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(54) **STRUCTURED LIGHT PROJECTOR**

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(52) **U.S. Cl.**

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(57) **ABSTRACT**

There is provided according to aspects of the present disclosure a structured light projector, a method of projecting a structured light pattern, and a depth sensing device. The projector includes an emitters array and a mask. The emitters array includes a plurality of individual light emitters. The light from each of the individual emitters diverges. The emitters array has a spatial intensity profile that is associated with the light divergence output of the array's individual emitters. The mask is designed to provide a structured light pattern when illuminated, and is positioned at a distance relative to the emitters array where rays from adjacent emitters overlap, and where such overlaps provide uniform light intensity distribution across the mask plane.

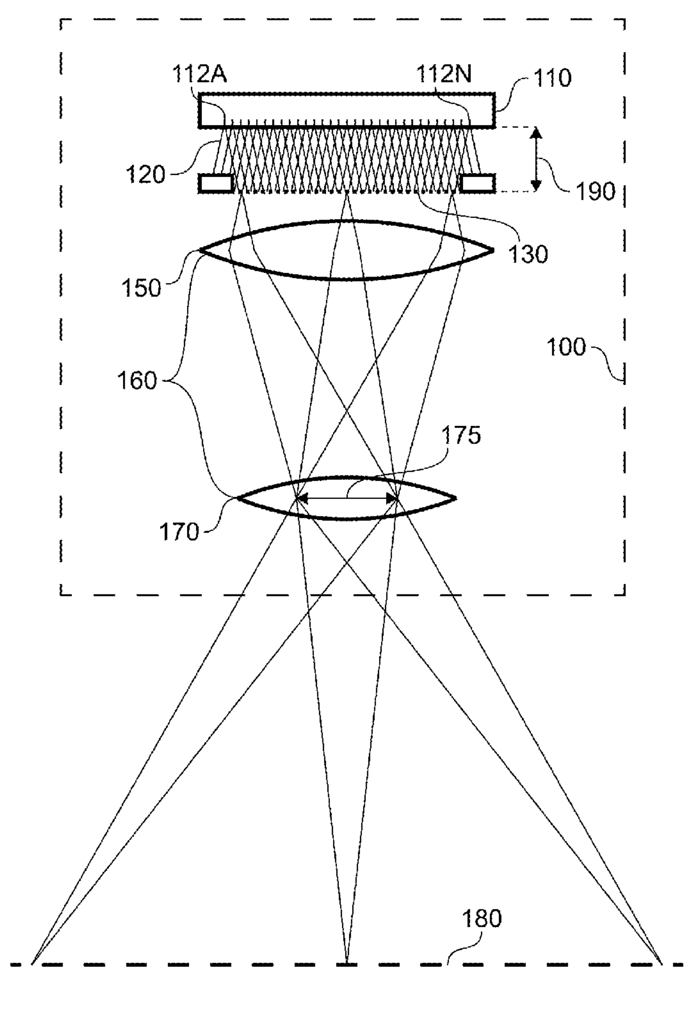
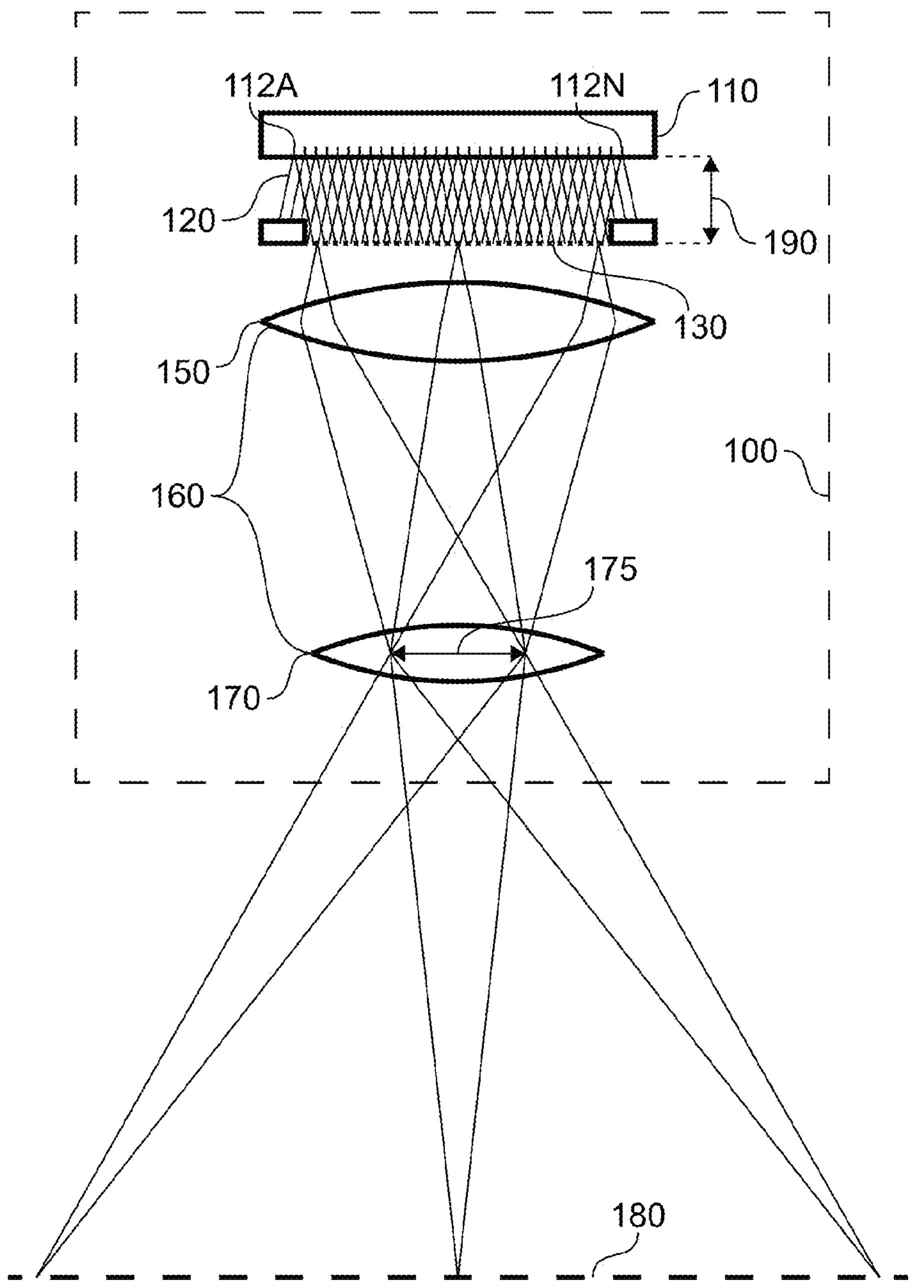


