose of developing new optical devices based on the specific properties of internal conical diffraction.

To attain this, certain embodiments of the present invention generally comprise biaxial crystals, and one or more polarization elements and optical elements. The biaxial crystal is an optical crystal which may, for example, belong to the trigonal, orthorhombic or monoclinic crystal classes. Suitable biaxial crystals include, for example, KTP, KTA, LBO, MDT, YCOB, $LiInS_2$, and LiInSe2 or organic biaxial crystals as POM or NPP. The polarization elements may be any optical elements able to modify or tailor the polarization of an incoming or outgoing beam. The optical elements may be any optical elements able to modify or tailor the spatial or temporal light distribution of an incoming or outgoing beam.

Once aspect of the present invention is to provide optical devices based on internal conical refraction that will overcome the shortcomings of the conventional devices and provide new optical function using specificities of the behavior of light in internal conical diffraction set-ups.

Embodiments of this invention include both Conical Vortex Imaging (CVI), and Polarization Conical Imaging (PCI). CVI is a technique in which the coherent, or partially coherent, incoming light is passing through a vortex conical diffraction set-up. CVI provides contrast enhancement, optical field derivation, phase object imaging, sub-Rayleigh resolution and frequency doubling. PCI - Polarization Conical Imaging works in coherent, partially coherent or fully incoherent light. PCI is a technique in which the coherent or incoherent, incoming light is passing through a vortex conical diffraction set-up and a linear polarization beamsplitter. PCI provides contrast enhancement, one-dimensional optical derivation, phase object imaging and sub-Rayleigh resolution.

Both CVI and PCI provide an Optical Superresolution Technique (OST). Both CVI and PCI provide a method to optically modify an incoming light distribution, originating from an object and to modify the incoming light distribution to create an outcoming light distribution. The subsequent light distribution when recorded on a light detector and processed numerically provides additional information or additional precision for given information, on the object.

An additional embodiment may provide for overlay metrology, i.e. retrieving the position of a fiducial mark on an object, in order to measure accurately the position of the fiducial mark. An additional embodiment may provide for the detection, measurement or qualification of small particles in a scene or, small marks or defects on a wafer or object. An additional embodiment may provide for an optical storage and to the ability to recognize the presence and/or the position of pits or lands on a disk, with higher resolution.

Another aspect is to provide a classical Poggendorff optical set-up, and to build additional functionalities and methods based on this set-up. Another aspect is to provide an optical set-up, referred to as the vortex conical diffraction set-up, and to build additional functionalities and methods based on this set-up. Another aspect is to provide a new optical set-up, referred to as the radial polarization conical diffraction set-up, and to build new functionalities and methods based on this set up. Another aspect is to provide an optical set-up, referred to as the reconstruction conical diffraction set-up, and to build new functionalities and methods based on this set up.

Another aspect is to provide new optical set-ups, methods, devices and applications to homogenize a light distribution. Another aspect is to provide a set-up for creating chromatic and achromatic optical vortices and doughnut shaped beams and arrays of them. Another aspect is to provide achromatic optical devices and optical applications based on internal conical refraction. Another embodiment is to provide a new set-up to measure accurately, in two dimensions, an angle. Another embodiment is to provide a coding/decoding scheme to process a light distribution.

Another aspect of this invention is to provide solutions for optical storage based on optical devices based on conical diffraction.

According to one embodiment of the invention there is provided an optical device. The optical device comprises: a circular polarizer arranged to provide a first circular polarization; a biaxial crystal disposed after the circular polarizer; and a circular analyzer disposed after the biaxial crystal, the circular analyzer arranged to provide a second circular polarization of an opposite handedness to the first polarization, wherein a geometrical axis traverses through the circular polarizer, the biaxial crystal and the circular analyzer, wherein an optic axis of the biaxial crystal is along the geometrical axis. The optical device may be part of a system where the optical system comprises: a projection lens arranged to receive light from an object to be viewed; an imaging lens arranged to receive light from the projection lens; an optical detector arranged to receive light imaged by the imaging lens; and the optical device arranged between the imaging lens and the optical detector.

According to another embodiment of the invention there is provided an optical device. The optical device comprises: a biaxial crystal; and a polarizing beamsplitter disposed after the biaxial crystal, wherein a geometrical axis traverses the biaxial crystal and the beamsplitter, wherein an optic axis of the biaxial crystal is along the geometrical axis.

The optical device may be part of a system where the optical system comprises:a projection lens arranged to receive light from an object to be viewed; an imaging lens arranged to receive light from the projection lens; two optical detectors, one for each channel of the beamsplitter, arranged to receive light imaged by the imaging lens; and the optical device arranged between the imaging lens and the optical detector.

According to another embodiment of the invention there is provided an optical device. The optical device comprises: a first polarization element arranged to provide a first polarization; a biaxial crystal disposed after the first polarization element; and a second polarization element disposed after the biaxial crystal, the second polarization element arranged to provide a second polarization, wherein a geometrical axis traverses through the first polarization element, the biaxial crystal and the second polarization element, wherein an optic axis of the biaxial crystal is along the geometrical axis.

According to another embodiment of the invention there is provided an optical system. The optical system comprises: an imaging module arranged to provide light to a spot on an optical disk, and to direct light reflected from the spot; a circular polarizer arranged to receive light reflected from the spot and directed to the circular polarizer; a biaxial crystal disposed after the circular polarizer; a circular analyzer disposed after the biaxial crystal, the circular analyzer arranged to provide a circular polarization of an opposite handedness to that provided by the circular polarizer; and a light detector arranged after the circular analyzer to detect the light received from the circular analyzer, wherein a geometrical axis traverses through the circular polarizer, the biaxial crystal and the circular analyzer, wherein an optic axis of the biaxial crystal is along the geometrical axis. The imaging module may comprise: a light source which provides light; a beam splitter arranged to receive light from the light source; and focusing optics arranged to focus light from the beam splitter to the spot and to receive light reflected from the spot and direct the light received from the spot to the beam splitter.

According to another embodiment of the invention there is provided an optical system. The optical system comprises: an imaging module arranged to provide light to a spot on an optical disk, and to direct light reflected from the spot; a circular polarizing beamsplitter arranged to receive light reflected from the spot and directed to the circular polarizer; a biaxial crystal disposed after the circular polarizer; a circular analyzer disposed after the biaxial crystal, the circular analyzer arranged to provide a circular polarization of an opposite handedness to that provided by the circular polarizing beamsplitter; and a light detector arranged after the circular analyzer to detect the light received from the circular analyzer, wherein a geometrical axis traverses through the circular polarizing beamsplitter, the biaxial crystal and the circular analyzer, wherein an optic axis of the biaxial crystal is along the geometrical axis, wherein the light detector comprises two separate detector modules used concurrently.

According to another embodiment of the invention there is provided a method. The method comprises: providing a biaxial crystal; inputting partially coherent light with an input light circular polarization from an unknown object through the biaxial crystal; providing a circular analyzer after the biaxial crystal, the circular analyzer arranged to provide a second circular polarization of an opposite handedness to the handedness of the input light circular polarization, wherein a geometrical axis traverses through the biaxial crystal and the circular analyzer, wherein an optic axis of the biaxial crystal is along the geometrical axis, wherein the initial light distribution has been imaged by an optical system onto a detector, wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal; detecting the distribution of intensity of the light in a plane after the circular analyzer with the detector, wherein the plane is perpendicular to the geometrical axis; imaging features of the unknown object from the detected distribution of intensity; and outputting the imaged features of the unknown object.

According to this embodiment the method may further comprise recording the imaged features of the unknown object.

According to this embodiment the detected distribution of intensity of the light is proportional to the derivative of the initial light distribution.

According to this embodiment the step of detecting the distribution of intentsity comprises: providing a second biaxial crystal after the circular analyzer along the geometrical axis; providing a rotator after the second biaxial crystal along the geometrical axis; providing a third biaxial crystal after the rotator along the geometrical axis; and detecting the distribution of the intensity of light in plane after the third biaxial crystal with the detector.

According to another embodiment of the invention there is provided a method. The method comprises: providing a circular polarizer arranged to provide a first circular polarization on incident light; providing a biaxial crystal after the circular polarizer; inputting unpolarized, partially coherent light from an unknown object through the circular polarizer and the biaxial crystal; providing a circular analyzer after the biaxial crystal, the circular analyzer arranged to provide a second circular polarization of an opposite handedness to the first polarization, wherein a geometrical axis traverses through the circular polarizer, the biaxial crystal and the circular analyzer, wherein an optic axis of the biaxial crystal is along the geometrical axis, wherein the unpolarized, partially coherent light has been imaged on the circular polarizer, wherein the initial light distribution has been imaged by an optical system onto a detector, wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal; detecting the distribution of intensity of the light in a plane after the circular analyzer with the detector; wherein the plane is perpendicular to the geometrical axis; imaging features of the unknown object from the detected distribution of intensity; and outputting the imaged features of the unknown object.

According to this embodiment the method may further comprise: recording the imaged features of the unknown object.

According to this embodiment the detected distribution of intensity of the light may be proportional to the derivative of the initial light distribution.

According to this embodiment the incident light may be provided from an assembly of points, wherein the imaging comprises projecting the intensity of light in a volume after the circular analyzer, wherein the volume is perpendicular to the geometrical axis, and the method, further comprising: using the intensity of the light to trap particles using optical trapping concepts.

According to this embodiment the incident light may comprise a plurality of wavelengths is provided from an assembly of points, wherein the imaging comprises projecting the intensity of light in a volume after the circular analyzer, wherein the volume is perpendicular to the geometrical axis, the method, further comprising: using the intensity of the light to trap particles using optical trapping concepts.

According to this embodiment the input unpolarized, partially coherent light may have a direction of propagation at an angle with respect to the geometrical axis, and the method further comprising: calculating the angle from the detected the distribution of intensity of the light.

According to this embodiment the unknown object may be a phase object.

According to this embodiment wherein the unknown object comprises pits and lands on the surface of an optical disk, the method may further comprise: reading information stored in the pits and lands.

According to this embodiment the step of detecting the distribution of intentsity may comprise: providing a second biaxial crystal after the circular analyzer along the geometrical axis; providing a rotator after the second biaxial crystal along the geometrical axis; providing a third biaxial crystal after the rotator along the geometrical axis; and detecting the distribution of the intensity of light in plane after the third biaxial crystal with the detector.

According to another embodiment of the invention there is provided a method. The method comprising: providing a first polarizing beamsplitter; providing a first quarter wave plate after the first polarizing beamsplitter; providing a biaxial crystal after the first quarter wave plate; providing a second quarter wave plate after the biaxial crystal; providing a second polarizing beamsplitter after the second quarter wave plate, wherein a geometrical axis traverses through the first quarter wave plate, the biaxial crystal and the second quarter waveplate, wherein an optic axis of the biaxial crystal is along the geometrical axis, directing light from a point through the first polarizing beamsplitter, splitting the light into two parallel beams at the first beamsplitter, wherein the two parallel beams traverse the first quarter wave plate, the biaxial crystal, the second quarter wave plate and the second polarizing beamsplitter, combining vortex waves from the two split parallel beams at the second beamsplitter into one beam propagating in a first direction; adding if necessary a wave plate or rotator element to transform azimuthal to radial polarization or vice versa, and combining fundamental waves from the two split parallel beams into another beam propagating in a second direction perpendicular to the first direction that the combined vortex waves are propagating, and using the light coming from the combined vortex waves as an azimuthal or radial polarized illumination source for lasers applications as lithography illumination and/or high power lasers for cutting, drilling and machining or for optical storage applications.

According to this embodiment the method may further comprise: performing photolithography with the light from the combined vortex waves to fabricate a device structure on a semiconductor wafer.

According to this embodiment the method may further comprisemachining materials with the light from the combined vortex waves.

According to this embodiment the method may further comprise writing information to an optical storage disk with the light from the combined vortex waves.

According to another embodiment of the invention there is provided a method. The method comprising: providing a biaxial crystal; inputting light either unpolarized or circularly polarized from an unknown object through the biaxial crystal; providing a linear polarization beamsplitter after the biaxial crystal, wherein a geometrical axis traverses through the biaxial crystal and is split in two conjugate axes after the polarizing beamsplitter, wherein the optic axis of the biaxial crystal is along the geometrical axis, wherein the initial light distribution has been imaged by an optical system onto a detector, wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal; detecting the distribution of intensity of the light in both optical channels emerging from the polarizing beamsplitter in planes perpendicular to the two geometrical axes created by the beamsplitter on the detector; imaging features of the unknown object from mathematical combinations of the detected distribution intensity; and outputting the imaged features of the unknown object.

According to this embodiment the method the detector may comprise two regions, wherein the light emerging from one of the optical channels is incident on one of the regions of the detector and the light emerging from the other optical channel is incident on the other region of the detector.

According to this embodiment the method the detector may comprise two detectors, wherein the light emerging from each optical channel is incident on each detector.

According to this embodiment the method may comprise recording the output, imaged features of the unknown object.

According to this embodiment the method the the unknown object may be a measurement mark, the method further comprising: calculating the position of the measurement mark from the mathematical calculations of the detected distribution of intensity.

According to this embodiment the method the unknown object maycomprise pits and lands on the surface of an optical disk, the method further comprising: reading information stored in the pits and lands.

According to another embodiment of the invention there is provided a method. The method comprising: providing a biaxial crystal; inputting light either unpolarized or circularly polarized from an unknown object through the biaxial crystal; providing a linear polarization beamsplitter after the biaxial crystal, wherein a geometrical axis traverses through the biaxial crystal and is split in two conjugate axes after the polarizing beam splitter, wherein the optic axis of the biaxial crystal is along the geometrical axis, wherein the initial light distribution has been imaged by an optical system onto a detector, wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal; detecting the distribution of intensity of the light in both optical channels emerging from the polarizing beamsplitter in planes perpendicular to the two geometrical axes created by the beamsplitter on the detector; imaging the features of the unknown object; and outputting the features of the unknown object.

According to this embodiment the method the detector may comprise two regions, wherein the light emerging from one of the optical channels is incident on one of the regions of the detector and the light emerging from the other optical channel is incident on the other region of the detector.

According to this embodiment the method the detector may comprise two detectors, wherein the light emerging from each optical channel is incident on each detector.

According to this embodiment the method may further comprise recording the output, imaged features of the unknown object.

According to this embodiment the method the the detected distribution of light may be proportional to the derivative in one axis of the intial light distribution.

According to this embodiment the method the unknown object comprises pits and lands on the surface of an optical disk, the method further comprising: reading information stored in the pits and lands.

According to this embodiment the method the the step of detecting the distribution of intentsity may comprise: providing a second biaxial crystal after the circular analyzer along the geometrical axis; providing a rotator after the second biaxial crystal along the geometrical axis; providing a third biaxial crystal after the rotator along the geometrical axis; and detecting the distribution of the intensity of light in plane after the third biaxial crystal with the detector.

According to another embodiment of the invention there is provided a method. The method comprises: providing a biaxial crystal; inputting light either unpolarized or circularly polarized from an unknown object through the biaxial crystal; providing a linear polarizer and a controllable rotator after the biaxial crystal, wherein a geometrical axis traverses through the biaxial crystal, the polarizer and the controllable rotator wherein the optic axis of the biaxial crystal is along the geometrical axis, wherein the initial light distribution has been imaged by an optical system onto a detector, wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal; detecting the distribution of intensity of the light in two or more polarization states by actuating the controllable rotator in a plane perpendicular to the geometrical axis; imaging features of the unknown object from mathematical combinations of the detected distribution of intensity; and outputting the imaged features of the unknown object.

According to this embodiment the method may further comprise: recording the imaged features of the unknown object.

