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(54) Title: LASER PROJECTION SYSTEM

(57) Abstract: A projection apparatus for an intraoral scanner has a laser diode energizable to generate a beam of laser light along an optical axis. A collimator lens is disposed along the optical axis in the path of the generated light beam. A uniform light generator is disposed along the optical axis to improve the uniformity of the generated light beam of the collimator lens. A spatial light modulator disposed in the path of the beam from the uniform light generator is energizable to impart a pattern to the beam. A projection optic projects the patterned light toward a focal plane. A spatial filter is disposed to block one or more diffraction orders of the patterned light at the Fourier plane of the projection optic to form a filtered projection beam.



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LASER PROJECTION SYSTEM

FIELD OF THE INVENTION

[0001] The disclosure relates generally to methods and apparatuses for light projection and, more particularly, to methods and apparatuses for structured light projection for an intraoral imaging system.

BACKGROUND OF THE INVENTION

[0002] The intraoral camera is increasingly used as a diagnostic tool to support a range of applications for accurate characterization of shape and condition of teeth and supporting structures and tissues. In order to provide image content of sufficient resolution and accuracy for diagnostic use, the intraoral camera must meet demanding requirements for image quality.

[0003] The design of the portable, handheld intraoral camera must address a number of inherent challenges related to overall usability as well as to the constraints of the intraoral environment. The camera must be sized and shaped for ease of use and configured to allow access to different regions of the mouth. Sufficient illumination must be provided, within tight spacing and size constraints, for any type of reflectance imaging. This includes illumination for a camera that performs either contour imaging with patterned illumination or 2-D image acquisition with full-field imaging, or both contour and full-field imaging.

[0004] Solid-state light sources are employed for illumination in existing designs for handheld camera devices. Light emitting diodes (LEDs) and laser diodes have a number of advantages over other light sources, including small size, low heat generation, and long life. Laser diodes, in particular, have advantages for brightness and color hue.

[0005] Light efficiency with existing designs that use laser diodes or LEDs has been disappointing. Light throughput as low as 3% to 8% is typical for many conventional intraoral scanner devices.

[0006] Among other concerns with existing illumination techniques using laser light sources is a limited depth of field (“DOF”). This problem can be particularly troublesome when using laser diode output with structured light illumination for surface contour characterization. Conventional approaches to compensate for depth of field limitations can be unsatisfactory,

effectively reducing illumination in a characteristically light-starved optical system. Further, there is need for improved illumination uniformity. Light homogenizers that employ lenslet arrays tend to be relatively sizable, thus poorly suited for systems where compact packaging of the optics is a requirement.

[0007] Therefore, there is need in the industry for laser projection systems, including apparatuses and methods, that have improved efficiency, that increase the DOF of projected light patterns, and that enable more compact system size for intraoral camera imaging.

SUMMARY OF THE INVENTION

[0008] Broadly described, the present invention comprises methods and apparatuses for structured light projection for an intraoral imaging system as defined by the claims hereof. The methods and apparatuses of the present invention advantageously advance the art of diagnostic imaging and address the need for improved optical efficiency. The methods and apparatuses of the present invention also advantageously extend the effective depth of field (“DOF”) for projected illumination from an intraoral imaging apparatus using laser diode light. Additionally, the methods and apparatuses of the present invention advantageously improve light uniformity without using approaches that increase system size.

[0009] According to an aspect of the present disclosure, there is provided a projection apparatus for an intraoral scanner comprising: (a) a laser diode energizable to generate a beam of laser light along an optical axis; (b) a collimator lens disposed along the optical axis in the path of the generated light beam; (c) a uniform light generator disposed along the optical axis to improve the uniformity of the generated light beam of the collimator lens; (d) a spatial light modulator disposed in the path of the beam from the uniform light generator and energizable to impart a pattern to the beam; (e) a projection optic that projects the patterned light toward a focal plane; and (f) a spatial filter that is disposed to block one or more diffraction orders of the patterned light at the Fourier plane of the projection optic to form a filtered projection beam.

[0010] According to an alternate aspect of the present disclosure, there is provided a projection apparatus for an intraoral scanner comprising: (a) a laser diode energizable to generate a beam of laser light along an optical axis; (b) a collimator lens disposed along the optical axis in the path of the generated light beam to produce a substantially collimated beam; (c) a homogenizer

comprising a plurality of lenslets disposed along the optical axis in the path of the collimated beam, wherein the homogenizer has a first etendue; (d) a condenser lens that directs a condensed light beam from the homogenizer along the optical axis; (e) a spatial light modulator that is energizable to impart a pattern to the condensed light beam; and (f) a projection optic having a second etendue, wherein the projection optic projects the patterned light toward a focal plane, wherein the first etendue of the homogenizer is less than ten times the second etendue of the projection optic; and wherein the collimated beam extends across at least ten lenslets of the homogenizer.

[0011] According to another alternate aspect of the present disclosure, there is provided a projection apparatus for an intraoral imaging comprising: (a) a laser diode energizable to generate a beam of laser light along an optical axis; (b) a first collimator lens disposed along the optical axis in the path of the generated light beam; (c) first and second gradient index lenses disposed along the optical axis in the path of the light beam that is conveyed through the first collimator lens, wherein the predominant optical power of the first gradient index lens is orthogonal to the predominant optical power of the second gradient index lens for shaping an energy profile of the light beam over mutually orthogonal axes; (d) a second collimator lens that directs a substantially collimated and uniformized light beam from the shaped beam output along the optical axis; (e) a spatial light modulator that imparts a pattern to the substantially collimated and uniformized light beam; and (f) a projection optic that projects the patterned light toward a focal plane.

[0012] The above advantages are given only by way of illustrative example, and such advantages may be exemplary of one or more example embodiments of the present invention. Other desirable advantages inherently achieved by the methods and apparatuses may occur or become apparent to those skilled in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The foregoing features and advantages of the present invention and others will be apparent from the following more particular description of example embodiments of the present invention, as illustrated in the accompanying drawings.

[0014] The elements of the drawings are not necessarily to scale relative to each other. Some exaggeration may be necessary in order to emphasize basic structural relationships or principles of operation. Some conventional components that would be needed for implementation

of the described embodiments, such as support components used for providing power, for packaging, and for mounting and protecting system optics, for example, are not shown in the drawings in order to simplify description.

[0015] FIG. 1 is a schematic diagram that displays an intraoral camera communicatively connected to a laptop computer.

[0016] FIG. 2 is a schematic diagram that displays the use of patterned light for characterizing surface contour.

[0017] FIG. 3 displays surface imaging using a pattern with multiple lines of light.

[0018] FIG. 4 is a schematic diagram that displays a projection apparatus that can be used for intraoral imaging.

[0019] FIG. 5 is a schematic diagram that displays a projection apparatus that can be used for intraoral imaging and that has improved throughput.

[0020] FIG. 6 is a schematic diagram of an apparatus using a spatial filter for extended depth of field.

[0021] FIG. 7 shows a beam cross-section at the Fourier plane.

[0022] FIG. 8 shows beam manipulation using a spatial filter at the Fourier plane.

[0023] FIGS. 9A and 9B show example results for structured light images captured at different projection image planes using the apparatus of FIG. 6.

[0024] FIG. 10 is a schematic diagram that displays an alternative approach for beam reshaping using crossed gradient index lenses (GRIN).

[0025] FIG. 11 shows an exemplary light output in cross section using multiple GRIN lenses.