FIG. 1



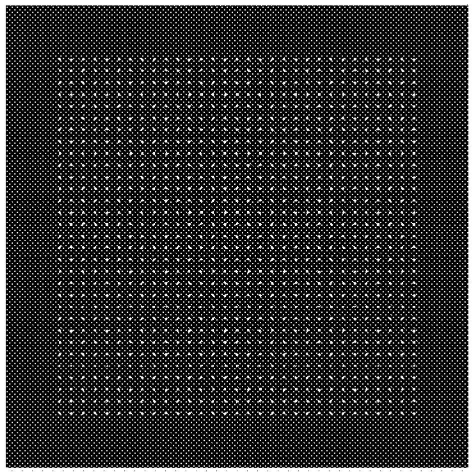


FIG. 2A

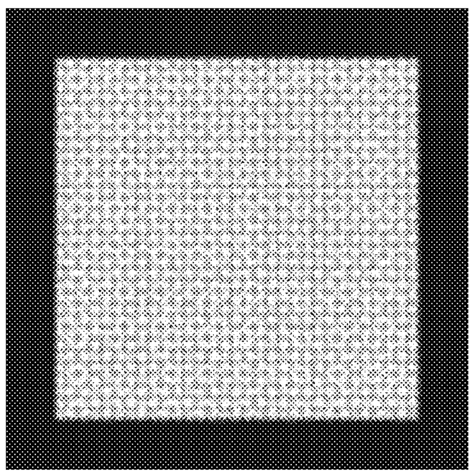


FIG. 2B

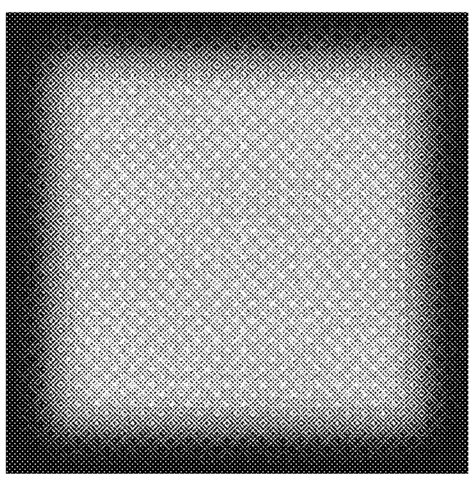


FIG. 2C