According to this embodiment the method the the detected distribution of light may be proportional to the derivative in one axis of the initial light distribution.
According to this embodiment the method the unknown object comprises pits and lands on the surface of an optical disk, the method further comprising: reading information stored in the pits and lands.

Other objects and advantages of the present invention will become obvious to the reader and it is intended that these objects and advantages are within the scope of the present invention.

To the accomplishment of the above and related objects, this invention may be embodied in the form illustrated in the accompanying drawings, attention being called to the fact, however, that the drawings are illustrative only, and that changes may be made in the specific construction illustrated.

Various other objects, features and attendant advantages of the present invention will become fully appreciated as the same becomes better understood when considered in conjunction with the accompanying drawings, in which like reference characters designate the same or similar parts throughout the several views, and wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram describing biaxial crystals definitions, where (a) describes optical frame and optical axes; (b) describes additional axes definitions.

FIG. 2 illustrates internal conical diffraction cone and cone centered geometry for a biaxial crystal.

FIG. 3 illustrates graphs showing the amplitude and intensity of the fundamental and vortex waves for Poggendorff rings of an imaged point in (a), (b) and (c).

FIG. 4 is a graph illustrating the Intensity transmittance for an imaged point in a conical vortex set-up as function of the beam parameter.

FIG. 5 is a schematic illustrating an optical device according to a CVI device which is a conical vortex set-up with a circular polarizer and a biaxial crystal cut along one of the optical axes according to an embodiment of the invention.

FIG. 6 is a schematic illustrating an optical device according to a PCI device which is a radially polarized doughnut light distribution set-up according to an embodiment of the invention.

FIG. 7 is a schematic illustrating an optical device according to a reconstruction set-up.

FIG. 8 depicts in view (a) the three-dimensional representation of the intensity from two points in a plane perpendicular to the geometrical axis, in view (b) a grey-scale representation of the intensity from two points in the plane and in view (c) isointensity patterns for one point, two points separated by the diffraction limit (DL) and two points separated by 0.75 of the diffraction limit (0.75 DL).

FIG. 9 depicts the two point's resolution in CVI.

FIG. 10 illustrates an optical system according to an embodiment of the invention which incorporates an optical device such as that of FIG. 5 or FIG. 6, and which may be used for optical metrology applications.

FIG. 11 illustrates a PCI set-up according to an embodiment of the invention.

FIG. 12 (a), (b), (c) illustrates simulations of optical derivation with PCI.

FIG. 13 (a), (b), (c) illustrates simulations of optical derivation with CVI

FIG. 14 (a)-(f) illustrates an improvement in resolution for PCI.

FIG. 15 illustrates an optical system according to an embodiment of the invention for use as a optical storage system.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The concepts of the present invention have several applications, which include for examples, as follows. The optical devices described in the following are able to perform several different functionalities, classified in this document as imaging, optical storage, light and illumination shaping, achromatic optical vortices, polarization doughnuts, angular measurement and coding and reconstruction.

Imaging: Optical resolution describes the ability of a system to distinguish, detect, and/or record physical details by electromagnetic means. Several techniques, named superresolution techniques, have been developed to exceed the classical resolution limits of the optical resolution of an imaging system. These techniques make a better use of the existing optical information and provide OST. OST refers to techniques in which an additional optical sub-assembly is used to increase the optical resolution of the final intensity image. The essence of OST is based on a modification of the characteristics of the light transfer function through different optical means. Three main functions are performed by imaging systems: measurement and metrology, detection and counting, direct imaging of an optical object. A measurement system is aimed to detect the exact position, at a given time, of a known feature. The feature may be a star in Astronomy, a fluorescent point in Biology or an AIM structure in Overlay Metrology, for example. A detection (counting) system is directed to detecting the presence of a particle. The particle may be a star in Astronomy, a defect in machine vision or a fluorescent point in Biology. A direct imaging system is aimed to transfer to an observer a faithful representation of a general unknown optical object. Several metrics to quantify optical resolution exist besides the omnipresent Rayleigh criterion; they depend on the task performed by the imaging system. The different functions are carried by processing the resulting image using dedicated algorithmic. OST techniques, as the ones described below, are able to improve the metrics of the performances of the tasks. They permit either a better precision in metrology, to detect particles or defects not recognized before, or to get a better image of an object under observation.

Optical Storage: One application for such optical devices is optical storage. The actual incoming generation in optical storage is based on the integration of blue diode laser technology as a replacement to red diode lasers. With the availability of the first systems to the general public, researchers and industry leaders are beginning their search for the concepts of the next generation of optical storage. Additionally, the current generation had evolved in two competing, incompatible standards, HD-DVD and Blu Ray. To permit to the user to read both standards on the same reader necessitate a very complex and expensive optical system due to the inherent complexity of each one of the standards. The additional resolution of CVI and PCI described below permit the building of an OPU – Optical Processing Unit – with a lower Numerical Aperture and a much lower complexity. This allows the realization of a hybrid OPU, able to read both HD-DVD and Blu Ray at a reasonable cost.

Light and Illumination Shaping: Several functionalities are necessary in illumination, especially when transforming raw laser light to high quality illumination. The light has to be homogenized and hot spots have to be removed. In some cases, a specific shape, as an annular pattern has to be created. Additionally the polarization and coherence states of the light have to be controlled.

Polarimeters: Many polarimeters and ellipsometers have been described in the literature. Some of them necessitate the acquisition of a time sequence of several frames, limiting their use for fast varying phenomena. Others are based on polarization selective elements, but the retrieval of the full polarization state for elliptically polarized light is cumbersome. Internal conical refraction may provide a simple set-up for a full polarimeter able to acquire either pulsed light or star images.

Achromatic Optical Vortices: The applications of monochromatic and achromatic vortices include but are not limited to Astronomy and optical trapping.

Polarized doughnuts:. The generation of a radially polarized doughnut light distribution, using different set-ups, has been described in the context of small spot generation and for lithographic illumination.

Angular Measurement: The capacity to assess, in the optical domain, the angle of the axis of a centrosymmetric light distribution opens the way to several practical devices. Today the main solution used is Fabry-Perot based devices, but these devices suffer from a strong wavelength and temperature dependence.

Coding and reconstruction: The ability to code the light as a singular light distribution and to reconstruct in a clear analogy to Fourier Transform processing allows several optical processing tasks to be performed on an incoming light distribution.

Turning now descriptively to the drawings, in which similar reference characters denote similar elements throughout the several views, the attached figures illustrate optical devices based on internal conical refraction, which comprises biaxial crystal(s), one or more polarization elements and optical elements.

The biaxial crystal is an optical crystal which may belong to the trigonal, orthorhombic or trigonal crystal classes.

The polarization elements may be any optical elements able to modify the polarization of an incoming beam. The polarization elements may include polarizing beamsplitters, polarizers, waveplates, rotators, or any other polarization element known to the skilled professional.

The optical elements may be any optical elements able to modify the spatial or temporal light distribution of an incoming beam. The optical elements may include lens, mirrors, prisms, HOE - Holographic Optical Elements - or grating able to fulfill the spatial and angular shaping of the input light at the input plane of the conical set-up or the shaping of the output light from the output plane of the conical diffraction set-up.

FIG. 1(a) and 1(b) depict biaxial crystals. FIG. 1(a) defines the optical frame and FIG. 1(b) defines the optical axes of a biaxial crystal. The *optical frame* represents the principal axes of the index ellipsoid, x_1, x_2 and x_3, of the biaxial crystal. The three principal dielectric constants ε_i and three refractive indices n_i, satisfy:

$$\varepsilon_1 = n_1^2 < \varepsilon_2 = n_2^2 < \varepsilon_3 = n_3^2, \qquad (1)$$

where n_2 is the median index. It is used along the following developments as a measure of the equivalent isotropic diffraction of the crystal. Additionally we define, θ_0 the angle of the optical axis relative to the z axis, A as the semi-angle of the cone, R_0 as the radius of the emerging rings, l as the crystal length and w as the width of incident beam. We define also the normalized width p as the ratio w/R_0. k represents the wavevector in the material, $(2\pi/n_2 \lambda)$.

We define, in FIG. 1(b), a Cartesian reference frame with its z-axis parallel to the optical axis, its y-axis parallel to the x_2 optical frame axis, and its x-axis perpendicular to both. We define additionally in the crystal, three axes, the T-axis, the A-axis and the B-axis; outside the crystal we define the A'-axis.

FIG. 2 illustrates the internal conical diffraction cone and cone centered geometry.. The crystal is positioned with its entrance face at z = 0; the geometrical axis of the system, referred as z, is in the direction of one of the optical axis, as described previously. We will refer in short to this set-up as a conical diffraction set-up. The coordinates used are transverse cone-centered coordinates [x, y, z] = [R,z], ad-hoc coordinates defined to simplify the solution of the equations of conical diffraction. The reference axis is the A-axis – and not the optical axis – inside the crystal. Outside the crystal the reference axis is the A'-axis.

FIG. 3(a-c) show simulations of the amplitude and intensity of the fundamental and vortex waves for Poggendorff rings of an imaged point. FIG. 3(a) presents the profile of the amplitude. FIG. 3(b) illustrates the intensity, for B_0, the fundamental wave function or B_1, the vortex wave function; both functions have been defined by Berry. In FIG. 3(c),a two-dimensional distribution of the intensity of B_0 or B_1 is depicted.

FIG. 4 represents simulations of the intensity transmittance for an imaged point in a conical vortex set-up as function of the beam parameter, w; the beam parameter is normalized to p_v, the vortex spot dimension of the set-up. FIG. 4 represents, for small p_0, the amplitude and intensity of the fundamental and vortex waves for an imaged point. Most of the energy is transferred to the vortex wave. For an imaged point in the image plane, for p_V, 80% of the incident energy is present in the vortex wave. For a Gaussian beam in the image plane, - for p_V, 64% of the incident energy is present in the vortex wave.

FIG. 5 illustrates a conical vortex set-up. In an embodiment, the incoming light 501 is circularly polarized, either naturally or by a suitable polarizer, such as by the illustrated circular polarizer 502. It comprises, at least, a biaxial crystal 503 cut along one of the optical axes and a circular analyzer 504 with handedness orthogonal to the handedness of the incoming light distribution. It may comprise additional polarization and optical elements able to tailor the incoming and outgoing light distribution in a suitable way. The conical vortex set-up permits only the vortex wave 505 created by an incoming wave. It includes an input circular polarizer – if the light is not naturally polarized, a biaxial crystal cut along one of the optical axes and a circular analyzer with inverse handedness to the input polarizer. The spot dimension for which the energy transmission is maximal, w_v, is the natural spot dimension of the set-up.

FIG. 6 depicts a radially polarized doughnut vortex set-up to create doughnut shaped light distribution. A set-up, bearing many similarities to the set-up used for an optical isolator is presented in Fig 6. The complete set-up maybe integrated as a monolithic compound module. A light source, not represented in the figure, creates a point with a given spot size. A first polarization separator separates the light in two beams. The two beams are spatially separated, with orthogonal linear polarizations. The separator 602 may use either a crystalline design – as a Wollaston or Rochon prism, or a polarization beamsplitters, based on thin film technologies as presented in the figure. A quarter wave plate 603 transforms the two beams with orthogonal linear polarizations into two beams with circular polarization with inverse handedness. A biaxial crystal 604 creates fundamental and vortex waves from each one of the two beams. A second quarter wave plate 605 transforms back the two couples of beams from circular polarizations to orthogonal polarizations. A second polarization separator 606, used as a combiner, combines separately the two vortex waves and the two fundamental waves into two spatially separated waves. Fine adjustment of the relative optical path length can be provided by a controlled translation of one of the polarization separators. The combination of the vortex wave 607 created by the right handed circular polarization with the vortex wave 607 created by the left handed circular polarization creates a doughnut shaped, radially polarized wave. There is also the resulting fundamental wave 608.

The generation of a radially polarized doughnut light distribution, using different set-ups, has been described in the context of small spot generation and for lithographic illumination. The Poggendorff rings have already a radial varying polarization; however, this polarization dependence is of order 1/2, i.e. the polarization of the light at two points opposite, geometrically, one to the other are orthogonal. Most of the systems described in the literature require a polarization variation of order 1, i.e., the polarization at two opposite points will be parallel, with opposite phase.

FIG. 7 depicts a reconstruction set-up in one configuration, exact reconstruction, there is no prerequisite condition on the incoming light 701. In a second configuration, approximate reconstruction, the incoming light is circularly polarized, either naturally or by a suitable polarizer. The reconstruction set-up may comprise additional polarization and optical elements able to tailor the incoming and outgoing light distribution in a suitable way.

FIG. 8 depicts in view (a) the three-dimensional representation of the intensity from two points in a plane perpendicular to the geometrical axis, in view (b) a grey-scale representation of the intensity from two points in the plane and in view (c) isointensity patterns for one point, two points separated by the diffraction limit (DL) and two points separated by 0.75 of the diffraction limit (0.75 DL).

FIG. 9 presents the basics of two point's resolution in CVI. The pattern created by CVI, for two coherent points, separated by the diffraction limit, differs much from the two point coherent pattern. It is closer to the pattern of two points with opposite phase and provides a new direction for many applications limited by the Rayleigh criterion.

The range of p_0 in the vicinity of 1 is also of great interest; it enables a simple solution for the creation of optical vortices, as described by Volkh for a Gaussian beam. For an imaged point at the focal plane, for circular polarization the amplitude of the vortex wave function, as defined by Berry, is given by:

$$B_1(\rho,\rho_0,0)=\frac{1}{kw^2}\int_0^1 dQ\,\sqrt{Q}\;\sin(\rho_0 Q)\,J_1(\rho Q) \tag{2}$$

It can be approximated by:

$$B_1(\rho,\rho_0,0)=\frac{\rho_0}{kw^2}\int_0^1 dQ\,Q^{3/2}J_1(\rho Q) \tag{3}$$

Additionally, The Amplitude Transfer Function – ATF – represented by $\kappa(P, \theta_P)$, for right circularly polarized light, relates the input and output Fourier Transforms of the light distribution, through the relationship:

$$a_M(P,\theta_P)=a(P,\theta_P)\,\kappa(P,\theta_P) \tag{4}$$

It is given by:

$$\kappa(P,\theta_P)=\cos(kR_0P)\,\mathbf{d}_\mathbf{R}-i\exp(-i\theta_P)\sin(kR_0P)\,\mathbf{d}_\mathbf{L} \tag{5}$$

In this equations P and θ_P are the radial representation of the two-dimensional wavevectors $\mathbf{d}_\mathbf{R}$ and $\mathbf{d}_\mathbf{L}$ are the unit vectors of right and left circular polarizations, respectively. In the previous equation the first term, with the same handedness as the incoming field and a cosine dependence is the fundamental field and the second term, with inverse handedness, with an azimuthal dependant phase term and a sine dependence is the vortex term. For small R_0 the previous equation simplify to:

$$\kappa(P,\theta_P)=\mathbf{d}_\mathbf{R}-i\,kR_0P\exp(-i\theta_P)\,\mathbf{d}_\mathbf{L} \tag{6}$$

With the fundamental field being identical to the incoming one and the vortex field containing a "P" component in the wavevector domain. The wavevector domain being a Fourier Transform plane, the "P" component in the Fourier Transform domain is equivalent to a derivative in the direct domain.

The crystal splits the circularly polarized optical field in two fields, the fundamental and vortex fields. The two fields are carried on two orthogonal circular polarization modes. The first optical field, the fundamental field, is an apodized version of the incoming field. Its polarization handedness is identical to that of the incoming field. The fundamental wave looks much like the incoming field.

The vortex field differs from the incoming optical field, in three different ways:

- **High frequency filter:**

The optical information is carried by the high frequencies of the optical field. In most cases, the low frequencies components contains only slowly varying background, but may include a large amount of energy, which in turn, creates photon noise and reduces the contrast of the intensity image.