DETAILED DESCRIPTION OF THE EXAMPLE EMBODIMENTS

[0026] The following is a detailed description of example embodiments of the present invention with reference being made to the drawings in which the same reference numerals identify the same elements of structure in each of the several figures.

[0027] Where used in the context of the present disclosure, the terms “first”, “second”, and so on, do not necessarily denote any ordinal, sequential, or priority relation, but are simply used to

more clearly distinguish one step, element, or set of steps or elements from another, unless specified otherwise.

[0028] As used herein, the term “energizable” relates to a device or set of components that perform an indicated function upon receiving power and, optionally, upon receiving an enabling signal.

[0029] In the context of the present disclosure, the term “optics” is used generally to refer to lenses and other refractive, diffractive, and reflective components or apertures used for shaping and orienting a light beam. An individual component of this type is termed an optic.

[0030] In the context of the present disclosure, the terms “viewer”, “operator”, and “user” are considered to be equivalent and refer to the viewing practitioner, technician, or other person who may operate a camera or scanner and may also view and manipulate an image, such as a dental image, on a display monitor. An “operator instruction” or “viewer instruction” is obtained from explicit commands entered by the viewer, such as by clicking a button on the camera or scanner or by using a computer mouse or by touch screen or keyboard entry.

[0031] In the context of the present disclosure, the phrase “in signal communication” indicates that two or more devices and/or components are capable of communicating with each other via signals that travel over some type of signal path. Signal communication may be wired or wireless. The signals may be communication, power, data, or energy signals. The signal paths may include physical, electrical, magnetic, electromagnetic, optical, wired, and/or wireless connections between the first device and/or component and second device and/or component. The signal paths may also include additional devices and/or components between the first device and/or component and second device and/or component.

[0032] In the context of the present disclosure, the term “camera” relates to a device that is enabled to acquire a reflectance, a two dimensional (“2D”) digital image from reflected visible or near-infrared (“NIR”) light, such as structured light that is reflected from the surface of teeth and supporting structures; in addition, the camera can operate in single-image mode or a continuous acquisition or video mode. In the context of the present disclosure, the terms “camera” and “scanner” can be used interchangeably to describe the same device, since the device can obtain different image types.

[0033] The term “subject” refers to the tooth or other portion of a patient that is being imaged and, in optical terms, can be considered equivalent to the “object” of the corresponding imaging system. The term “lens” can be used to identify a single-element lens or a lens group, such as a doublet or other arrangement in which lenses are positioned adjacently, for example.

[0034] The phrase “at or near” for placement of an optical component describes component placement at a position along an optical path where it performs its intended function, within tolerances acceptable in optical fabrication practice. Placement of a phase modulator near the optical stop means positioning the phase modulator at a position close enough to the stop to provide suitable phase modulation to yield an extended depth of field for imaging, as described in more detail subsequently. For a hand-held optical imaging apparatus, a position that is at least within a few mm of the stop can be sufficient for positioning an optical phase modulator.

[0035] In the context of the present disclosure, a reflectance image is a 2D image of a subject obtained by illuminating the subject with a field of light and obtaining the reflected light from the subject. A reflectance image can be monochrome or polychromatic and can use full field illumination or patterned light, such as for surface contour characterization. A polychromatic reflectance image can be obtained using a monochrome sensor with illumination fields of different colors, that is, of different wavelength bands.

[0036] In the context of the present disclosure, a beam is considered to have circular symmetry along an axis when, considered in cross-section through the axis, the difference between a first radial distance from the axis to the nearest edge of the beam and a second radial distance from the axis to the farthest edge of the beam is less than 20% of the first radial distance. A beam not symmetric according to this metric is considered to be cross-sectionally asymmetric.

[0037] FIG. 1 is a schematic diagram displaying an imaging apparatus 70 that can operate as a still image or video camera 24 for polychromatic reflectance image data capture, as well as a scanner 28 for projecting and imaging functions that characterize surface contour using structured light patterns 46. A handheld imaging apparatus 70 can use camera 24 for image acquisition for both contour scanning and image capture functions according to an embodiment of the present disclosure.

[0038] As shown in FIG. 1, a control logic processor 80, or other type of computer may be part of camera 24, controlling the operation of an illumination array 10, as a part of an illumination

system 11, that generates the structured light and directs the light toward a surface position, and controlling operation of an imaging sensor array 30. Image data from a dental object surface 20, such as from a tooth 22, is obtained from imaging sensor array 30 and stored as image data in a memory 72. Imaging sensor array 30 is part of a sensing apparatus 40 that includes a lens assembly 34 and associated elements for acquiring image content. Control logic processor 80, in signal communication with camera 24 components that acquire the image, processes the received image data and stores the mapping in memory 72. The resulting image from memory 72 is then optionally rendered and displayed on a display 74, which may be part of another computer 75 used for some portion of the processing described herein. Memory 72 may also include a display buffer. One or more sensors 42, such as a motion sensor, can also be provided as part of scanner 28 circuitry. The image sensor array 30 can be a charge-coupled device (CCD) or a complementary metal oxide semiconductor (“CMOS”) array, for example.

[0039] In structured light imaging, a pattern of lines or other shapes is projected from illumination array 10 toward the surface of an object from a given angle. The projected pattern from the illuminated surface position is then viewed from another angle as a contour image, taking advantage of triangulation in order to analyze surface information based on the appearance of contour lines. Phase shifting, in which the projected pattern is incrementally shifted spatially for obtaining additional measurements at the new locations, is typically applied as part of structured light imaging, used in order to complete the contour mapping of the surface and to increase overall resolution in the contour image.

[0040] The schematic diagram of FIG. 2 displays, with the example of a single line of light “L”, how patterned light projection is used for obtaining surface contour information by a scanner using a handheld camera or other portable imaging device. A mapping is obtained as illumination system 11 directs a pattern of light onto surface 20 and a corresponding image of a line “L” is formed on imaging sensor array 30. Each pixel 32 on imaging sensor array 30 maps to a corresponding pixel 12 on illumination array 10 according to modulation by surface 20. Shifts in pixel position, as represented in FIG. 2, yield useful information about the contour of surface 20. It can be appreciated that the basic patterns shown in FIG. 2 can be implemented in a number of ways, using a variety of illumination sources and sequences for light pattern generation and using one or more different types of sensor arrays 30. Illumination array 10 can utilize any of a number

of types of arrays used for light modulation, such as a liquid crystal array or digital micromirror array, such as that provided using the Digital Light Processor or “DLP” device from Texas Instruments, Inc. of Dallas, TX. This type of spatial light modulator is used in the illumination path to change the light pattern as needed for the mapping sequence.

[0041] By projecting and capturing images that show structured light patterns that duplicate the arrangement shown in FIG. 2 multiple times, the image of the contour line on the camera simultaneously locates a number of surface points of the imaged object. This speeds up the process of gathering many sample points, while the plane of light (and usually also the receiving camera) is laterally moved in order to “paint” some or all of the exterior surface of the object with the plane of light.

[0042] A synchronous succession of multiple structured light patterns can be projected and analyzed together for a number of reasons, including to increase the density of lines for additional reconstructed points and to detect and/or correct incompatible line sequences. The use of multiple structured light patterns is described in commonly assigned U.S. Patent Application Publication Nos. US2013/0120532 and US2013/0120533, both entitled “3D INTRAORAL MEASUREMENTS USING OPTICAL MULTILINE METHOD” and incorporated herein in their entirety.