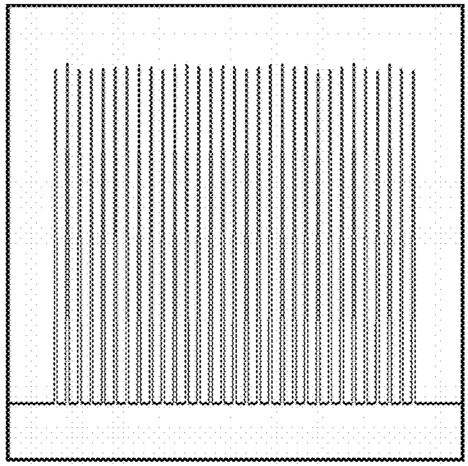


FIG. 3A

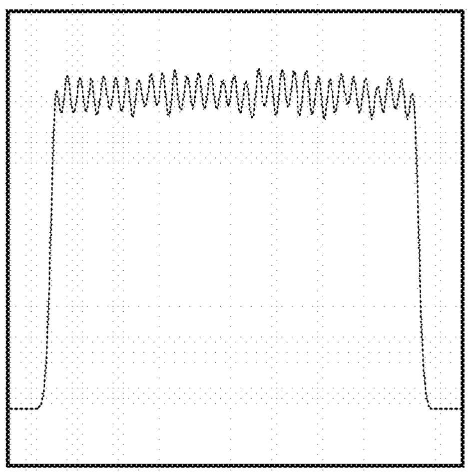


FIG. 3B

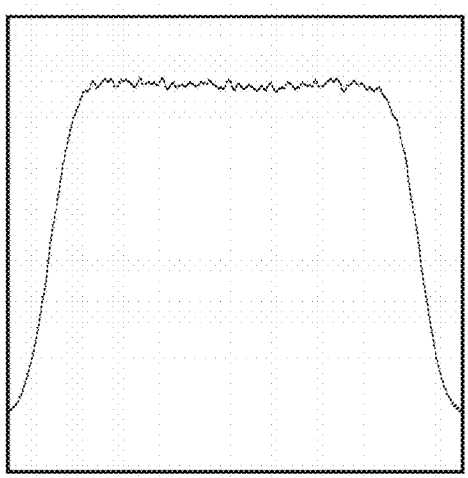


FIG. 3C

FIG. 4

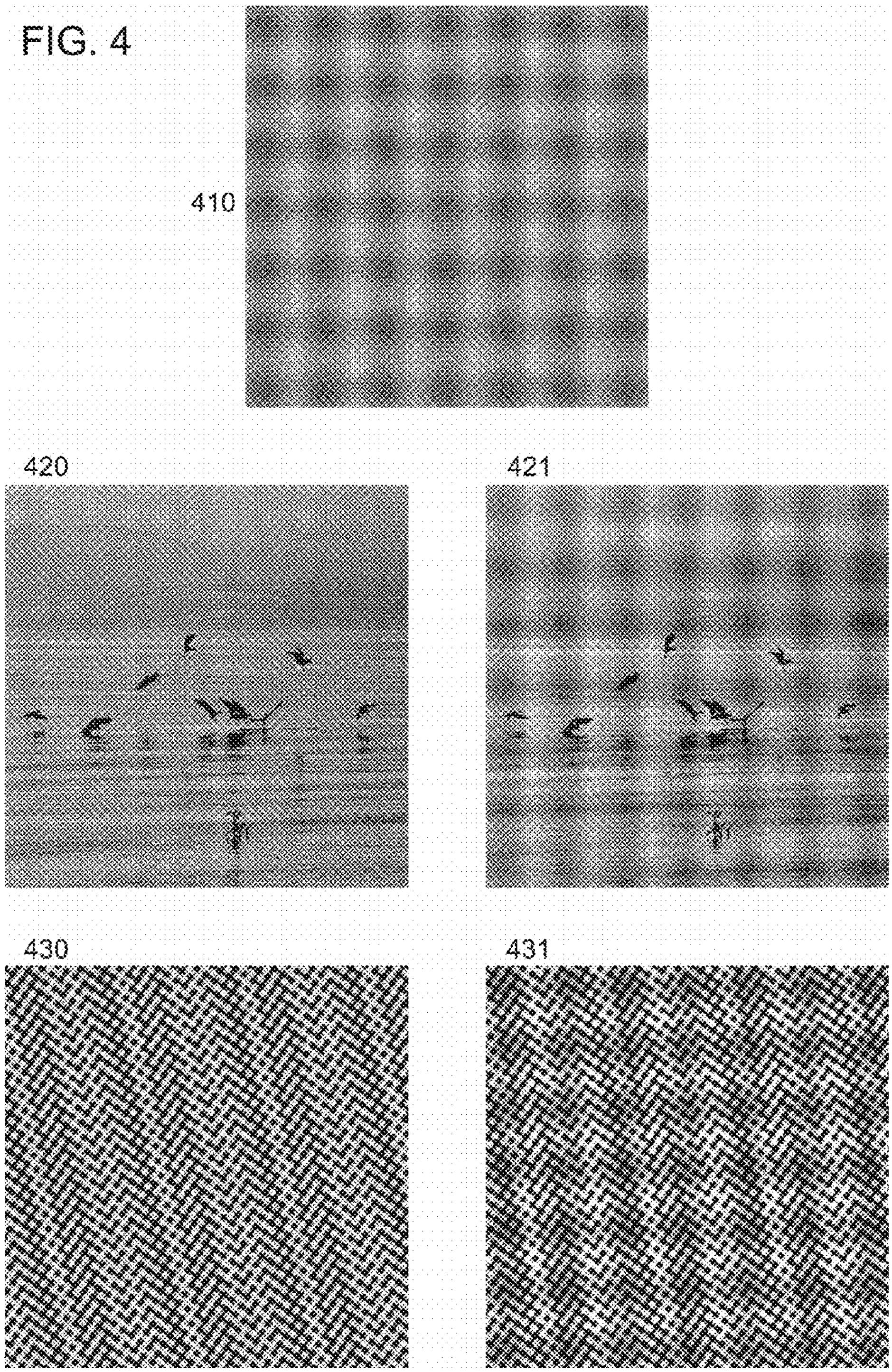