- **Orthogonal polarization and azimuthal polarizer:**

  The transfer of a chosen part of the field to the orthogonal polarization can be used in two different ways, which delineate between the CVI and the PCI, described below.

  - In the phase mode, the fundamental field is absorbed by a polarizer and the vortex field is used. It removes the low frequency and the DC components of the incoming field, which had been transmitted to the fundamental field. The information consists of a phase and a minimal spatial coherence is necessary to express it in the final intensity image.
  - In the polarization mode, the fundamental field, in some cases attenuated to remove useless energy, is interfering with the vortex field. Because they are derived from the same incoming field, they interfere even in fully incoherent light. The information is carried as polarization information and can be detected by recording separately the two orthogonal linear polarizations and subtracting numerically the two images.

- **Vortex phase:**

  The vortex phase term inverts the phase between pairs of terms, in the frequency domain, with the same k vector and opposite phases. It transforms amplitude to phase modulation (and vice versa). Its action is even more noticeable for line patterns, creating *frequency doubling* (described below), reminiscent of phase masks – and their resolution enhancement – in Lithography.

These three effects can be used, separately or in combination, to improve contrast and resolution of optical information carried by the incoming optical field. Several different set-ups can be built depending on the addition of simple optical and polarization components. These concepts provide the way for numerous different devices, optimized for different applications, by modifying polarization, phase and geometrical optics components of the set-up.

The conical diffraction element modifies the incoming field in a very elaborate way; it modifies at the same time the amplitude, the phase and the polarization of the incoming field.

In this respect, the conical diffraction element is the most potent optical element available to an optical designer.

Additionally, all these capabilities are obtained using an optical element which is amazingly simple to integrate in an optical system. From a practical point of view the conical diffraction element itself may be a simple piece of commercial, off the shelf, biaxial optical crystal. It does not necessitate exotic specifications. Its homogeneity requirements are inherently less stringent than those of non-linear optics; its polishing and orientation tolerances need only to adhere to "best practice requirements" of standard optical manufacturing.

As explained above, the fundamental field can be absorbed and only the vortex field is transmitted; which occurs for a CVI set up, or the fundamental field can be kept and brought to interfere with the vortex field; which occurs for a PCI set up.

CVI provides a new OST for coherent or partially coherent imaging. CVI provides contrast enhancement, optical field derivation, phase object imaging, sub-Rayleigh resolution and frequency doubling.

PCI provides a new OST able to work in coherent, partially coherent or fully incoherent light. PCI provides contrast enhancement, one-dimensional optical derivation, phase object imaging and sub-Rayleigh resolution. Several additional features of PCI are described below.

In CVI the fundamental field is absorbed and the outgoing field contains only the vortex field. A CVI setup may include, for example, an input circular polarizer, a biaxial crystal and a polarization analyzer, in order, where the polarization analyzer has handedness orthogonal to the input circular polarizer. One such setup is shown in Figure 5. The biaxial crystal length is adapted to provide, as much as possible, for a given spot size and shape, as much as possible intensity in the vortex field.

Figure 13 illustrates, using simulations, the concept of optical derivation using CVI. The same figure illustrates also contrast enhancement, and the phase object imaging. All three features are direct consequences of the high frequency filtering of the conical diffraction element. In Figure 13, the picture shown in (a) represents an object, where a small phase defect has been added, but cannot be seen in standard imaging. In Figure 13, (b) and (c) are pictures representing the simulations of the fundamental and vortex images, respectively, due to a conical diffraction. In Figure 13, two points are resolved via CVI, below the diffraction limit, due to the phase inversion relative to the centre caused by the vortex term. Because of this, in a region positioned between the projection of the centre of the two points the amplitudes of the light incoming from the two points are inverted and also create a zero crossing. This feature permits resolution of points and small features below the Rayleigh limit.

An additional important feature of CVI is frequency doubling. For a dense array of small phase marks, as used in different arrays of metrology, the frequency of the marks is doubled. This feature is due to the phase term of the vortex field which translates, in a line pattern, to line doubling with the two lines having inverted phases. This feature allows an important improvement of the information content and of the precision of measurement of the position of the mark array.

In PCI the fundamental field is kept, as a reference field, and the outgoing field contains both the fundamental and the vortex fields. A PCI set up may include only a biaxial crystal and a linear polarization beamsplitter. The biaxial crystal length is adapted to balance, as much as possible, for a given spot size and shape, between the fundamental and vortex field.

Unlike other polarization based imaging concepts, an input polarizer is not required for the system for unpolarized light. This surprising feature is a consequence of *Lloyd law*, and will be explained in detail below. For Lloyd law, for an emergent cone from a biaxial crystal, the angle between the planes of polarization of any two rays of the cone is half the angle contained by the planes passing through the rays themselves and its axis.

A PCI set-up for this explanation is shown in Figure 11, which includes a biaxial crystal 1104, polarizing beamsplitter 1106, and light detector 1110. The polarizing beamsplitter 1106 at its output, creates two separated images, with opposite polarizations. The two images will be referred as the positive image 1112 and the negative image 1114. The two images are then added and subtracted one from the other numerically.

Figure 12 in (a), (b) and (c) illustrate, using simulations, the concept of optical derivation using a PCI. In (a) the first picture represents an object, where a small phase defect has been added but cannot be seen in standard imaging. The picture in (b) presents the difference between the positive and negative intensity images obtained using PCI. As in CVI it creates derivative image, however, it differs from CVI by derivating only in one direction in a way reminiscent of the DIC microscope. We present in the image the absolute value of the signal. In (c) the image presents the concept of phase objects separation based on the extended Loyd law as explained bellow. The same figure 12 illustrates also contrast enhancement, and the phase object imaging (for coherent and partially coherent light). All three features are direct consequences of the high frequency filtering of the conical diffraction element. As always, since no good solution exists to present bipolar images in black and white, the solution which is used is the most acceptable, representing the absolute value of the image in (b).

The two points creates, in the region positioned between them, light with orthogonal polarizations. This property permits the discrimination for two point sources, in the area between them, between the light incoming from the sources from the left and right. This physical property creates an additional segregation mechanism, able to differentiate optically in any spatial position between light incoming from different angles. This mechanism translates into additional resolution using a polarization mode imaging, in which the two polarization images are recorded separately. PCI being dependant on polarization variables is able to perform adequately for fully incoherent light.

Figure 14 illustrates an improvement of resolution due to PCI. The standard imaging (a)-(c) shows its normal behavior; the two points are barely separated by the well-known 26% dip at Rayleigh criterion and are not separated at 75% Rayleigh criterion. The PCI (d)-(f) distinguishes clearly between a single point and two points positioned either at Rayleigh distance or even at 75% of DL. While additional processing may be needed, the information is clearly available as shown in Figure 14.

PCI may be applied directly to unpolarized light without the need of an input polarizer. By contrast, in other polarization based optical systems, for unpolarized light, an additional input polarizer is necessary to polarize the incoming light. To avoid losing half of the energy, many systems use an input polarizing beamsplitter, and carry the light in two separate channels adding some complexity to the system.

Lloyd law avoids the inherent loss of half the energy inherent in all polarization optics systems, without the need to separate in two separate channels. It may be considered that the biaxial crystal is its own polarizer even if its azimuthal angular variation makes it quite special.

The present inventors have determined, from both theory and simulations that Lloyd law applies only to amplitude objects. For phase objects the image of the right and left circularly polarized light differs. This new feature, which we call *Lloyd extended law*, exists to our knowledge only in PCI, and opens an interesting way to differentiate phase and amplitude of small objects. A new optical set-up can be realized, able to separate phase objects and defects from amplitude variations show in (c) of Figure 12. The set-up is simply a PCI set-up, separating the two input circular polarizations on two channels.

Three main functions are performed by imaging systems: measurement and metrology, detection and counting, imaging of an optical object.

A measurement system is aimed to detect the exact position, at a given time, of a known feature. The feature may be a star in Astronomy, a fluorescent point in Biology or an AIM structure in Overlay Metrology, for example. A detection (counting) system is aimed to detect the presence of a particle. The particle may be a star in Astronomy, a defect in machine vision or a fluorescent point in Biology, for example. An imaging system is aimed to transfer to an observer a faithful representation of a general unknown optical object.

The parameters describing the performances of a system need to take into account its function and cannot be only of a general nature. A system, improving the visual impression may – or may not – increase the positioning capacity or the accuracy of detection of a particle. Because of this, the Rayleigh criterion cannot be the only metrics.

We define the contrast of a target or of a particle, as the ratio of the difference between the minimal and maximal signals and the dynamic range of the detector, in an optimal alignment. For measurement, the adequate metrics is the *information contents* as defined by Seligson for Metrology. A similar concept, *intrinsic imprecision*, introduced by Lindegren is used in Astrometry. The information content, for a one-dimensional optical feature represented by a function f(x), is defined as:

$$E_0 = \int \left(\frac{df}{dx} \right)^2 dx \qquad (7)$$

It is equal to the variance of the error of the feature position for an optimal algorithm.

A detection system is directed to detect the presence or absence of a particle in a given field. One of the main applications is particle counting and defect inspection. The metrics used is the capacity to detect particles with low contrast and/or low size. It is quantified experimentally by the number of correct hit/miss of a particle/defect, with a given size, shape and contrast using a standard detection algorithm. A system will correctly detect a particle of a given size and contrast if its number of hit/miss is above a predetermined threshold.

For imaging the criterion remains the diffraction limit or extended Rayleigh criterion (DL). However, many optical systems use either acquisition of several images and data merging or powerful algorithmic for post-processing of the intensity data.

Overlay Metrology, in Semiconductor Lithography, refers to systems which purpose is to measure the relative position of two superposed layers and to assess that their position one relative to the other is within a specified tolerance. Several technologies are in use for overlay metrology including scatterometry and SEM.

The workhorse of Overlay Metrology has been the Imaging Overlay Metrology systems. Over the last 15 years, imaging techniques using overlay fiducial marks have met the needs of overlay metrology. As the current 45 nm node drops to 32 nm and below, the future of imaging techniques is being threatened due to the optical diffraction limit.

Typically, imaging overlay metrology systems are comprised of an imaging system imaging overlay fiducial marks positioned on each one of the layers. The main fiducial mark used up to the 65 nm node was the Box in Box or Frame in Frame whether new marks have been introduced for the lower nodes as the AIM marks family.

The main problem with conventional imaging overlay metrology is indeed due to the optical diffraction limit. Because overlay metrology can use wavelengths in the visible, or the near UV, the diffraction limit creates a limit on the motif size available. Although clever algorithmic had been developed to measure the position of the fiducial mark to a fraction of the diffraction limit, reaching the 1 nm precision, these algorithms are less and less robust and less prone to process variability for larger ratio of the required precision to the diffraction limit.

While these devices may be suitable for the nodes above 45 nm and possibly for the 32 nm node, they are not as suitable for enabling Imaging Overlay Metrology to reach the precision level necessary for the 22 nm node or below. Additionally, the new technique of Double patterning creates additional requirements on Overlay Metrology by creating an additional step with higher overlay requirements and using materials, as hard coatings, which reduce greatly the contrast of the overlay mark image.

CVI and PCI provide additional precision which may permit the extension of overlay metrology systems, without major modifications, towards the 22 nm node.

Using CVI or PCI on fiducial marks, instead of standard imaging creates a situation in which the full surface contribute to the signal, and not only the edges; it makes theoretically the system more prone to asymmetry error referred as TIS - Tool Induced Shift – and WIS – Wafer Induced Shift. Additionally, fiducial marks can be of a very small size (as low as actual Moore's nodes), without affecting their information content. By reducing the target size, one of the major error sources of Overlay Metrology, the Placement Pattern Error (PPE) is lowered.

Optical defect inspection, detecting and classifying optically defects is a major requirement in Lithography, as well as in Flat Panel Display, in Machine Vision, in Steel and Paper industries, as well as in any discipline in which surface defects can impair the quality or function of a device or part.
The additional detectivity contained in CVI and PCI can be translated in the ability to detect defects with lower contrast or size and to increase the probability of detection and the classification accuracy of defects.

CVI and PCI have applications to optical storage where the disk is the physical layer in optical storage. The performances of any optical storage system resort to its capacity to separate two pits with minimal length. The minimal pit is, in DVD and HD-DVD, using the EMF coding/decoding scheme, a "3T" mark; in Blu- Ray it is a "2T" mark using the 1.7pp scheme. CVI and PCI will permit reducing the track pitch and the minimum pith length, independently of the technology of realization of the pit or land on the disk substrate.

Additionally, the current generation had evolved in two competing, incompatible standards, HD-DVD and Blu Ray. An hybrid OPU able to read both standards in a single OPU is badly required by the users of optical storage. To permit to the user to read both standards on the same reader necessitates a very complex and expensive optical system due to the inherent complexity of each one of the standards. The Blu Ray had reach the huge Numerical Aperture of 0.85, used only in Lithography and high end Microscopy. The HD-DVD had reach the high but lower Numerical Aperture of 0.65 but unlike Blu Ray kept the original thickness of the optical disk, making the system strongly dependant on coma aberration especially caused by a slight tilt of the disk surface. These two extremes requirements are quite mutually exclusive and a hybrid OPU able to read both standards are almost impossible or at least very difficult to realize.

The additional resolution of CVI and PCI described in this application can be translated either in reading pits and lands closer to one another then in previous technologies creating additional resolution. Additionally it can be used to read existing optical disks with lenses of lower Numerical Aperture and a much lower complexity. This will allow the realization of a hybrid OPU, able to read both HD-DVD and Blu Ray at a reasonable complexity and cost.

In a more evolved version, CVI or PCI allow detecting several close pits at once, increasing both the capacity and speed of an optical storage systems by reading denser marks in groups at higher speed.

Differential Interference Contrast (DIC) microscopy is a powerful visualization tool used to study live biological cells, but its use so far has been limited to qualitative observations. The inherent non-linear relation between the object properties and the image intensity makes quantitative analysis difficult. Additionally the DIC output intensity depends on a directional phase gradient and is a mix of amplitude and phase gradients. The peculiar properties of CVI and PCI, namely the capacity of CVI to create an isotropic derivative and the capacity of PCI to separate phase and amplitude information using the extended Lloyd law open new avenues to phase object imaging, both for qualitative and quantitative measurement especially in Biology.

Figure 10 illustrates an optical system 1000 according to an embodiment of the invention which incorporates an optical device such as that of FIG. 5 or FIG. 6. The system 10 has applications for metrology, for example. The system 1000 includes a projection lens 1016 arranged to receive light from an object to be viewed 1018, such as a wafer, on a substrate 1020. An imaging lens 1014 is arranged to receive light from the projection lens 1016. An optical detector 1010, such as a charge coupled device (CCD) is arranged to receive light imaged by the imaging lens 1014. In the case the system incorporates an optical device such as the PCI system of FIG. 6, the optical detector 1010 may comprise two optical detectors, for of each channel of the beam splitter. The optical detector 1010 may comprise a single CCD detector, wherein two images fall on two different regions of the CCD detector, or two separate CCD detectors. The system also include an optical device 1012, such as that described with respect to Figures 5 or 6 arranged between the imaging lens 1014 and the optical detector 1010, where the optical device 1012 provides improved resolution. The system 10 has applications for metrology, such as for determining the position of a fiducial mark. In this case, the object to be imaged by the system may a fiducial mark, for example, and data retrieved based on the light received by the optical detector 1010 may provide the position of the fiducial mark.

An additional domain in which quantitative measurement of phase objects is required is that of reticles and masks inspection for Lithography. The complexity of masks growing tremendously in the newest nodes create the need to use phase masks and also the need to measure and characterize them quantitatively

The low ρ_0 conical diffraction provides a very simple mechanism to create an array - or a volume - of achromatic optical vortices. It separates the generation process in two independent steps:

o creating an array or volume of point emitters.

o using the conical diffraction, each emitting point being replaced by an optical vortex.