[0043] FIG. 3 displays surface imaging using a pattern with multiple lines of light. Incremental shifting of the line pattern and other techniques help to compensate for inaccuracies and confusion that can result from light encountering abrupt transitions along the surface, whereby it can be difficult to positively identify the segments that correspond to each projected line. In FIG. 3, for example, it can be difficult over portions of the surface to determine whether line segment 16 is from the same line of illumination as line segment 18 or adjacent line segment 19. If line features are blurred or defocused, it can be much more difficult to identify and trace line segments.

[0044] Light projectors using spatial light modulators are advantaged over raster scanned projectors for structured light projection from handheld cameras and scanners, but suffer from reduced brightness, limited depth of field (“DOF”), and relatively large size. Example embodiments of the present disclosure are directed to improved system designs that can help to counteract these shortcomings.

Etendue Considerations

[0045] As is well known in the optical arts, etendue or “geometrical extent” relates to the amount of light, in terms of size and angular spread, that can be handled by an optical system. For illumination, the following general expression is typically used:

$$Etendue \approx A\Omega$$

where “A” represents the source emitting area and “Ω” represents the solid angle from which light is collected at the entrance pupil.

[0046] Thus, numerically, etendue is proportional to the product of two factors, namely the image or source area and the solid angle subtended by the entrance pupil, also considered as the square of the numerical aperture. Increasing the numerical aperture, for example, increases etendue so that light propagates through the system with a larger angular spread. Increasing the source size, so that light originates over a larger area, also increases etendue and, therefore, brightness.

[0047] Similar to entropy in a thermodynamic system, once the etendue of a light beam has been increased (for example, using a light homogenizer), it cannot be decreased, no matter what type of additional passive optical system is used to further modify the beam’s spatial and angular characteristics. Etendue is expressed as a value in units of area-steradian, for example, in mm²-sr.

[0048] The schematic diagram of FIG. 4 displays a projection apparatus 100 for projecting images, structured light, or a light field. A laser diode 112 directs light along an optical axis OA through a collimator lens L1 to a uniform light generator 90 that includes a light homogenizer 120, such as a lenslet array. Homogenizer 120 increases the etendue of the light. A condenser lens L2 with a given focal length f1 condenses the light, directed to a spatial light modulator (“SLM”) 130, such as a Digital Light Processor (“DLP”) from Texas Instruments Inc. of Dallas, TX. SLM 130 can alternately be some other type of light modulator, such as a liquid crystal on silicon (“LCOS”) or liquid crystal display (“LCD”) device.

[0049] SLM 130 spatially modulates the shaped, condensed light beam from lens L2 to impart a light pattern or other modulation of the light density, such as to emulate gray level changes. The modulated light beam from SLM 130 is directed through a projection lens L3 with

a stop aperture 136. Projection optics L3, schematically represented as a single lens element in FIG. 4, can be a multi-lens system. Aperture 136 determines the depth of field for the projected light. In some applications, such as where a large depth of focus is needed, such as in 3D stereo imaging using structured light, a small stop aperture 136 size is used to provide a relatively large depth of field, at the expense of light throughput. Light is projected toward a focal plane 140. Dotted lines indicate bounds of an approximate depth of field (“DOF”) for projection apparatus 100.

[0050] By comparison with FIG. 4, the schematic diagram of FIG. 5 displays a projection apparatus 110 having higher brightness and thus higher overall efficiency, using the same laser diode 112, SLM 130, and projection optics L3 as that of FIG. 4. Similar to the arrangement of FIG. 4, laser diode 112 directs light through collimator lens L1’ to homogenizer 120’.

[0051] In the projection apparatus 110 of FIG. 5, design parameters for collimator lens L1’ and homogenizer 120’ are different from those for collimator lens L1 and homogenizer 120 in FIG. 4. A condenser lens L2’ with a given focal length f_2 , longer than focal length f_1 in FIG. 4, condenses the light, directed to SLM 130. SLM 130 spatially modulates the light from lens L2’ to generate a light pattern or other modulation of the light density, such as to emulate gray level changes. The modulated light is directed through projection optics L3 with stop aperture 136. As was described with reference to FIG. 4, projection optics L3, schematically represented as a single lens element in FIG. 5, can be a multi-lens system. Light is projected toward focal plane 140. Dotted lines indicate bounds of an approximate depth of field (“DOF”) for projection apparatus 110.

Efficiency Improvement

[0052] It is instructive to show how etendue considerations are used in the design of the system illustrated in FIG. 5 to provide a higher light efficiency than the system in FIG. 4.

[0053] For FIG. 4, the divergent light at SLM 130 has etendue as follows:

$$Etendue_m = A_4 \Omega_4$$

wherein “ A_4 ” is the active area of SLM 130; “ Ω_4 ” represents the solid angle for light at SLM 130, as determined by the conditioned output of homogenizer 120 and condenser lens L2. Ω_4 is generally large due to the light redistribution caused by homogenizer 120.

[0054] Value “ Ω_p ” represents the solid angle of light at projection optics L3, determined by the area of stop aperture 136 and by the distance from SLM 130 to optics L3. The projection optics etendue is:

$$Etendue_p = A_4 \Omega_p$$

[0055] In general, the projection system is designed with a relatively small stop aperture 136 in order to provide larger depth of field, and thus Ω_p is small. In fact, the etendue of the projection optics is much smaller than that of the light at SLM 130 so that the optical efficiency for projection is generally low.

[0056] The throughput efficiency at the projection optics is calculated as:

$$Throughput = \frac{\mu Etendue_p}{Etendue_m}$$

wherein factor “ μ ” relates to general optical efficiency, including other factors of the system optics.

[0057] By comparison with FIG. 4, projection apparatus 110 of FIG. 5 has an improved design with a smaller Ω_4 , that is, a smaller solid angle for light at SLM 130. This reduces the value of $Etendue_m$, increasing the overall light throughput value, as described in the equations above. The inventors have found that, in practice, the improved design according to the present disclosure can boost throughput efficiency for a laser diode projection apparatus from typical values of about 5% to values as high as about 42%.

[0058] For the embodiments shown in FIGs. 4 and 5, light homogenizer 120, 120' is typically a lenslet array, providing a uniform light energy distribution with a flat-top beam profile. Other types of suitable homogenizer can include a diffractive beam homogenizer, for example. Light homogenizer 120, 120' provides a substantially uniform beam, with beam energy varying by no more than 50% over 75% of the beam width, for example.

[0059] Due to the extremely small etendue of the laser diode 112 light source, the inventors have found it useful to design and use controlled beam collimation and a lenslet array system to produce a low-etendue flat-top beam, which consequently enables high throughput projection. The following equation guides the design of lenslet array 120', collimation lens L1', and condenser lens L2' in the system of FIG. 5:

$$\begin{pmatrix} a \\ x \end{pmatrix} = \begin{pmatrix} \frac{D_{collimate}}{2f_{condenser}} \\ \frac{f_{condenser} * d_{lenslet}}{f_{lenslet}} \end{pmatrix}$$

wherein values “ a ” and “ x ” are the divergence angle and beam size along the x axis direction, respectively, of flat-top homogenized light incident onto SLM 130; value “ $D_{collimate}$ ” is the collimated laser beam diameter; value “ $f_{condenser}$ ” is the focal length of the condenser lens; and “ $d_{lenslet}$ ” and “ $f_{lenslet}$ ” are the diameter and focal length of the lenslets, respectively. The beam size along the y axis is calculated in similar manner.