In short, any light distribution consisting of a volume of light points will create a volume of vortices with a one to one correspondence between the point spatial position and the vortex centre.

A proper choice of material permits the realization of achromatic vortices. From a practical point of view the main advantage of a conical diffraction set-up for creating optical vortices, compared to existing set-ups based on holography, is the removal of the coherence requirement. Such a set-up may use high power laser diodes, which can provide tens of Watts, in a miniature package and for a ridiculous cost. Several low cost technologies and devices, developed for example for display applications, may be used for creating sequentially or in parallel, arrays and volume of point sources. Additionally, the vortex wave being orthogonally polarized to the incident beam, much spurious light intensity, as scattering or reflections, will be removed efficiently from the set-up.

The doughnut shaped beam is similar to the vortex, with two distinctions:

o The set-up used is the doughnut beam set-up described in Figure 6 instead of the conical vortex set-up of Figure 5,

o The polarization variable in a doughnut shaped beam is rotating around the azimuthal angle at the same rate as is the phase variable in a vortex wave.

In conical vortex imaging and polarization conical imaging, the light is transformed from a linear optics shape to a singular one. Complimentarily, in the reconstruction process, the singular beam is transformed back into the initial light distribution. This characteristic permits integration of singular optics as part of an optical system, as a reversible intermediate processing step.

The reconstruction set-up is presented in Figure 7; a first biaxial crystal 701 is cut with its geometrical optical axis aligned with one of the optical axis. A second crystal 705, identical to the first one, is placed after the first biaxial crystal 701. A polarization rotator 704, with a rotation angle of $\pi/2$ is inserted between the two crystals. The action of the polarization rotator 704 can also be described as the addition of an additional phase of π radians to one of the circular polarized components. Let describe the case of a right-handed circular input polarization. The ATF – Amplitude Transfer Function, which can be calculated from Berry's equations - of the complete set-up, $\kappa_{REC}(P)$, is given by the multiplication of the ATF of the first crystal, the rotator Jones matrix and the ATF of the second crystal:

$$\kappa_{REC}(P) = \boldsymbol{\kappa}(P, \theta_P, R_0, Z)\begin{pmatrix} \cos\frac{\pi}{2} & \sin\frac{\pi}{2} \\ -\sin\frac{\pi}{2} & \cos\frac{\pi}{2} \end{pmatrix}\boldsymbol{\kappa}(P, \theta_P, R_0, Z) \quad (8)$$

Reorganizing and grouping the different components leads to:

$$\kappa_{REC}(P) = \exp\left(ikZP^2\right) \quad (9)$$

The transfer function consists of a propagation term along a distance corresponding to an isotropic media of index n_2 with thickness equal to the thickness of both crystals.

Two variations of the reconstruction set-up can be used: In the first one, both the fundamental and the vortex waves are kept after the first conical diffraction set-up. This is the case described in the previous equations. The reconstruction does not contain a conjugate image. It performs mathematically a reciprocation of the light wave and because of this is identical to the incoming light distribution. In many cases we will keep only one of the waves, in most cases the vortex wave. The reconstruction contains a conjugate image. The first term is the reconstruction term and has the same handedness as the incoming wave. The third term, the cross term, can be removed using a right-handed circular polarizer. The second term is a conjugate image, as in holography; however, unlike in holography the light of the conjugate image, for each point, is concentrated on a ring with radius $2R_0$ instead of being spread on the full surface.

The conical diffraction, reconstruction, vortex and radial polarizer set-ups can be extended to the case in which the input light distribution is represented as an assembly of sources, in a plane or in a volume. Such a light distribution will create an assembly of diffracted points, each one centered, laterally and longitudinally at the conjugate point of the source. This feature can be applied to Poggendorff rings, to vortices and to radially polarized distributions.

The intensity contains, folded into the azimuthal dependence, all the information on the polarization state of the incoming light. The only ambiguity is in the case whether either j_R or j_L are zero, i.e. in the case of circularly polarized light, in which, as stated before, we cannot distinguish the handedness of the light polarization. The intensity and polarization of the output light distribution is identical for unpolarized light, to the intensity of the two circular polarized modes. It is a corollary of the previous discussion because unpolarized light can be represented as a superposition of left and right circularly polarized light with random phase.

The internal conical diffraction creates a mapping of the polarization into the geometrical domain. For a centrosymmetric beam, the polarization state is unfolded into the azimuthal dependence of the light distribution. The whole information on the polarization state of a polarized light distribution is retrievable from the azimuthal light distribution. Even the unpolarized light may be distinguish from a linear polarized light, even if it cannot be separated from circularly polarized light.

Internal conical refraction may provide a simple set-up for a full polarimeter, as compared to many conventional polarimeters and ellipsometers. Some of the conventional polarimeters and ellipsometers necessitate the acquisition of a time sequence of several frames, limiting their use for fast varying phenomena. Others are based on polarization selective elements, but the retrieval of the full polarization state for elliptically polarized light is cumbersome. Internal conical refraction may provide a simple set-up for a full polarimeter able to acquire either pulsed light or star images.

From an application point of view, for annular illumination, widely used in lithography, microscopy and machine vision, the conical diffraction set-up performs three functionalities at once; it creates an annular pattern, homogenises the light distribution and transforms the unpolarized light into a polarized one, without losses. However, the axis of the polarization direction is rotating by 90 degrees along the azimuthal direction; in most applications it has to be modified by appropriate additional polarization elements.

Azimuthal coherence is a new coherence state created by an incoherent or partially coherent illumination passing through a conical diffraction set-up. It may create new optical functionalities, especially in the domains of Microscopy, Lithography, and Spectroscopy and machine vision. Following the Van Cittert-Zernike theorem, the incoherent light source is represented by the incoherent superposition of the intensities at the detection plane, of a collection of small coherent emitting points, propagated along the optical system. Using the equivalent light distribution concept, each small coherent emitting point is replaced by an equivalent light distribution. This light distribution is coherent and is of a large geometrical extent. It can include points far away one from the other, which propagation regime may differ markedly. Propagating further the light, in some configurations, light emerging from one part of the equivalent light distribution may reach the same spatial position as light emerging from another part of the light distribution. This case is especially meaningful if the light illuminates a grating – or a grating like structure as a mask. In this case, depending upon the choice of proper geometrical parameters, different orders of the grating may interfere coherently, created by light originating from different geometrical position on the equivalent light distribution, even if at the beginning they were created by a small emitting point. The application of azimuthal coherence for illumination allows coherent interference using incoherent light. Azimuthal coherence is a first example of spatially tailored coherence states, which may be especially useful in Lithography.

The conical diffraction set-up is a very efficient angular filter; the angular aperture can be reduced to the order of a few minutes of arc or below. It is a corollary of the small angle limitation of internal conical diffraction. The capacity to assess, in the optical domain, the angle of the axis of a centrosymmetric light distribution opens the way to several practical devices. It is a more robust solution then a Fabry-Perot based device, and does not suffer from the Fabry-Perot strong wavelength and temperature dependence.

As an example, we describe a very simple device in the embodiments, potentially adapted to optical control. Numerous systems in robotics and automation can be reduced to a "six axes" problem, i.e. bringing a rigid object at a predetermined spatial and angular position to perform a *task*. In many applications, it is required to assess that the object is at the right position, spatially and angularly, before performing the task. To measure or assess simultaneously, in real-time, the six parameters representing the spatial and angular variables is quite complex. The solutions used today are based either on the use of several sensors and the merging of the information or on stringent design of the system in order to reduce the number of degrees of freedom.

For example, let an emitter, creating a circularly symmetrical beam; be rigidly attached on the object to control. This emitter is characterized by its position, but also by the geometrical axis of the emitted beam. The receiver includes a conical diffraction set-up. The light distribution is, after passing through the conical diffraction set-up, imaged on a small image detector and analyzed by an adequate algorithm. If the source is exactly aligned with the optical axis of the crystal, the light will experience conical diffraction and create Poggendorff rings. The presence of Poggendorff rings instead of light points, assess that the tilt and yaw of the object are in a predetermined angular range. The roll variable, the most elusive parameter to be measured in optical control, can be retrieved if the light is linearly polarized. A simple solution is the measurement of the angle of polarization of the emitter. The translation of the roll variable into an azimuthal distribution permit to retrieve the roll variable using the common tools of machine vision. The coding of the angular information into the light distribution spatial distribution is performed in the optical domain. Because of this, the spatial information of the same beam has not been destroyed and can be measured to complete the device function. The two lateral positions can be retrieved from the motif centroid. Finally the focus condition is able to retrieve the longitudinal position. In cases in which a higher longitudinal precision is necessary, a devoted sensor can be used to measure the longitudinal position. From the six degrees of freedom of a rigid object, such a simple device will measure three of them – the roll and the lateral positions - and assess being in a predetermined range for the other three.

The dependency of the vortex wave upon the spatial frequency in coherent light creates a simple mechanism to remove coherent background. In the following we show that for a wave made of a small signal and a large background, all the energy of the background light is transferred to the fundamental wave; the energy of the signal is split between the background and vortex waves. This effect will occur only for coherent and partially coherent background whether the signal is coherent, partially coherent or incoherent. Let an incoming distribution represents a small amplitude or phase object on a background. It is given by:

$$\mathbf{D}_1(\mathbf{R},0)=C\,\mathbf{d}_B(\mathbf{R},0)+\varepsilon\,\mathbf{d}_S(\mathbf{R},0) \qquad (10)$$

The difference between amplitude and phase objects is contained in the variable ε, which is real for an amplitude object and imaginary for a phase object.

For a background represented by a coherent uniform distribution of amplitude C and radius V, the Fourier Transform of the incoming light is given by:

$$a_{\mathbf{B}}(P) = C\frac{kV}{P}J_1(kVP). \tag{11}$$

The fundamental and vortex waves are given, for the background, by:

$$\begin{aligned} B_{0\mathrm{B}}(R,R_0,Z) &= Ck^2V\int_0^\infty dP\, J_1(kVP)\ \exp\left\{-\frac{1}{2}kZP^2\right\}\cos(kR_0P)\, J_0(kRP) \\ B_{1\mathrm{B}}(R,R_0,Z) &= Ck^2V\int_0^\infty dP\, J_1(kVP)\ \exp\left\{-\frac{1}{2}kZP^2\right\}\sin(kR_0P)\, J_1(kRP) \end{aligned} \tag{12}$$

For $R_0 << V$, the cosine term $\cos(kR_0P)$ can be approximated to one and the fundamental wave does not differ markedly from the wave which will have propagated without the crystal. For a stop, covering half the background radius the energy of the background can be reduced, in the vortex wave, – for a perfect polarizer by 10^5 - 10^6.

Homogenization: the conical diffraction set-up homogenises the light distribution because it scrambles the light in the azimuth dimension.

CVI opens new potentialities to detect two points, close one to the other, below the diffraction limit. The venerable two stars problem has indeed applications in almost all optical disciplines. CVI has applications in Astronomy, Lithography, machine vision or optical storage, to name a few, and any other optical application necessitating separating two close optical peaks.

An optical device, made of a homogeneous material, in which the material boundaries consist of planar surfaces, is shift-invariant, neglecting vigneting issues. From a geometrical optics point of view, the transfer function of such a device is independent of the field variable, removing all field related aberrations, of any order, as coma, astigmatism or distortion. This characteristic simplifies much the subsequent optical design of all crystal optics based devices, including conical diffraction set-ups.

For a point positioned at Z_l from the entrance face of the crystal, its ATF is given by the ATF of propagation in space by a – corrected - distance of Z_l

$$\kappa_Z(P,Z_1) = \exp\left\{-\frac{1}{2}ikZ_1P^2\right\} \tag{13}$$

It can be modified – by replacing Z by $Z'=Z+Z_l$ – to include the propagation term before the crystal. In this case the zero of the longitudinal corrected parameter is positioned at the input light distribution original position. The modified equation represents a system independent of the longitudinal position of the crystal, simplifying much the optical and optomechanical design of the system. The shift and longitudinal invariance of conical diffraction simplifies greatly the optical design and the engineering of the system. The angular alignment of the geometrical axis of the incoming light relative to the optical axis of conical diffraction is stringent. In specific cases it is very small, reaching even a few minutes of arc. Even so, this tolerance is easily achievable by modern optical technology and precision assembly. In other systems, this constraint will have to be dealt with from the earliest stage of system design.

KTP, KTA, LBO, MDT, YCOB, $LiInS_2$, and LiInSe2 are examples of crystals suitable for the biaxial crystal component of embodiments of the invention. All these crystals are available commercially with large dimensions, very high homogeneity ($\delta n \sim 10^{-6}$), good parallelism, optical flatness and surface good quality. In the UV, especially in the deep UV, LBO is the choice for conical diffraction. Its transmission window extends to 193 nm, with a small transmission penalty. In the visible and in the near infrared, between 400 and 1300 nm, YCOB, KTP, MDT and LBO may be used unless a very large conical effect is necessary. YCOB has the clear advantage of a full paraxiality and a very small wavelength dependence of the optical axis direction. Around 1550 nm, MDT and KTP may be used. All of them provide easily achromaticity in the entire telecommunications window, extending from the lower wavelength of the S-band, to the higher wavelength of the L-band.

In the SWIR and MWIR wavelength ranges, between 1000 and 5000 nm, MDT, KTP, and KTA (a KTP isomorph) may be used. KTP is achromatic for the SWIR range, between 1000 and 3000 nm. Above these wavelengths, in most of the LWIR range, up to 12 μm, LiInS, $LiInSe_2$ and $Sn_2P_2S_6$ are available.

Additionnally organic crystals, as POM, DAST, MBANP or NPP with very large cone angle are available

Theoretical diffraction parameters, θ_0, A (and R_0) depend on the difference between the dispersion of the indices and can made close to achromatic for some materials. In most practical applications, the variation of the optical axis direction, θ_0, is critical and has to be kept to a fraction of the material parameter, $\bar{A}$. Fortunately the variation for some crystals of the optical axis direction is very small. In MDT, between 540 nm and 700 nm, the direction varies by less then 0.1 degrees. in KTP, the angle varies by 0.05 degrees between 1350 nm and 2100 nm and less then 0.02 degrees on the telecommunication window – 1450 nm to 1650 nm. YCOB varies by close to 0.3 degrees on the huge range of 400 nm to 1300 nm. On the other hand, θ_0 may vary strongly in some crystals, for example MBANP. Additionally, achromatization of a conical diffraction set-up does not differ intrinsically from the standard procedure of correction of chromatic aberration in geometrical optics. Simple achromatization solutions using a single or double-wedged plate exist, based on the natural dispersion of glass. However, the addition of any dispersive element has to be taken into account in the overall system design. A slight modification of the material parameter maybe also quite easily tolerated. In vortex applications, the variation will not be noticed; whether in large ρ_0 applications it will create a dispersion of the conical radius. It may also be compensated as part of the overall chromatic design of the system. In some crystals, such as YCOB and KTP, it can be of second order in comparison to the natural dispersion of refractive elements. For orthorhombic and triclinic crystals the optical frame coincides with the crystallographic axes. For monoclinic crystals the two sets of axes differ. In monoclinic crystals the relative orientation of the optical frame and the crystallographic axes depends on the wavelength creating an optical axes dispersion, which has to be accounted for in the chromatic design. Methods have been developed to measure separately the variation of θ_0, and the orientation of the optical frame, as a function of the wavelength.