[0060] The active area (“ A_4 ”) of spatial light modulator 130 is predetermined. In order to have $Etendue_m$ as small as possible, the rest of the projection apparatus optical components are designed such that the beam divergence angle (and thus solid angle Ω_4) is minimized. This means that lens L1’ must be designed such that the collimated beam size $D_{collimate}$ should be correspondingly as small as possible, but still covering sufficient lenslet elements to maintain uniformity. The collimated beam area should, in general, have sufficient width to cover or extend across at least 10 lenslets of the homogenizer to result in a reasonably uniform flat-top homogenized light. Meanwhile, focal length value “ $f_{condenser}$ ” of condenser lens L2’ should be as large as possible, within practical constraints of the mechanical configuration and considering the size of the handheld imaging apparatus. The active area of spatial light modulator 130 determines the x and y dimensions for ideal beam cross-section; this, in turn, determines the design of lenslet components by fixing the relationship $d_{lenslet}/f_{lenslet}$. To keep $D_{collimate}$ small, it is desirable for $d_{lenslet}$ to be as small as practically manufacturable, thus constraining $f_{lenslet}$. The inventors have determined that, within the constraints of handpiece size and lenslet array manufacturability, in order to significantly improve the light efficiency of the projection system, lenslet array parameters should have values such that the etendue of the homogenizer 120’ is less than ten times (10x) the etendue of the projection lens L3.

[0061] By way of example, an etendue estimate for an embodiment can be computed as follows: for a digital micromirror array having an active area “ A ” in mm^2 and used as SLM 130, the half-angle of acceptance can be approximately 12 degrees. Given these conditions, etendue of light at the digital micromirror array can be calculated in terms of area “ A ”, using:

$$A \times 2\pi(1 - \cos(12 \text{ degrees})) = 0.137 A$$

Depth of Field Improvement

[0062] For structured light imaging using triangulation, as described previously with reference to FIGS. 1-3, high brightness is advantageous for image capture. At the same time, maintaining a narrow line width throughout imaging range is important for accurate detection of surface features and improved usability of the device.

[0063] Brightness increases at higher numerical aperture (“NA”) of the imaging lens, with some corresponding loss of depth of field. There is an inverse-squared relationship between the NA and depth of field of the lens. However, by controlling the imaging system’s NA differently in two orthogonal directions by blocking higher diffractive orders according to an embodiment of the present disclosure, it is possible to significantly increase the depth of field with minimal loss of image brightness.

[0064] The inventors address the problem of providing a non-symmetric NA using a spatial filter along one direction at the back focal plane of lens L3. As shown in FIG. 6, a projection apparatus 200 has laser diode light source 112, which directs light along optical axis OA and through a small collimation lens L1’ having a relatively large NA. This generates a collimated illumination beam of small diameter. It should be noted that multiple collimated illumination beams, each of a different wavelength for a primary color (for example, Red, Green, and Blue) could be used, typically combined along the same optical axis OA. Beam re-shaping is performed by conveying the light through homogenizer 120’, such as a lenslet array, and by condenser lens L2’, which has a relatively large focal length. The small diameter illumination beam is thereby conditioned to provide a uniform beam of relatively low divergence at the plane of SLM 130. SLM 130 can be an array of micromirrors for forming image content, such as a structured light image projected onto an intraoral surface. Each micromirror accepts illumination and reflects the light toward projection lens L3.

[0065] Due to the coherent character of light from the laser source, the micromirror array behaves as a type of reflective diffraction grating. Represented at the output of SLM 130 in FIG. 6 are different representative diffraction orders, indicated in solid, dashed, and long-dashed lines. Most of the light energy is in the principal (0th and 1st) diffracted orders, indicated in solid lines.

The projection lens L3 then directs the SLM 130 output toward focal plane 140, which may include a tooth or other intraoral surface, display screen, or other object or surface used by the projection apparatus 200.

[0066] Still referring to FIG. 6, the Fourier plane “FP” for the projection optics is located at the back focal plane of projection lens L3, where a spatial filter 150 can be positioned to selectively block diffraction orders at higher angles. FIG. 7 shows Fourier plane “FP” from a cross-section view through the projected beam. FIG. 8 shows the action of spatial filter 150, with two blocking filter segments 150a and 150b for blocking higher diffraction orders at Fourier plane “FP”, and effectively reducing the NA for light in the corresponding direction. According to an embodiment of the present disclosure, the spatial filter 150 blocks one or more higher diffracted orders at Fourier Plane “FP”.

[0067] Using the arrangement shown in FIGs. 6 and 8 for spatial filter 150 use, an embodiment of the present disclosure passes the light of principal diffraction orders, such as the 0th (un-diffracted) and 1st order diffracted light, through filter 150 to form the final projection image, while blocking the light of higher orders in the direction orthogonal to the projected line length. Given this beam conditioning arrangement, the light beam used to construct the final projection image at focal plane 140 has different divergence angles in the two orthogonal directions, with reduced divergence in the direction orthogonal to the projected line length. Manipulation of the gap width in spatial filter 150 (referring to FIG. 8) allows selection of which diffraction orders to block in order to meet enlarged DOF requirements for the imaging application and, at the same time, allows the projection apparatus 200 to achieve high light throughput values.

[0068] FIGS. 9A and 9B show exemplary results for structured light images captured at different projection image planes using the embodiment of FIG. 6 that has spatial filter 150. FIG. 9A shows the projected image at the focal plane 140. FIG. 9B shows the projected image at about 50mm from the focal plane 140. For comparison, the DOF of the optical apparatus without spatial filter 150 (such as in the arrangement of FIG. 5) is only about +/- 8mm. Accordingly, the novel use of the spatial filter according to an embodiment of the present disclosure can provide significant improvement of the projection apparatus’s depth of field with minimum loss of image brightness.

Beam Reshaping and Light Energy Redistribution

[0069] In the embodiment of FIG. 6, flat-top beam generation is performed using a lenslet array as homogenizer 120'. FIG. 10 displays an alternative approach for beam reshaping using crossed gradient index lenses ("GRIN") 210, 220. The laser diode 112 emission has horizontal and vertical profiles with pronouncedly different divergence, so that the asymmetric cross-sectional output of the emitted light beam from laser diode 112 is highly elliptical in shape. The difference in divergence can be on the order of 3:1 or more, for example.

[0070] In the FIG. 10 example embodiment, each of the gradient index lenses 210, 220 has predominant optical power in one direction orthogonal to the optical axis; power in the other orthogonal direction to the axis is much smaller or zero. As lenses 210 and 220 are disposed, the predominant optical power of the first gradient index lens is orthogonal to the predominant optical power of the second gradient index lens for shaping an energy profile of the light beam over mutually orthogonal axes.

[0071] Following collimation at a first collimating lens "L1a", the shaped beam is directed through first GRIN lens 210 and through second GRIN lens 220 that has an optical power perpendicular to the optical power of first GRIN lens 210. The output shaped beam then goes to a second collimating lens "L1b". The resulting collimated output beam is substantially uniform, having the relatively uniform light energy output shown in FIG. 11 in a highly magnified cross-section 230, with the flat-top energy profile shown in the example graph 232. The GRIN lens pair 210, 220 and second collimating lens L1b in FIG. 10 can replace the component group with homogenizer 120' and lens L2' that provide a uniform light generator 90 in FIG. 6, producing collimated, flat-top beam that is incident onto SLM 130, the flat-top beam having no more than 50% intensity variation over 75% of the beam width, for example.