Figure 15 illustrates an optical system for use in optical storage including a CVI set up. The system includes a light source 1601, such as a laser diode, for providing light. Light from the light source 1601 is collimated by the lens 1602, and directed to the polarizing beam splitter 1603. Light from the polarizing beam splitter 1603 is directed to focusing optics 1604 and then focused onto a spot 1605 on the optical disk 1606. Light reflected from the spot 1605 passes back through the focusing optics 1604 and is directed by the beam splitter 1603 to a CVI setup including a quarter wave plate 1607, which acts as a circular polarizer in conjunction with the beamsplitter 1603, biaxial crystal 1608 and circular analyzer 1609, such as a quarter wave plate, in order. Together the elements 1601-1604 constitute an imaging module which is arranged to provide imaged light from the spot 1605 to the first quarter wave plate 1607. The light is then focused by focusing lens 1610 and passes through beam splitter 1611 and onto a detector 1612, which may be a single or dual detector, for example. The detector 1612 may one of a single light detector, a segmented light detector ,or a light detector comprised of a matrix of elements, for example. Alternatively to the CVI set up in Figure 16, a PCI setup may be used.

As to a further discussion of the manner of usage and operation of the present invention, the same should be apparent from the above description. Accordingly, no further discussion relating to the manner of usage and operation will be provided.

With respect to the above description then, it is to be realized that the optimum dimensional relationships for the parts of the invention, to include variations in size, materials, shape, form, function and manner of operation, assembly and use, are deemed readily apparent and obvious to one skilled in the art, and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present invention.

It is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of the description and should not be regarded as limiting.

Therefore, the foregoing is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation shown and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

CLAIMS

WHAT IS CLAIMED IS:

1. An optical device comprising:

a circular polarizer arranged to provide a first circular polarization;

a biaxial crystal disposed after the circular polarizer; and

a circular analyzer disposed after the biaxial crystal, the circular analyzer arranged to provide a second circular polarization of an opposite handedness to the first polarization,

wherein a geometrical axis traverses through the circular polarizer, the biaxial crystal and the circular analyzer,

wherein an optic axis of the biaxial crystal is along the geometrical axis.

2. An optical system comprising:

a projection lens arranged to receive light from an object to be viewed;

an imaging lens arranged to receive light from the projection lens;

an optical detector arranged to receive light imaged by the imaging lens; and

the optical device of claim 1 arranged between the imaging lens and the optical detector.

3. The optical system of claim 2, wherein the optical detector is a charge coupled device (CCD) detector.

4. An optical device comprising:

a biaxial crystal; and

a polarizing beamsplitter disposed after the biaxial crystal,

wherein a geometrical axis traverses the biaxial crystal and the beamsplitter,

wherein an optic axis of the biaxial crystal is along the geometrical axis.

5. An optical system comprising:

a projection lens arranged to receive light from an object to be viewed;

an imaging lens arranged to receive light from the projection lens;

two optical detectors, one for each channel of the beamsplitter, arranged to receive light imaged by the imaging lens; and the optical device of claim 4 arranged between the imaging lens and the optical detector.

6. The optical system of claim 5, wherein the optical detectors comprise a single charge coupled device (CCD) detector, wherein two images fall on two different regions of the CCD detector, or two separate CCD detectors.

7. An optical device comprising:

a first polarization element arranged to provide a first polarization;

a biaxial crystal disposed after the first polarization element; and

a second polarization element disposed after the biaxial crystal, the second polarization element arranged to provide a second polarization,

wherein a geometrical axis traverses through the first polarization element, the biaxial crystal and the second polarization element,

wherein an optic axis of the biaxial crystal is along the geometrical axis.

8. An optical system comprising:

an imaging module arranged to provide light to a spot on an optical disk, and to direct light reflected from the spot;

a circular polarizer arranged to receive light reflected from the spot and directed to the circular polarizer;

a biaxial crystal disposed after the circular polarizer;

a circular analyzer disposed after the biaxial crystal, the circular analyzer arranged to provide a circular polarization of an opposite handedness to that provided by the circular polarizer; and

a light detector arranged after the circular analyzer to detect the light received from the circular analyzer,

wherein a geometrical axis traverses through the circular polarizer, the biaxial crystal and the circular analyzer,

wherein an optic axis of the biaxial crystal is along the geometrical axis.

9. The optical system of claim 8, wherein the imaging module comprises:

a light source which provides light;

a beam splitter arranged to receive light from the light source; and

focusing optics arranged to focus light from the beam splitter to the spot and to receive light reflected from the spot and direct the light received from the spot to the beam splitter.

10. The optical system of claim 9, wherein the light detector comprises one of a single light detector, a segmented light detector, or a light detector comprised of a matrix of elements.

11. An optical system comprising:

an imaging module arranged to provide light to a spot on an optical disk, and to direct light reflected from the spot;

a circular polarizing beamsplitter arranged to receive light reflected from the spot and directed to the circular polarizer;

a biaxial crystal disposed after the circular polarizer;

a circular analyzer disposed after the biaxial crystal, the circular analyzer arranged to provide a circular polarization of an opposite handedness to that provided by the circular polarizing beamsplitter; and

a light detector arranged after the circular analyzer to detect the light received from the circular analyzer,

wherein a geometrical axis traverses through the circular polarizing beamsplitter, the biaxial crystal and the circular analyzer,

wherein an optic axis of the biaxial crystal is along the geometrical axis,wherein the light detector comprises two separate detector modules used concurrently.

12. The optical system of claim 2, wherein the object is a fiducial mark, and data retrieved based on the light received by the optical detector provides the position of the fiducial mark.

13. The optical system of claim 5, wherein the object is a fiducial mark, and data retrieved based on the light received by the two optical detectors provides the position of the fiducial mark.

14. The optical system of claim 1, wherein the biaxial crystal is one of KTP, KTA, LBO, MDT, YCOB, $LiInS_2$, LiInSe2, organic POM, or organic NPP.

15. The optical system of claim 4, wherein the biaxial crystal is one of KTP, KTA, LBO, MDT, YCOB, $LiInS_2$, LiInSe2, organic POM, or organic NPP.

16. The optical system of claim 7, wherein the biaxial crystal is one of KTP, KTA, LBO, MDT, YCOB, $LiInS_2$, LiInSe2, organic POM, or organic NPP

17. The optical system of claim 7, wherein the biaxial crystal is one of KTP, KTA, LBO, MDT, YCOB, $LiInS_2$, LiInSe2, organic POM, or organic NPP

18. The optical system of claim 11, wherein the biaxial crystal is one of KTP, KTA, LBO, MDT, YCOB, $LiInS_2$, LiInSe2, organic POM, or organic NPP

19. A method comprising:

providing a biaxial crystal;

inputting partially coherent light with an input light circular polarization from an unknown object through the biaxial crystal;

providing a circular analyzer after the biaxial crystal, the circular analyzer arranged to provide a second circular polarization of an opposite handedness to the handedness of the input light circular polarization,

wherein a geometrical axis traverses through the biaxial crystal and the circular analyzer,

wherein an optic axis of the biaxial crystal is along the geometrical axis,

wherein the initial light distribution has been imaged by an optical system onto a detector,

wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal;

detecting the distribution of intensity of the light in a plane after the circular analyzer with the detector,

wherein the plane is perpendicular to the geometrical axis;

imaging features of the unknown object from the detected distribution of intensity; and

outputting the imaged features of the unknown object.

20. The method of claim 19, further comprising:

recording the imaged features of the unknown object.

21. The method of claim 19, wherein the detected distribution of intensity of the light is proportional to the derivative of the initial light distribution.

22 The method of claim 19, wherein the step of detecting the distribution of intentsity comprises:

providing a second biaxial crystal after the circular analyzer along the geometrical axis;

providing a rotator after the second biaxial crystal along the geometrical axis;

providing a third biaxial crystal after the rotator along the geometrical axis; and

detecting the distribution of the intensity of light in plane after the third biaxial crystal with the detector.

23. A method comprising:

providing a circular polarizer arranged to provide a first circular polarization on incident light;

providing a biaxial crystal after the circular polarizer;

inputting unpolarized, partially coherent light from an unknown object through the circular polarizer and the biaxial crystal;

providing a circular analyzer after the biaxial crystal, the circular analyzer arranged to provide a second circular polarization of an opposite handedness to the first polarization,

wherein a geometrical axis traverses through the circular polarizer, the biaxial crystal and the circular analyzer,

wherein an optic axis of the biaxial crystal is along the geometrical axis, wherein the unpolarized, partially coherent light has been imaged on the circular polarizer,

wherein the initial light distribution has been imaged by an optical system onto a detector,

wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal;

detecting the distribution of intensity of the light in a plane after the circular analyzer with the detector;

wherein the plane is perpendicular to the geometrical axis;

imaging features of the unknown object from the detected distribution of intensity; and

outputting the imaged features of the unknown object.

24. The method of claim 23, further comprising:

recording the imaged features of the unknown object.

25. The method of claim 23, wherein the detected distribution of intensity of the light is proportional to the derivative of the initial light distribution.

26. The method of claim 23, wherein the incident light is provided from an assembly of points,

wherein the imaging comprises projecting the intensity of light in a volume after the circular analyzer, wherein the volume is perpendicular to the geometrical axis,

the method, further comprising:

using the intensity of the light to trap particles using optical trapping concepts.

27. The method of claim 23, wherein the incident light comprising a plurality of wavelengths is provided from an assembly of points,

wherein the imaging comprises projecting the intensity of light in a volume after the circular analyzer, wherein the volume is perpendicular to the geometrical axis,

the method, further comprising:

using the intensity of the light to trap particles using optical trapping concepts.

28. The method of claim 23, wherein the input unpolarized, partially coherent light has a direction of propagation at an angle with respect to the geometrical axis,

the method further comprising:

calculating the angle from the detected the distribution of intensity of the light.

29. The method of claim 23, wherein the unknown object is a phase object.

30. The method of claim 23, wherein the unknown object comprises pits and lands on the surface of an optical disk, the method further comprising:

reading information stored in the pits and lands.

31. The method of claim 23, wherein the step of detecting the distribution of intentsity comprises:

providing a second biaxial crystal after the circular analyzer along the geometrical axis;

providing a rotator after the second biaxial crystal along the geometrical axis;

providing a third biaxial crystal after the rotator along the geometrical axis; and

detecting the distribution of the intensity of light in plane after the third biaxial crystal with the detector.

32. A method comprising:

providing a first polarizing beamsplitter;

providing a first quarter wave plate after the first polarizing beamsplitter;

providing a biaxial crystal after the first quarter wave plate;

providing a second quarter wave plate after the biaxial crystal;

providing a second polarizing beamsplitter after the second quarter wave plate,

wherein a geometrical axis traverses through the first quarter wave plate, the biaxial crystal and the second quarter waveplate,

wherein an optic axis of the biaxial crystal is along the geometrical axis,

directing light from a point through the first polarizing beamsplitter,

splitting the light into two parallel beams at the first beamsplitter,

wherein the two parallel beams traverse the first quarter wave plate, the biaxial crystal, the second quarter wave plate and the second polarizing beamsplitter, combining vortex waves from the two split parallel beams at the second beamsplitter into one beam propagating in a first direction;

adding if necessary a wave plate or rotator element to transform azimuthal to radial polarization or vice versa, and

combining fundamental waves from the two split parallel beams into another beam propagating in a second direction perpendicular to the first direction that the combined vortex waves are propagating.

using the light coming from the combined vortex waves as an azimuthal or radial polarized illumination source for lasers applications as lithography illumination and/or high power lasers for cutting, drilling and machining or for optical storage applications.

33. The method of claim 32 further comprising:

performing photolithography with the light from the combined vortex waves to fabricate a device structure on a semiconductor wafer.

34. The method of claim 32 further comprising:

machining materials with the light from the combined vortex waves.

35. The method of claim 32 further comprising:

writing information to an optical storage disk with the light from the combined vortex waves.

36 A method comprising:

providing a biaxial crystal;

inputting light either unpolarized or circularly polarized from an unknown object through the biaxial crystal;

providing a linear polarization beamsplitter after the biaxial crystal,

wherein a geometrical axis traverses through the biaxial crystal and is split in two conjugate axes after the polarizing beamsplitter,

wherein the optic axis of the biaxial crystal is along the geometrical axis,

wherein the initial light distribution has been imaged by an optical system onto a detector, wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal;

detecting the distribution of intensity of the light in both optical channels emerging from the polarizing beamsplitter in planes perpendicular to the two geometrical axes created by the beamsplitter on the detector;

imaging features of the unknown object from mathematical combinations of the detected distribution intensity; and

outputting the imaged features of the unknown object.

37. The method of claim 36, wherein the detector comprises two regions, wherein the light emerging from one of the optical channels is incident on one of the regions of the detector and the light emerging from the other optical channel is incident on the other region of the detector.

38. The method of claim 36, wherein the detector comprises two detectors, wherein the light emerging from each optical channel is incident on each detector.

39. The method of claim 36, further comprising recording the output, imaged features of the unknown object.

40. The method of claim 36, wherein the unknown object is a measurement mark, the method further comprising:

calculating the position of the measurement mark from the mathematical calculations of the detected distribution of intensity.

41. The method of claim 36, wherein the unknown object comprises pits and lands on the surface of an optical disk, the method further comprising:

reading information stored in the pits and lands.

42. A method comprising:

providing a biaxial crystal;

inputting light either unpolarized or circularly polarized from an unknown object through the biaxial crystal;

providing a linear polarization beamsplitter after the biaxial crystal,

wherein a geometrical axis traverses through the biaxial crystal and is split in two conjugate axes after the polarizing beam splitter,

wherein the optic axis of the biaxial crystal is along the geometrical axis,

wherein the initial light distribution has been imaged by an optical system onto a detector,

wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal;

detecting the distribution of intensity of the light in both optical channels emerging from the polarizing beamsplitter in planes perpendicular to the two geometrical axes created by the beamsplitter on the detector;

imaging the features of the unknown object; and

outputting the features of the unknown object.

43. The method of claim 42, wherein the detector comprises two regions, wherein the light emerging from one of the optical channels is incident on one of the regions of the detector and the light emerging from the other optical channel is incident on the other region of the detector.

44. The method of claim 42, wherein the detector comprises two detectors, wherein the light emerging from each optical channel is incident on each detector.

45. The method of claim 42, further comprising recording the output, imaged features of the unknown object.

46. The method of claim 42, wherein the detected distribution of light is proportional to the derivative in one axis of the intial light distribution.

47. The method of claim 42, wherein the unknown object comprises pits and lands on the surface of an optical disk, the method further comprising:

reading information stored in the pits and lands.

48. The method of claim 42, wherein the step of detecting the distribution of intentsity comprises:

providing a second biaxial crystal after the circular analyzer along the geometrical axis;

providing a rotator after the second biaxial crystal along the geometrical axis;

providing a third biaxial crystal after the rotator along the geometrical axis; and

detecting the distribution of the intensity of light in plane after the third biaxial crystal with the detector.

49. A method comprising:

providing a biaxial crystal;

inputting light either unpolarized or circularly polarized from an unknown object through the biaxial crystal;

providing a linear polarizer and a controllable rotator after the biaxial crystal,

wherein a geometrical axis traverses through the biaxial crystal, the polarizer and the controllable rotator

wherein the optic axis of the biaxial crystal is along the geometrical axis,

wherein the initial light distribution has been imaged by an optical system onto a detector,

wherein, if the biaxial crystal were replaced by an isotropic material with an index equal to about the biaxial crystal median index, the image would fall on the detector, before inputting in the biaxial crystal;

detecting the distribution of intensity of the light in two or more polarization states by actuating the controllable rotator in a plane perpendicular to the geometrical axis;

imaging features of the unknown object from mathematical combinations of the detected distribution of intensity; and

outputting the imaged features of the unknown object.