[0072] The use of crossed GRIN optics enables controlled shaping of the beam energy profile with a highly rectangular, flat-top output profile. By changing the divergence angle of the GRIN lenses (that is, the predominant optical power), the rectangular profile can be suitably varied to an alternate rectangular aspect ratio for a particular projector application. The GRIN lenses used in this application provide a flat-top energy profile with a specified divergence angle. Cascaded GRIN lenses can be used to adjust the cross-sectional aspect ratio of the beam to match the dimension of the SLM 130.

[0073] The invention has been described in detail herein, and may have been described with particular reference to a suitable or presently preferred example embodiment, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention. The presently disclosed example embodiments are, therefore, considered in all respects to be illustrative and not restrictive. The scope of the invention is indicated by the appended claims, and all changes that come within the meaning and range of equivalents thereof are intended to be embraced therein.

CLAIMS

What is claimed is:

1. A projection apparatus for an intraoral scanner comprising:
 - a) a laser diode energizable to generate a beam of laser light along an optical axis;
 - b) a collimator lens disposed along the optical axis in the path of the generated light beam;
 - c) a uniform light generator disposed along the optical axis to improve the uniformity of the generated light beam of the collimator lens;
 - d) a spatial light modulator disposed in the path of the beam from the uniform light generator and energizable to impart a pattern to the beam;
 - e) a projection optic that projects the patterned light toward a focal plane; and
 - f) a spatial filter that is disposed to block one or more diffraction orders of the patterned light at the Fourier plane of the projection optic to form a filtered projection beam.
2. The projection apparatus of claim 1 wherein the uniform light generator comprises a plurality of lenslets and a condenser lens.
3. The projection apparatus of claim 1 wherein the uniform light generator comprises of two gradient index lenses oriented with optical power orthogonal to each other and another collimator lens.
4. The projection apparatus of claim 3 wherein the two gradient index lenses differ in divergence by three times or more.
5. The projection apparatus of claim 1 wherein the spatial filter blocks a portion of the patterned light in one direction orthogonal to the optical axis.
6. The projection apparatus of claim 1 wherein the uniform light generator comprises a

diffractive beam homogenizer.

7. The projection apparatus of claim 1 further comprising an image sensor array that is disposed to capture image data related to a dental object from the projected patterned light.

8. A projection apparatus for an intraoral scanner comprising:

- a) a laser diode energizable to generate a beam of laser light along an optical axis;
- b) a collimator lens disposed along the optical axis in the path of the generated light beam to form a substantially collimated beam;
- c) a homogenizer comprising a plurality of lenslets disposed along the optical axis in the path of the collimated beam, wherein the homogenizer has a first etendue;
- d) a condenser lens that directs a condensed light beam from the homogenizer along the optical axis;
- e) a spatial light modulator that is energizable to impart a pattern to the condensed light beam; and
- f) a projection optic having a second etendue, wherein the projection optic projects the patterned light toward a focal plane,
 - wherein the first etendue of the homogenizer is less than ten times the second etendue of the projection optic; and
 - wherein the collimated beam extends across at least ten lenslets of the homogenizer.

9. The projection apparatus of claim 8 wherein the condensed light beam has etendue less than or equal to the etendue of the spatial light modulator.

10. The projection apparatus of claim 8 further comprising an image sensor array that captures an image of the projected patterned light on a dental object.

11. The projection apparatus of claim 8 wherein the spatial light modulator has an array of micromirrors.

12. The projection apparatus of claim 8 wherein the pattern that is imparted comprises a plurality of parallel lines of light.
13. A projection apparatus for intraoral imaging comprising:
- a) a laser diode energizable to generate a beam of laser light along an optical axis;
 - b) a first collimator lens disposed along the optical axis in the path of the generated light beam;
 - c) first and second gradient index lenses disposed along the optical axis in the path of the light beam that is conveyed through the first collimator lens, wherein the predominant optical power of the first gradient index lens is orthogonal to the predominant optical power of the second gradient index lens for shaping an energy profile of the light beam over mutually orthogonal axes;
 - d) a second collimator lens that directs a substantially collimated and uniformized light beam from the shaped beam output along the optical axis;
 - e) a spatial light modulator that imparts a pattern to the substantially collimated and uniformized light beam; and
 - f) a projection optic that projects the patterned light toward a focal plane.
14. A method for projection in intraoral scanning comprising:
- a) energizing a laser diode to generate a beam of laser light along an optical axis;
 - b) collimating the beam of laser light and conditioning the energy profile of the collimated beam for improved uniformity;
 - c) imparting a pattern to the uniformized beam; and
 - d) projecting the patterned light toward a focal plane of a projection optic, through a spatial filter that is disposed to block one or more diffraction orders of the patterned light at a Fourier plane of the projection optic.
15. The method of claim 14 wherein imparting the pattern to the uniformized beam comprises modulating the light at an array of micromirrors.
16. The method of claim 15 wherein the imparted pattern is a set of parallel lines.

17. The method of claim 14 wherein conditioning the energy profile of the collimated beam comprises conveying the collimated beam through a light homogenizer.