50. The method of claim 49, further comprising:

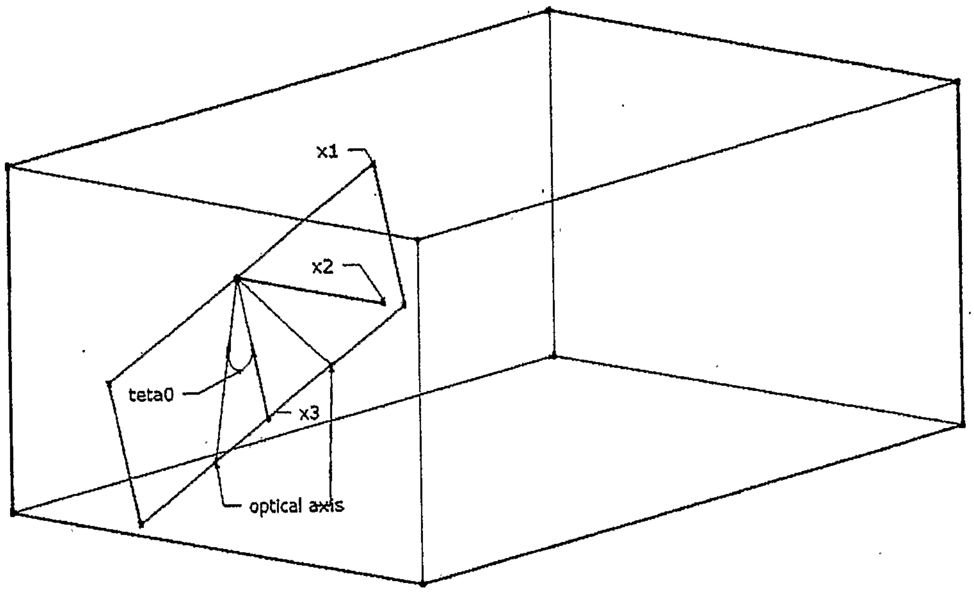
recording the imaged features of the unknown object.

51. The method of claim 50, wherein the detected distribution of light is proportional to the derivative in one axis of the initial light distribution.

52. The method of claim 51, wherein the unknown object comprises pits and lands on the surface of an optical disk, the method further comprising:

reading information stored in the pits and lands.

Figure 1


x1
x2
teta0
x3
optical axis

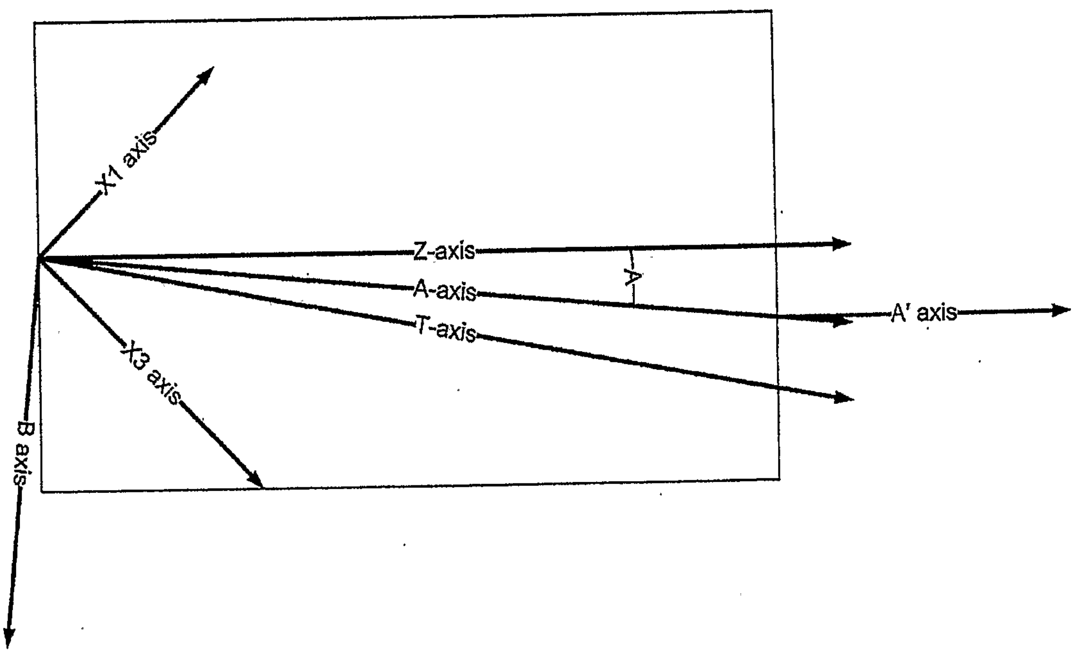
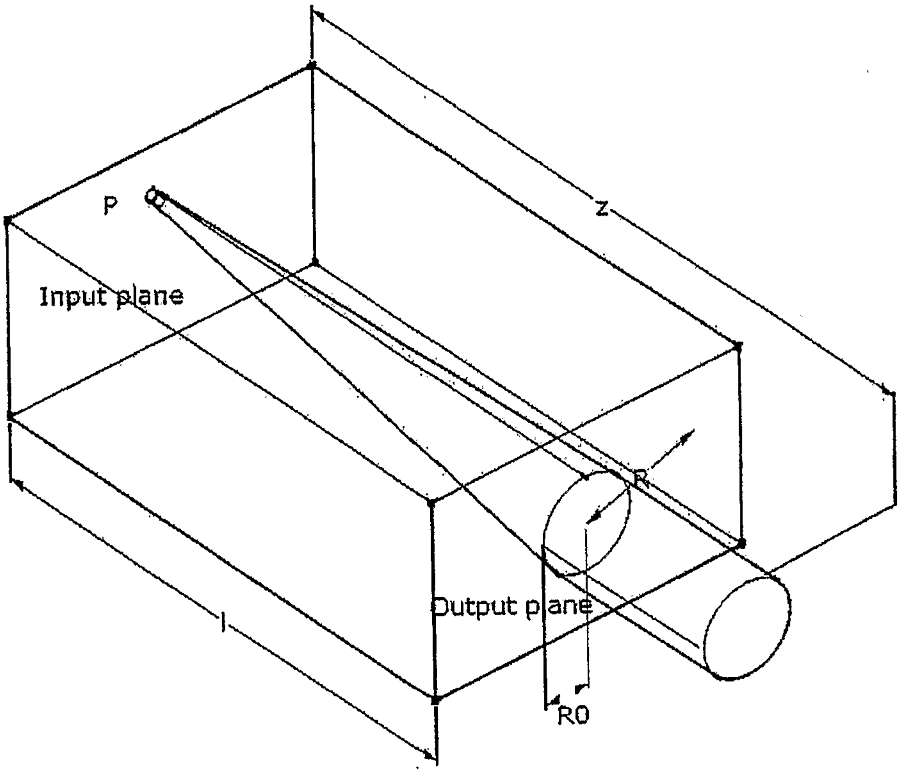

X1 axis
Z-axis
A
A-axis
A' axis
T-axis
X3 axis
B axis

Figure 2



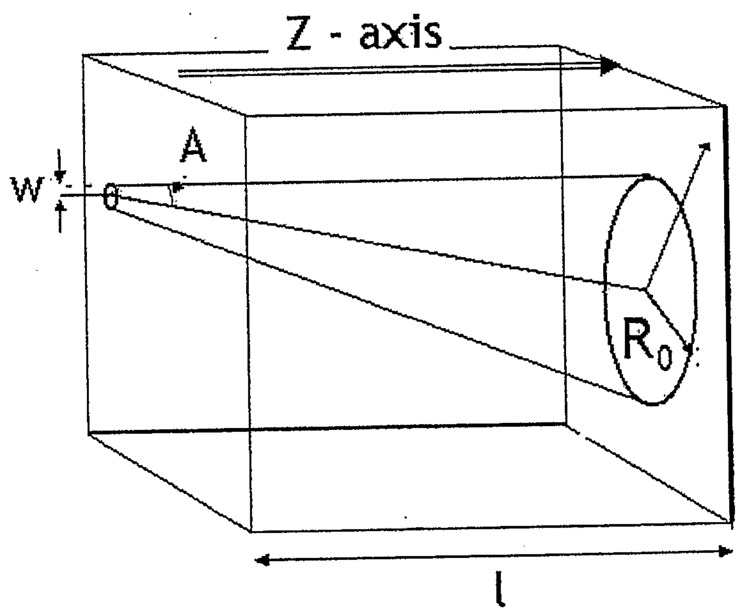


Figure 3

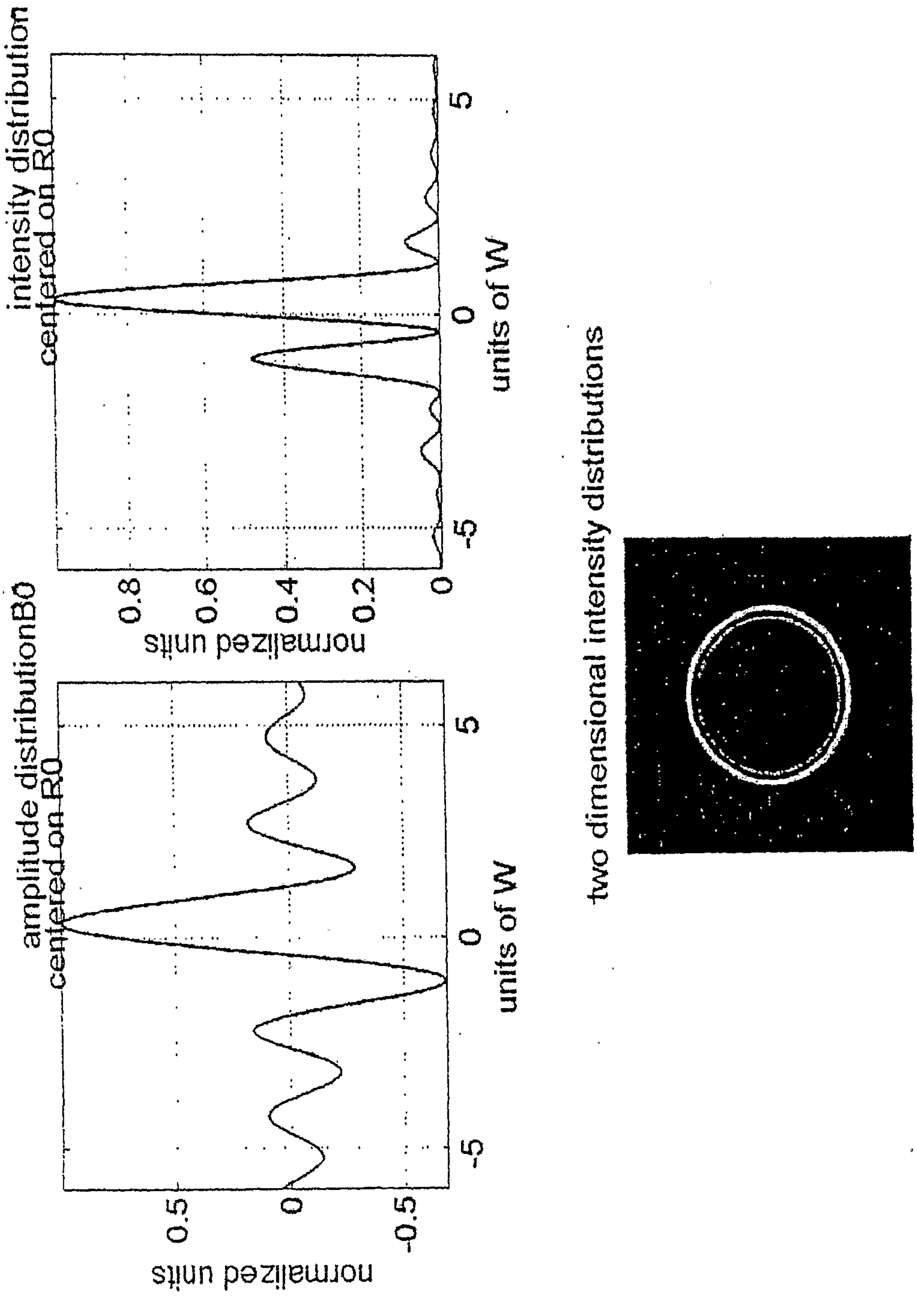

amplitude distributionB0
centered on R0
normalized units
0.5
0
-0.5
-5
0
5
units of W
intensity distribution
centered on R0
normalized units
0.8
0.6
0.4
0.2
0
-5
0
5
units of W
two dimensional intensity distributions

Figure 4

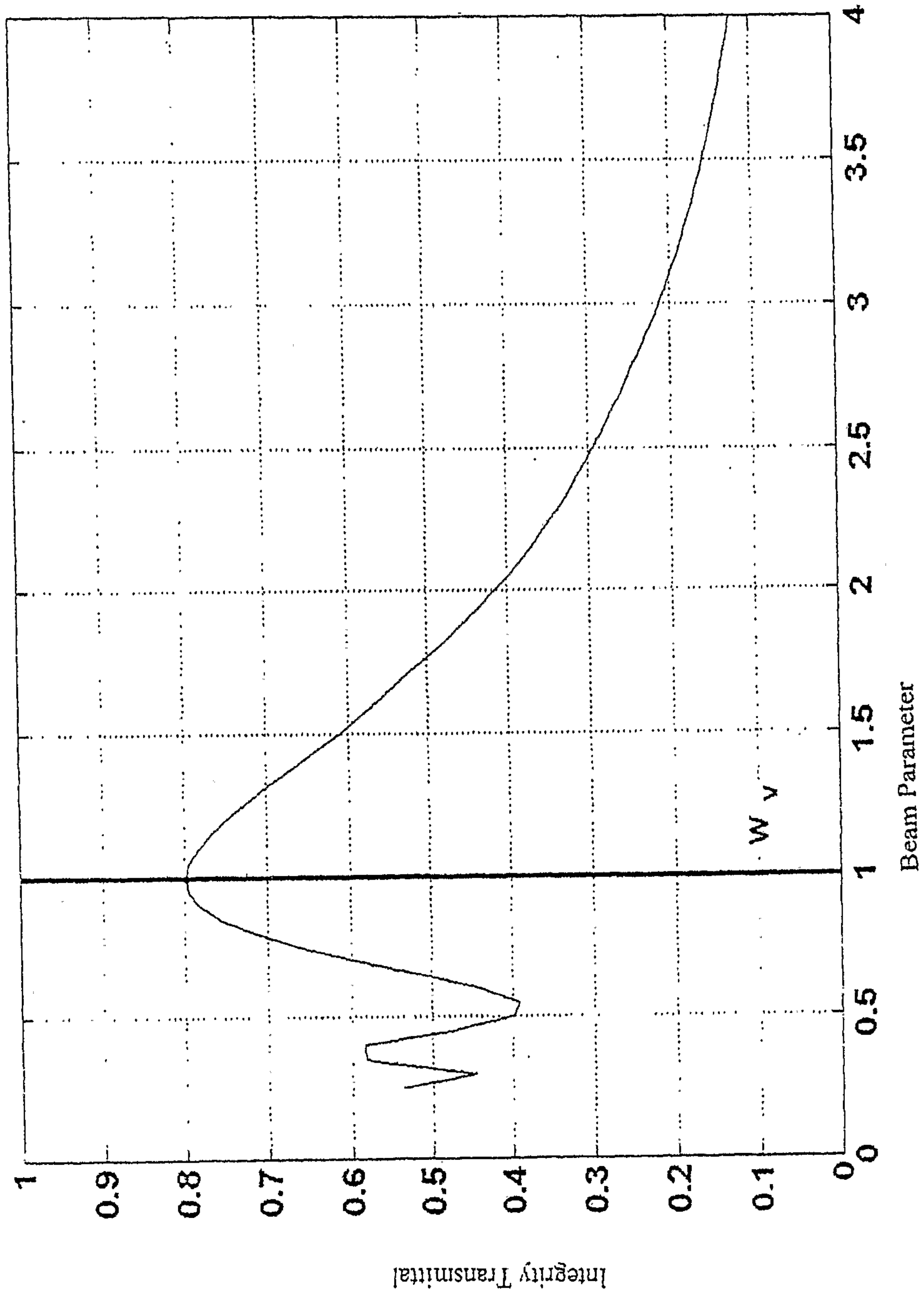

Integrity Transmittal
Beam Parameter
W v
0 0.5 1 1.5 2 2.5 3 3.5 4
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Figure 5