18. The method of claim 14 further comprising capturing an image of the projected patterned light on a dental object.

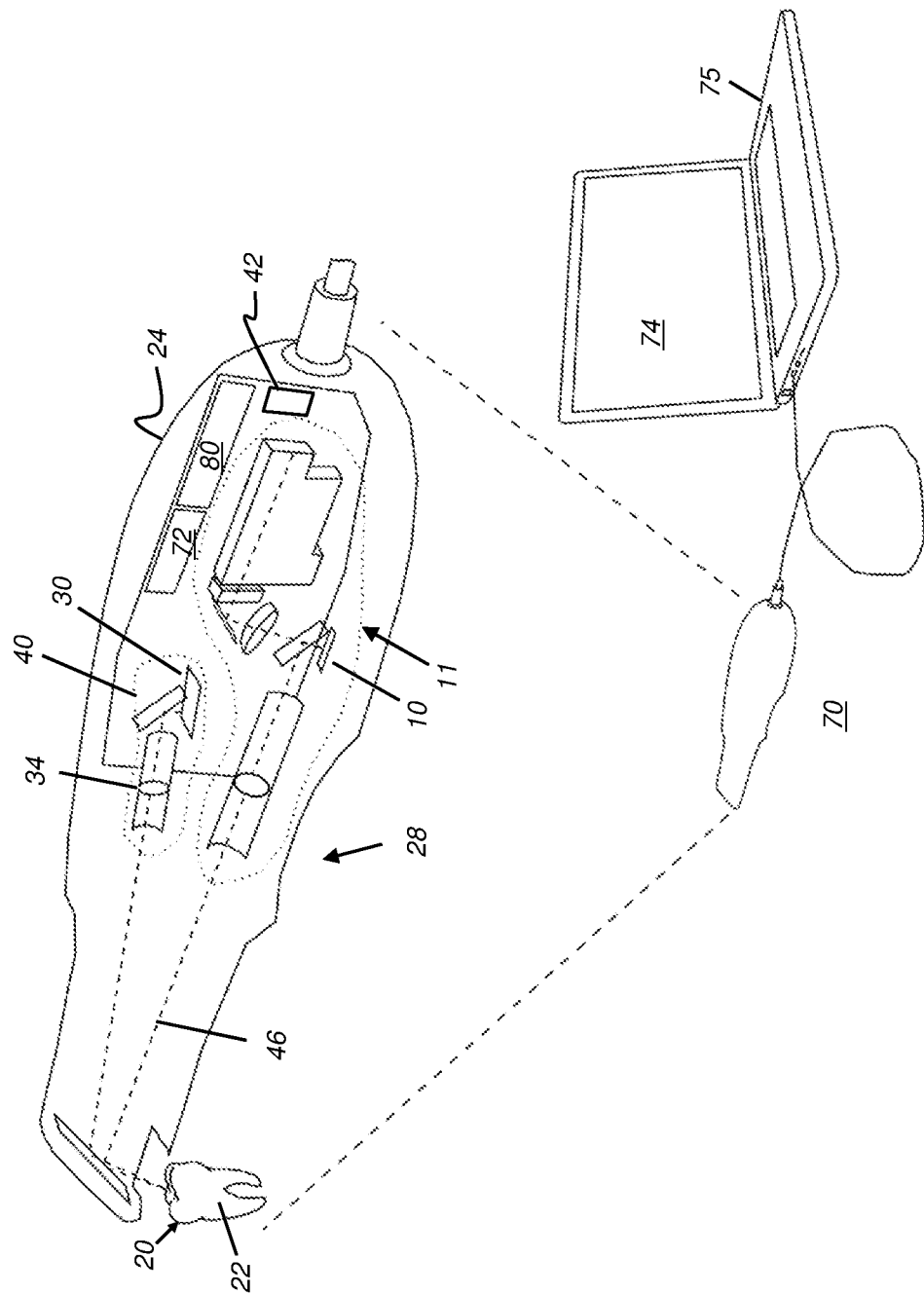


FIG. 1

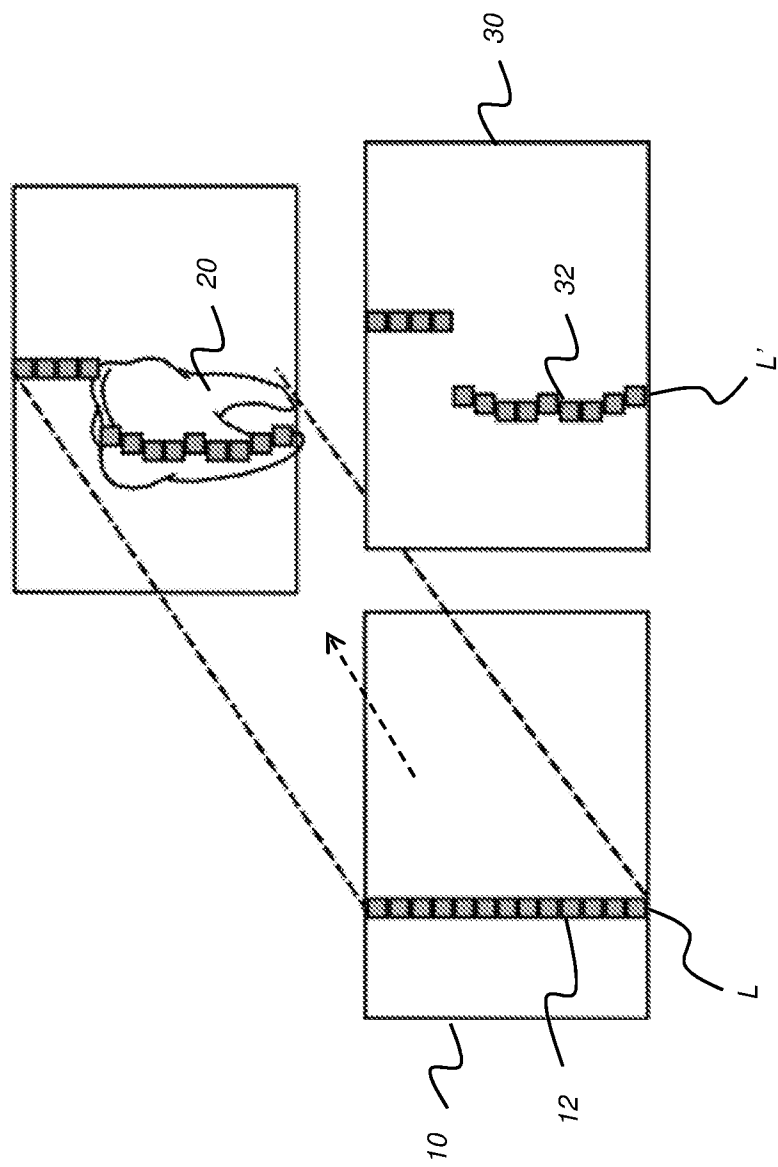


FIG. 2

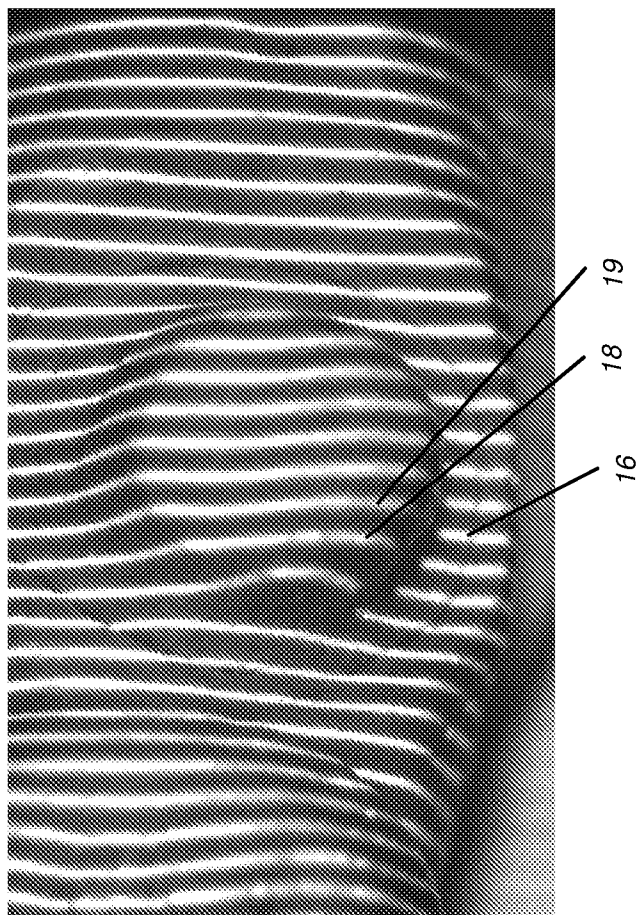