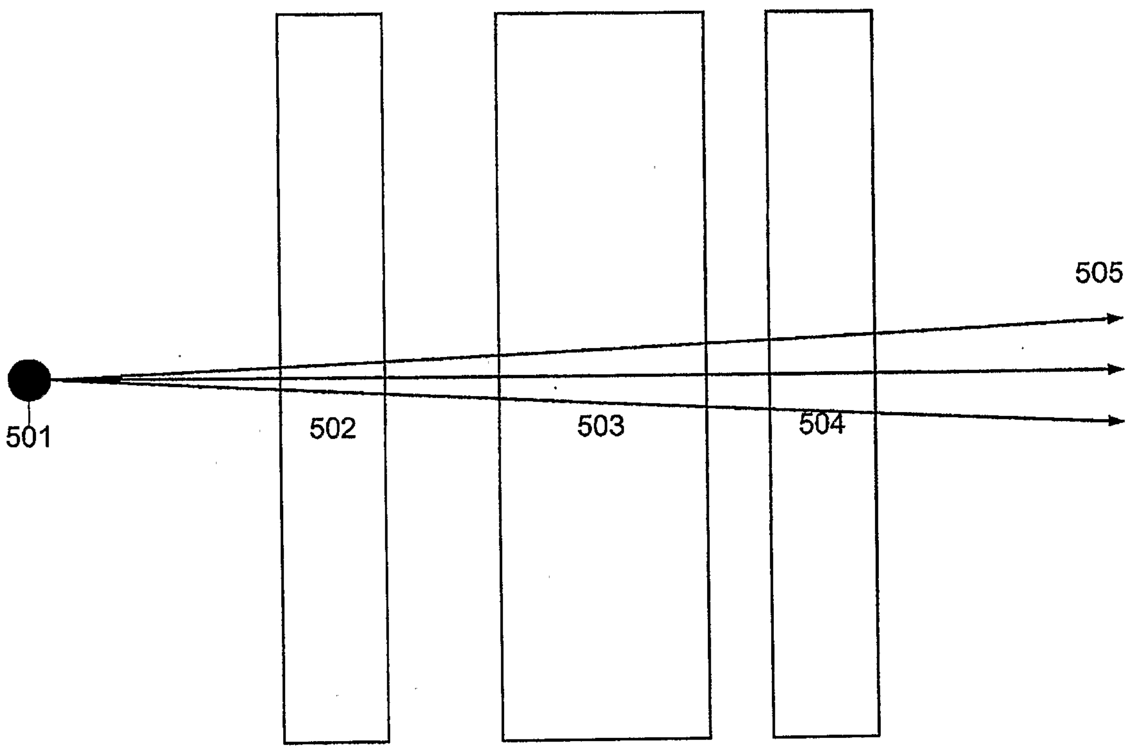


Figure 6

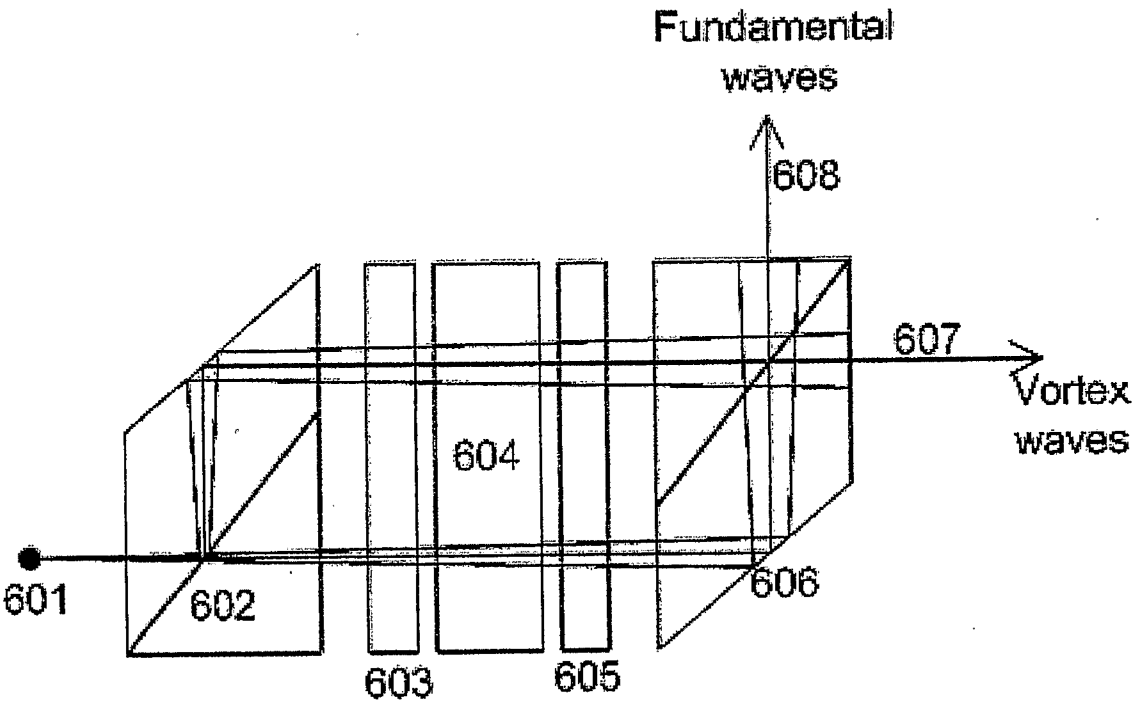

Fundamental waves
608
607
Vortex waves
604
601
602
606
603
605

Figure 7

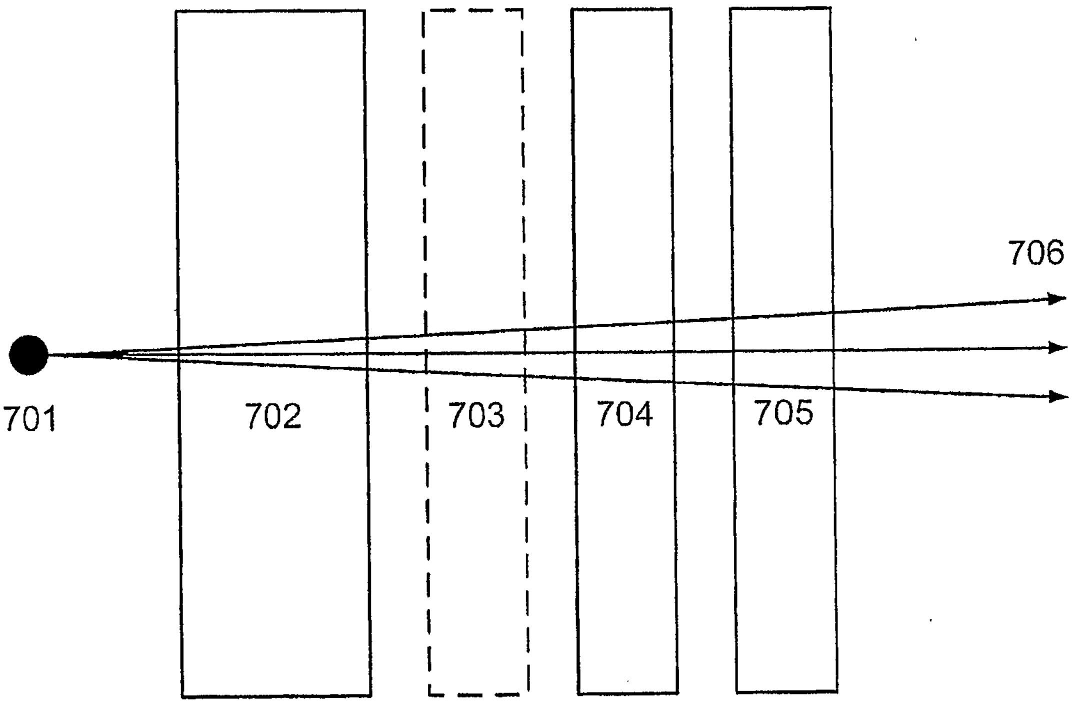
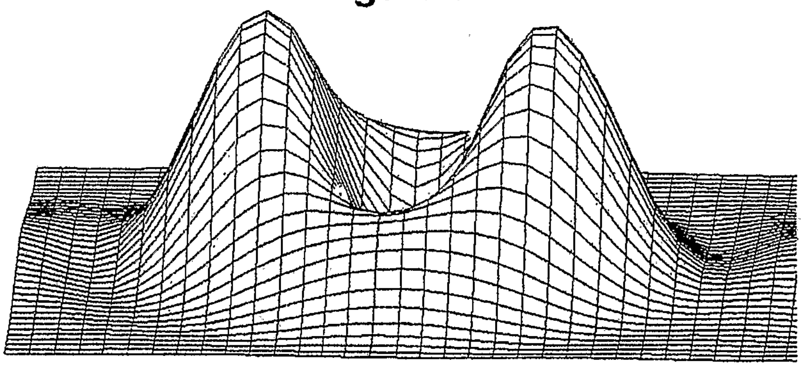
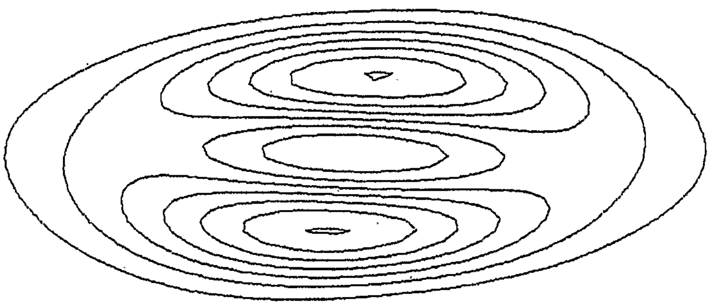


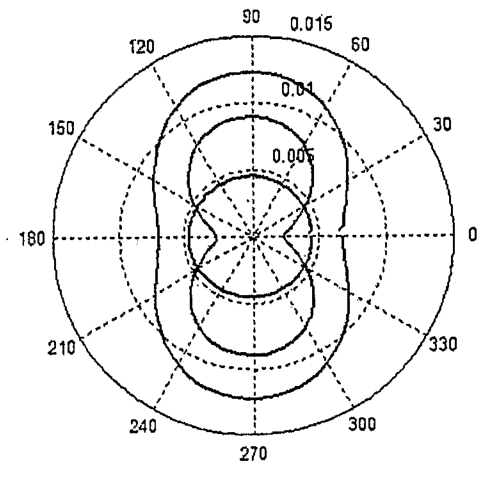
Figure 8



(a)

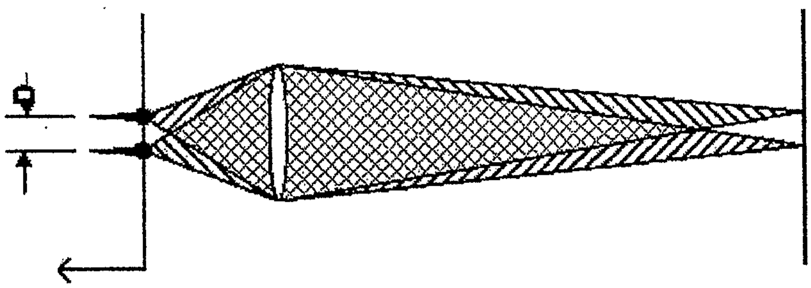


(b)

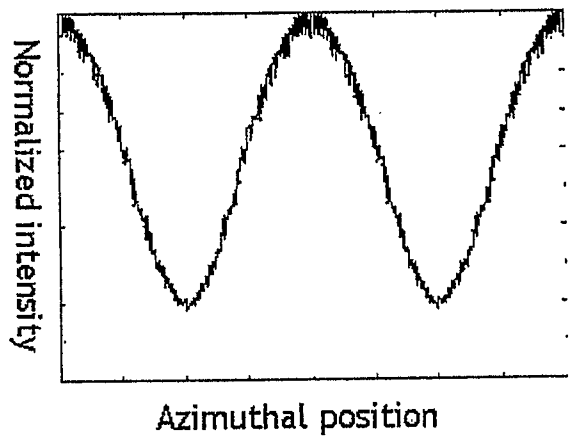


(c)

Figure 9



(a)



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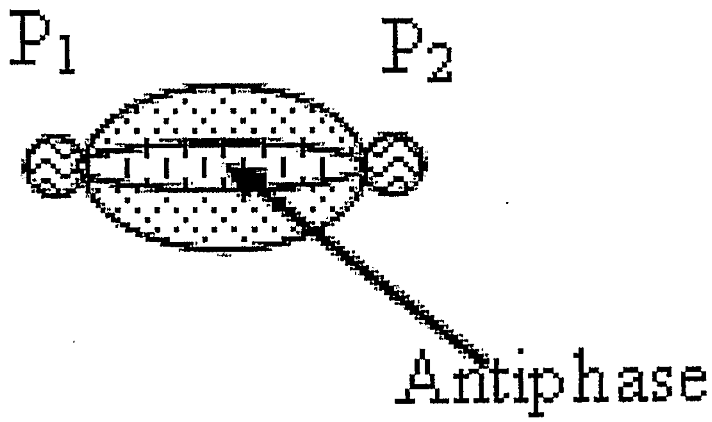