FIG. 3

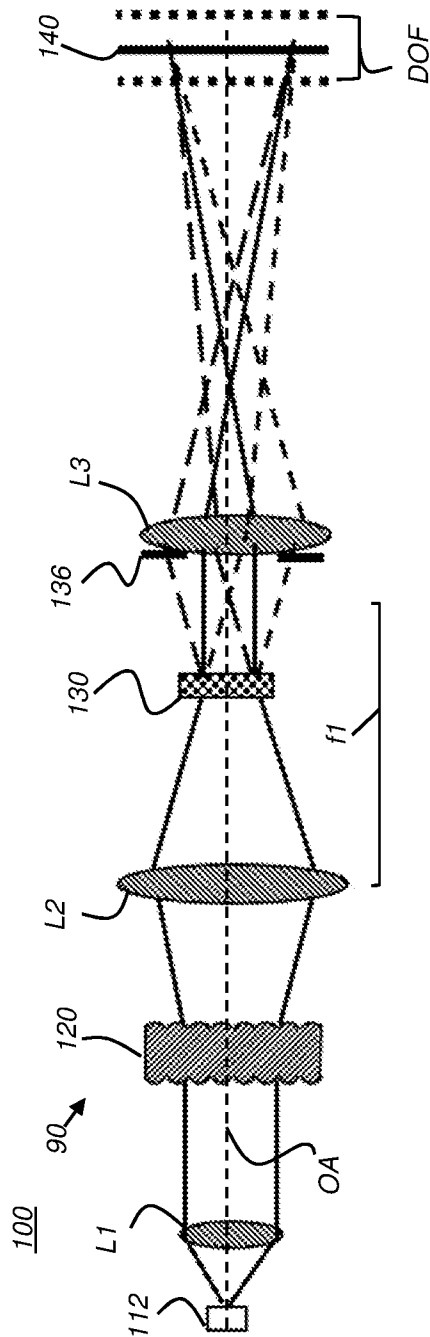


FIG. 4

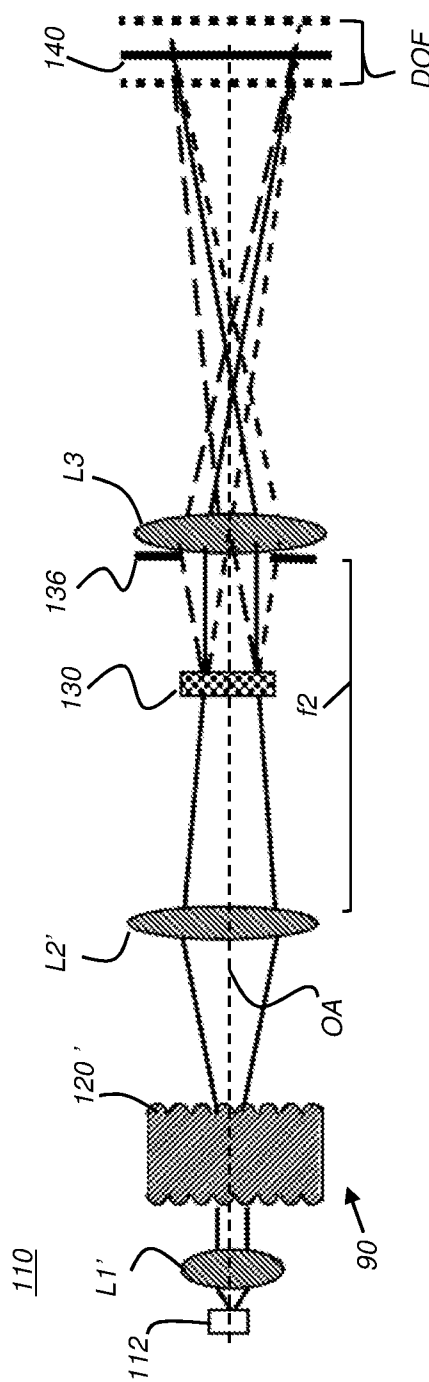


FIG. 5

200

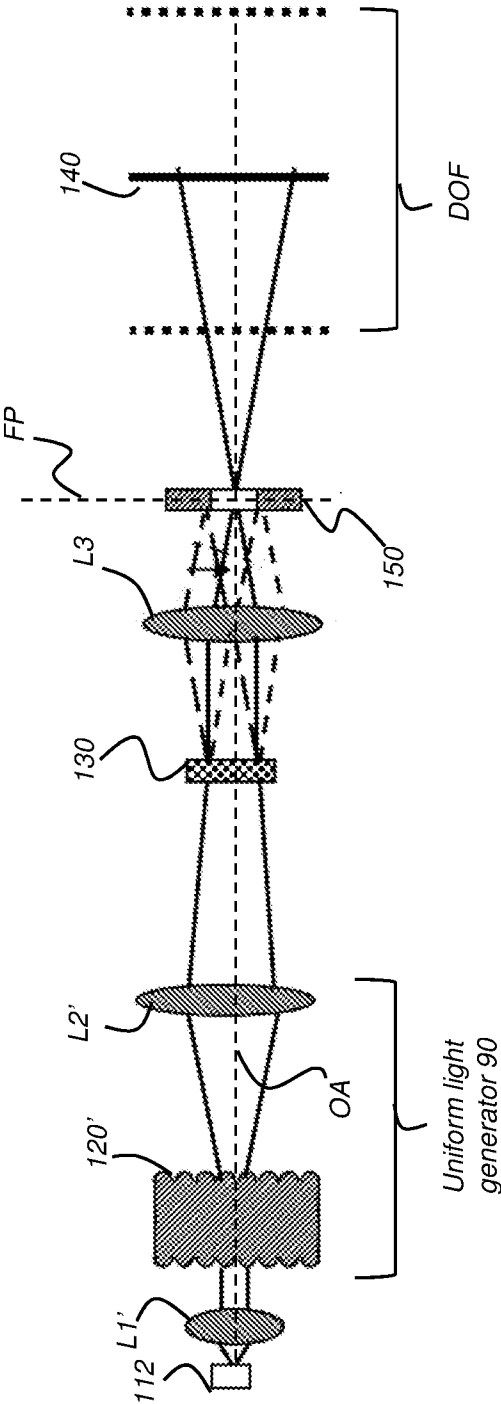


FIG. 6

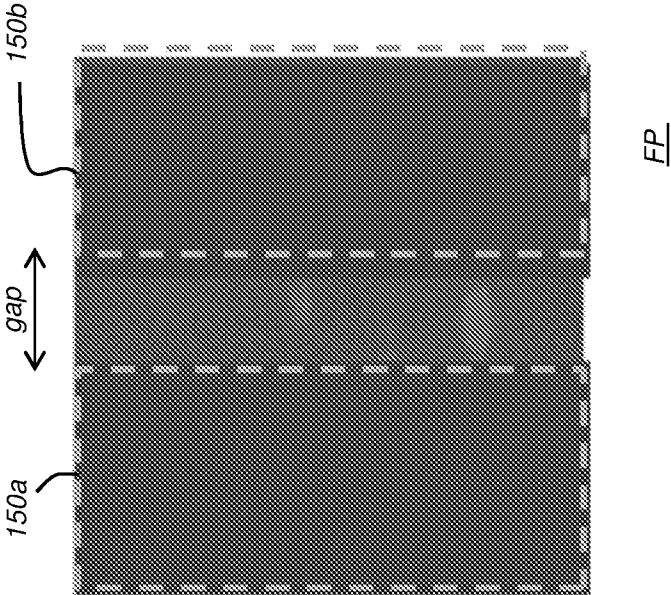


FIG. 8

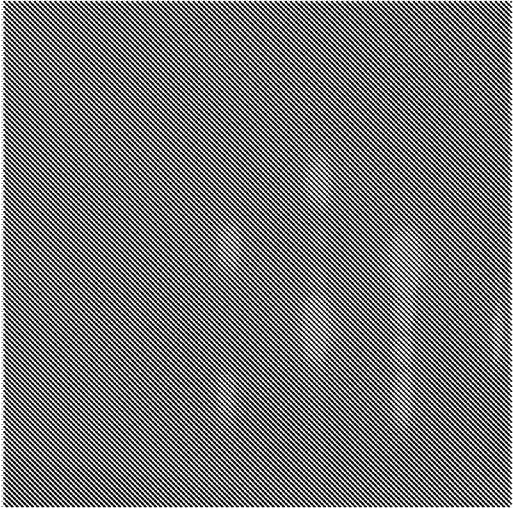


FIG. 7

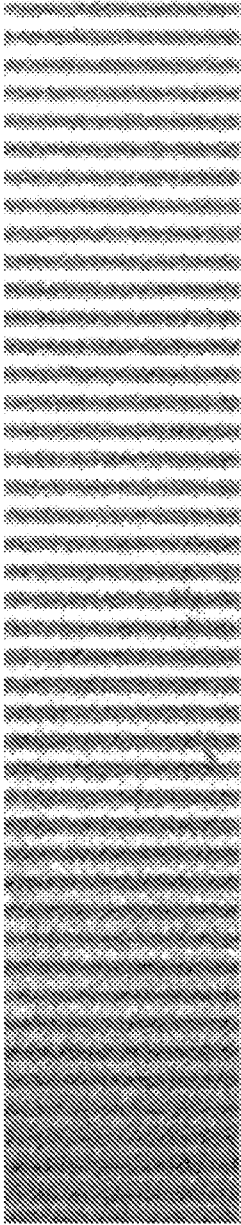


FIG. 9A

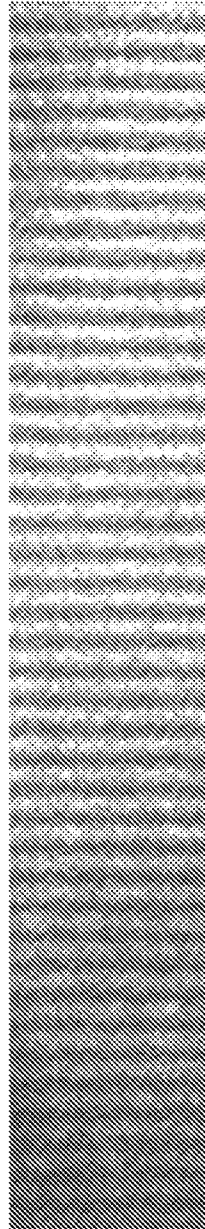


FIG. 9B

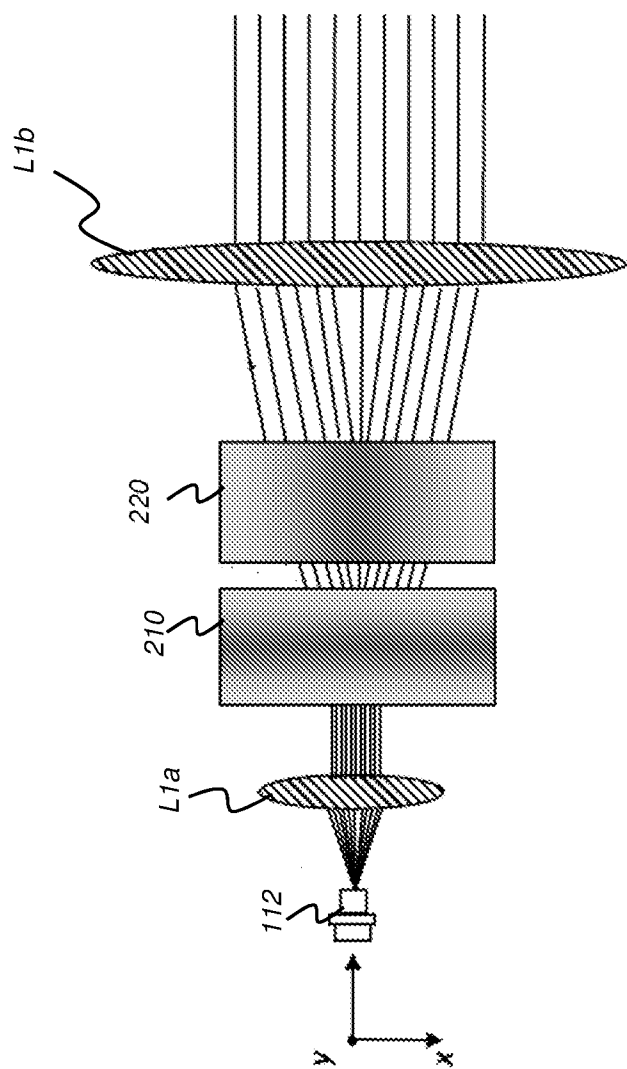


FIG. 10

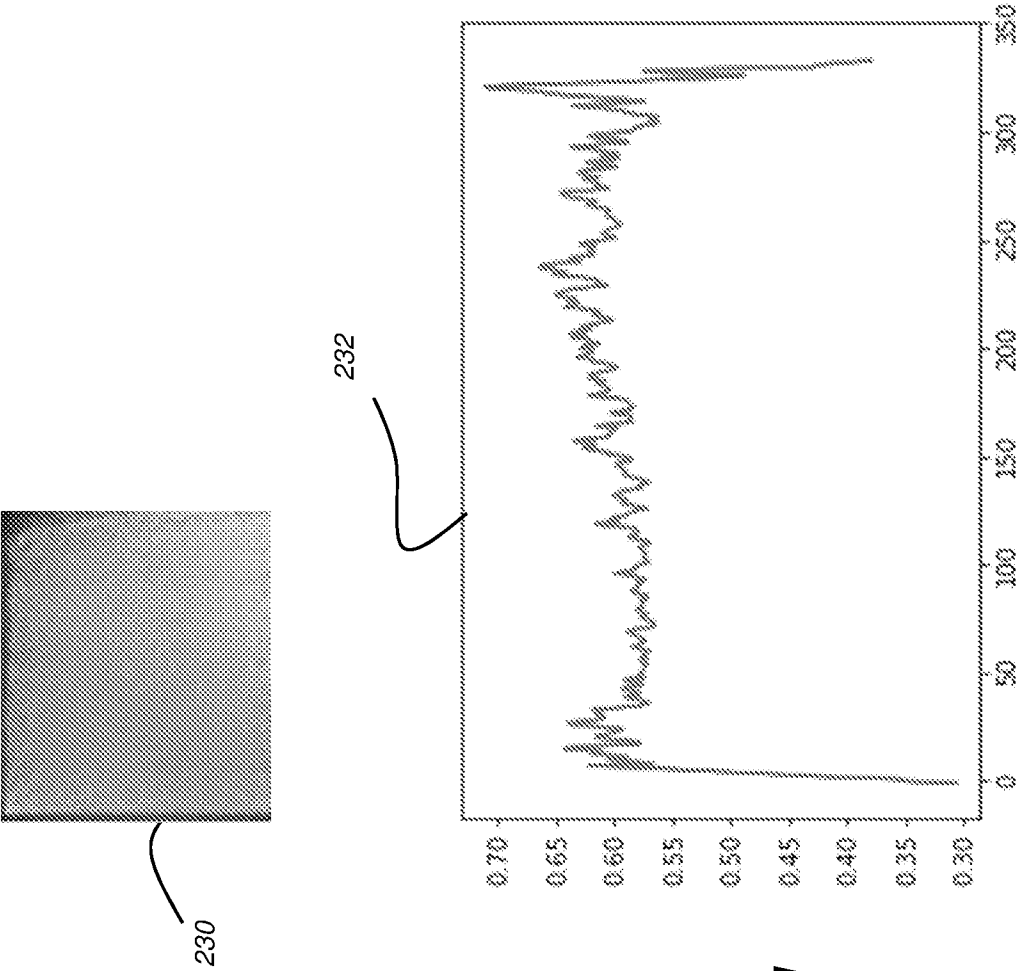


FIG. 11