Figure 9c

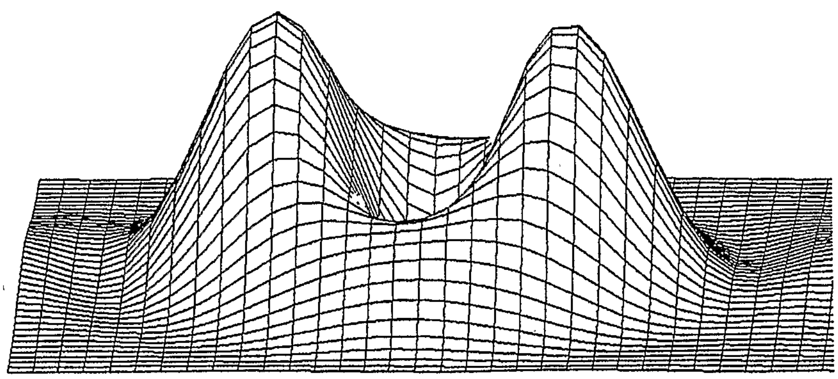


Figure 9d

Figure 10

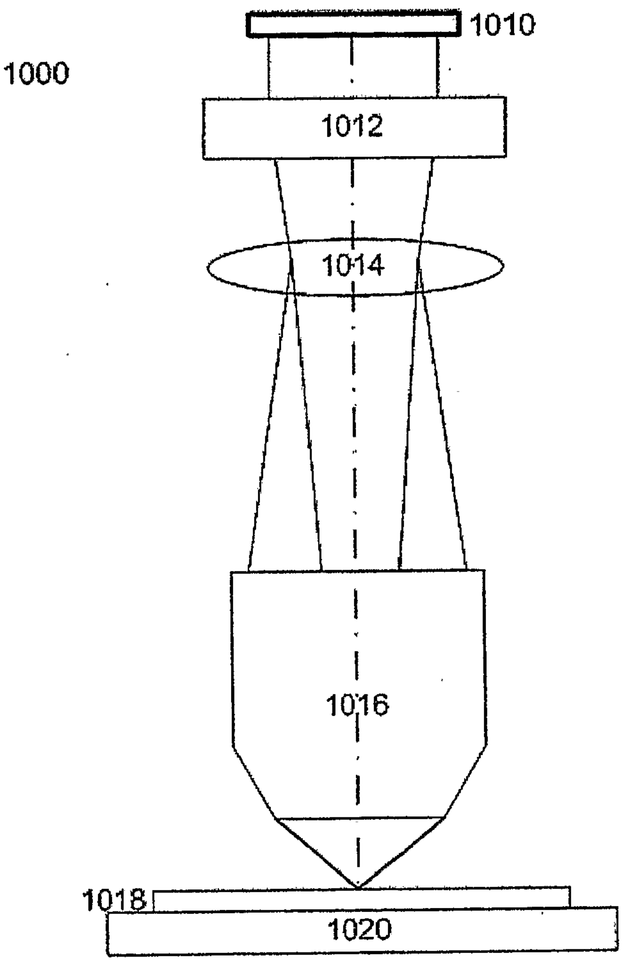
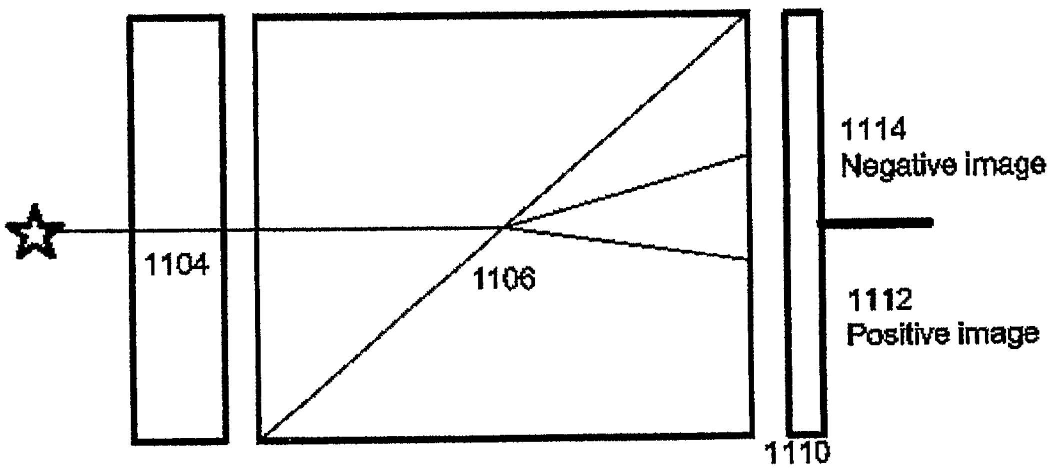


Figure 11



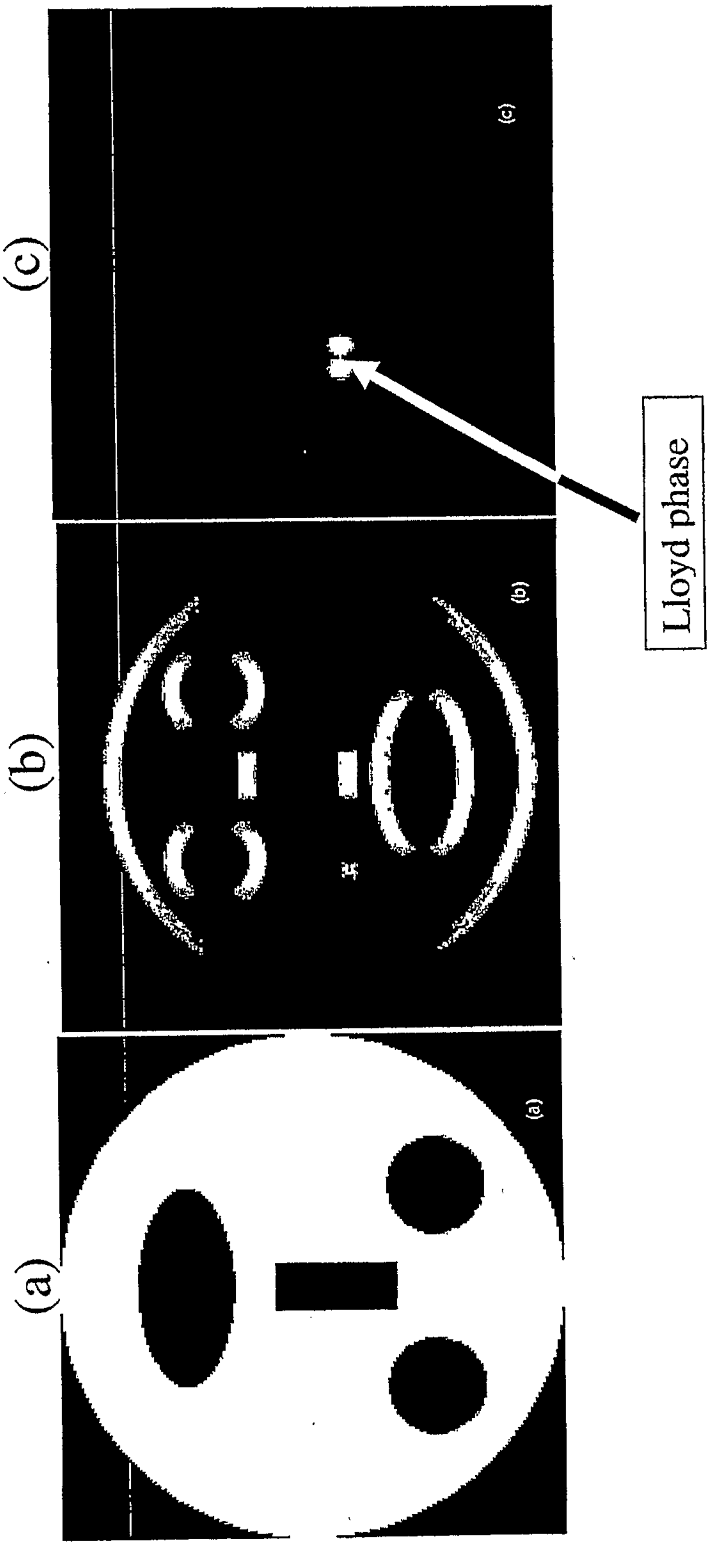


Figure 12

Figure 13

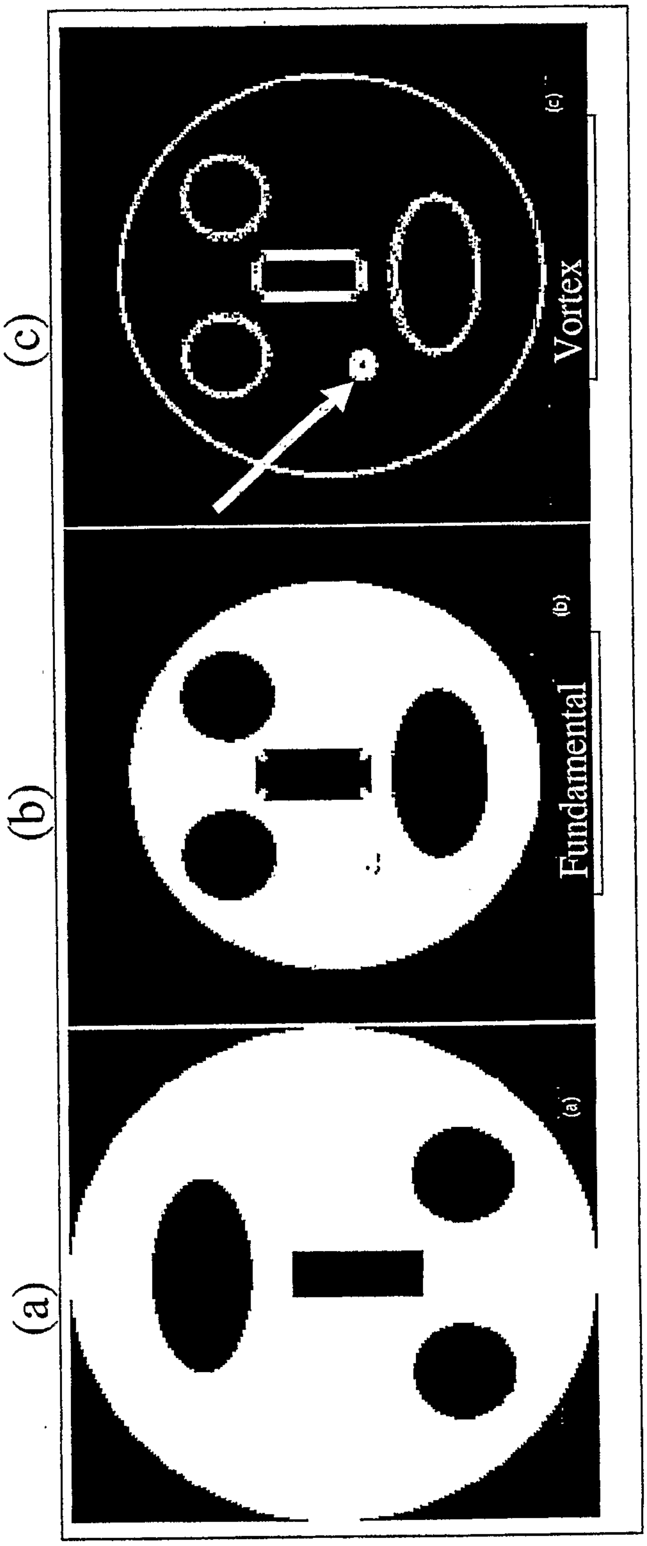
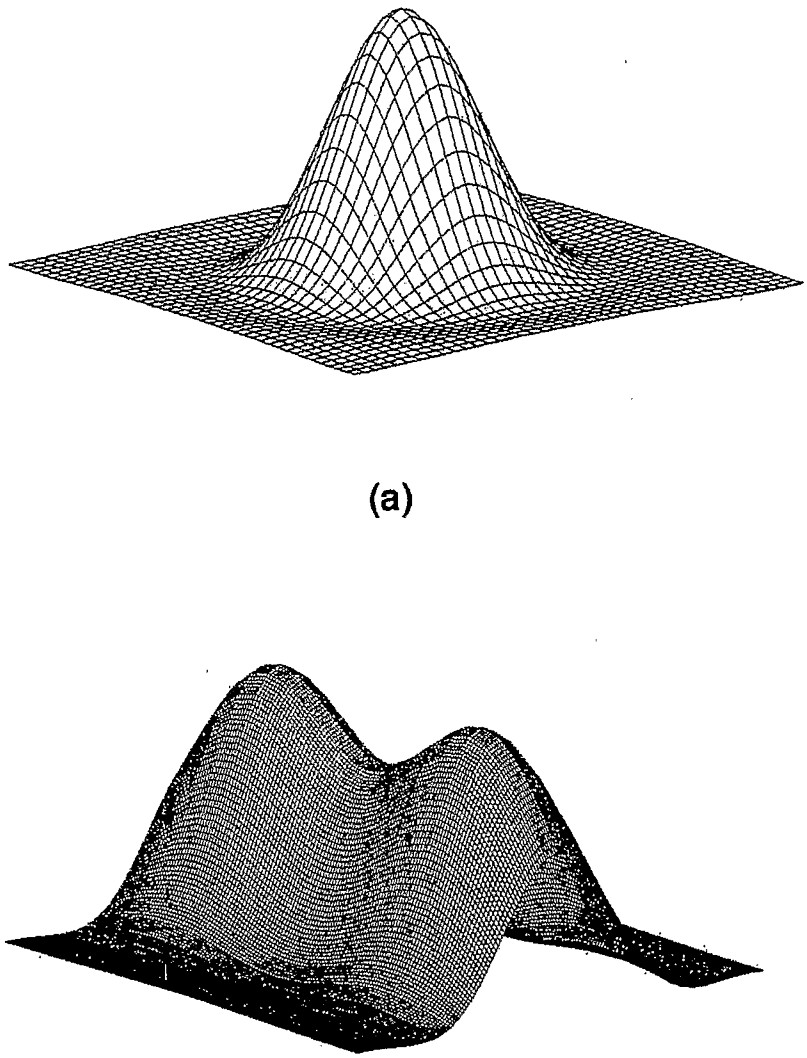
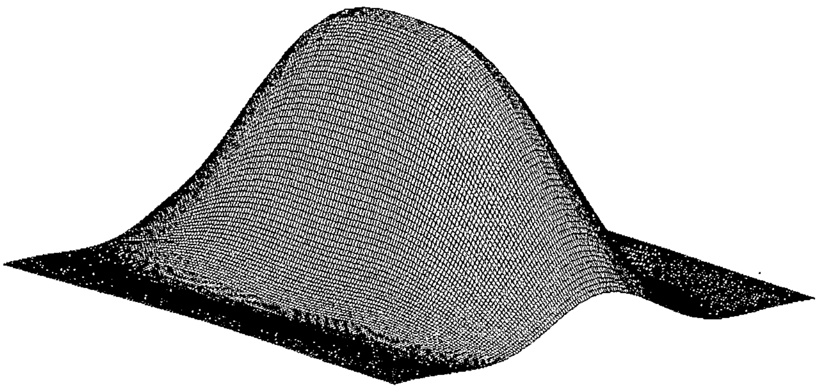


Figure 14



(a)

(b)



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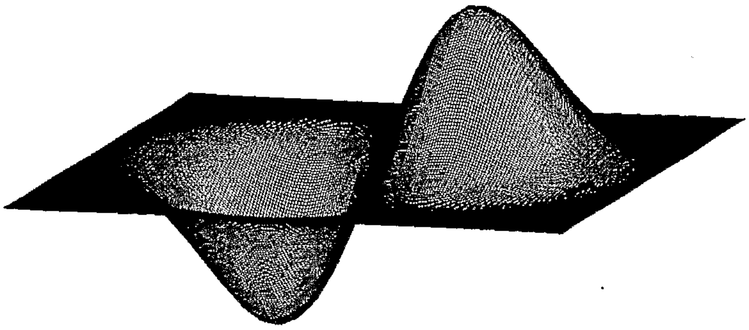

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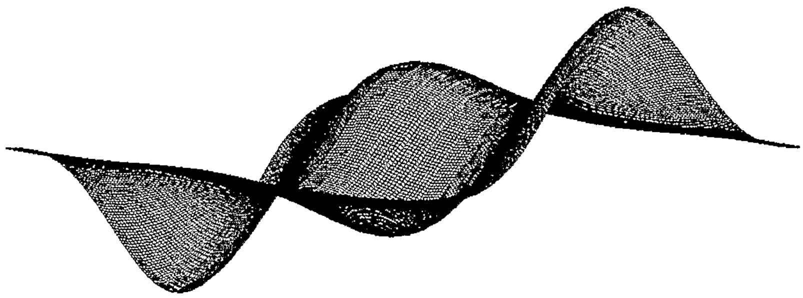

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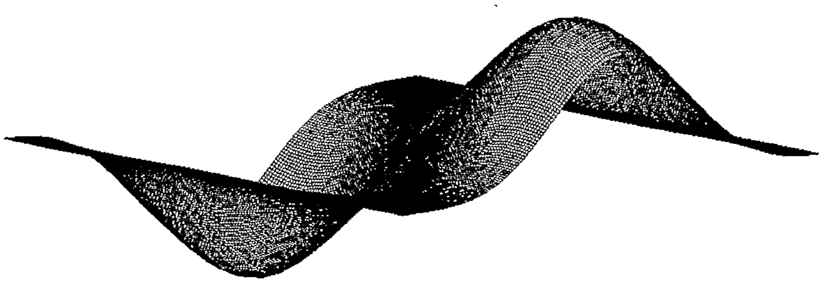

(f)

Figure 15