FIG. 5

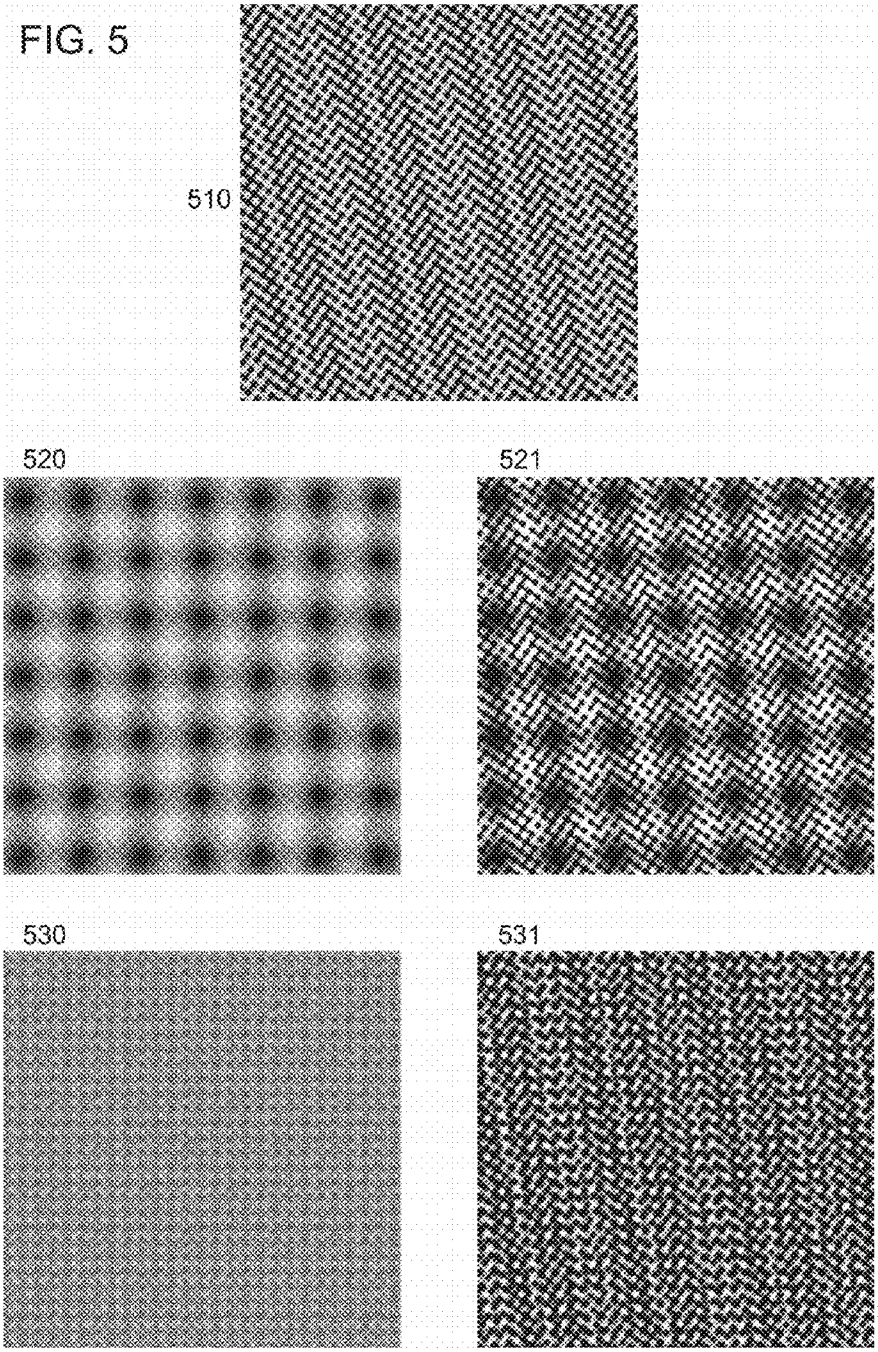


FIG. 6

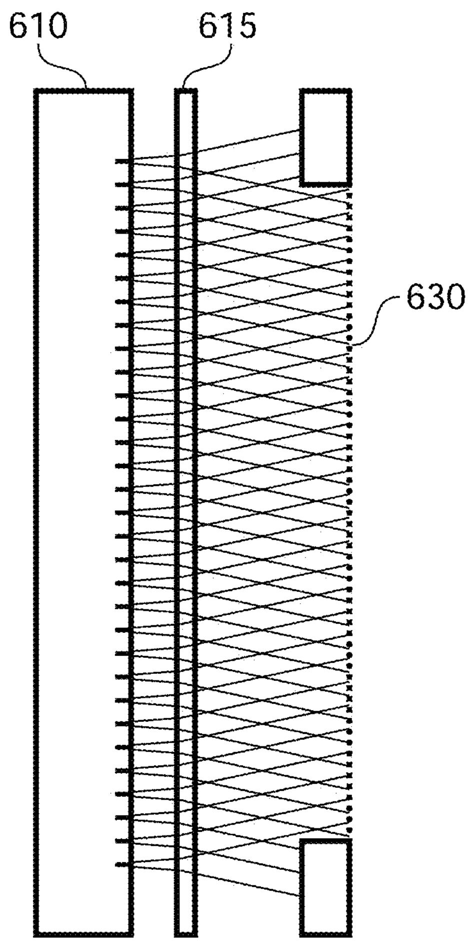


FIG. 7

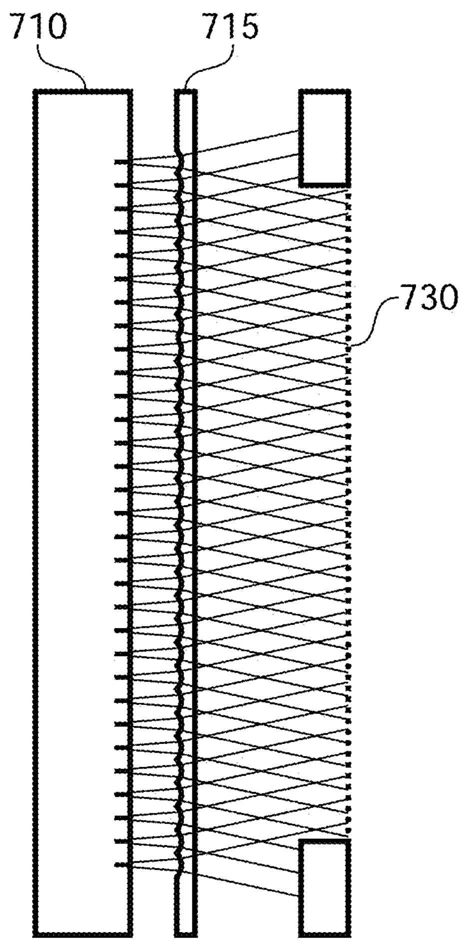


FIG. 8

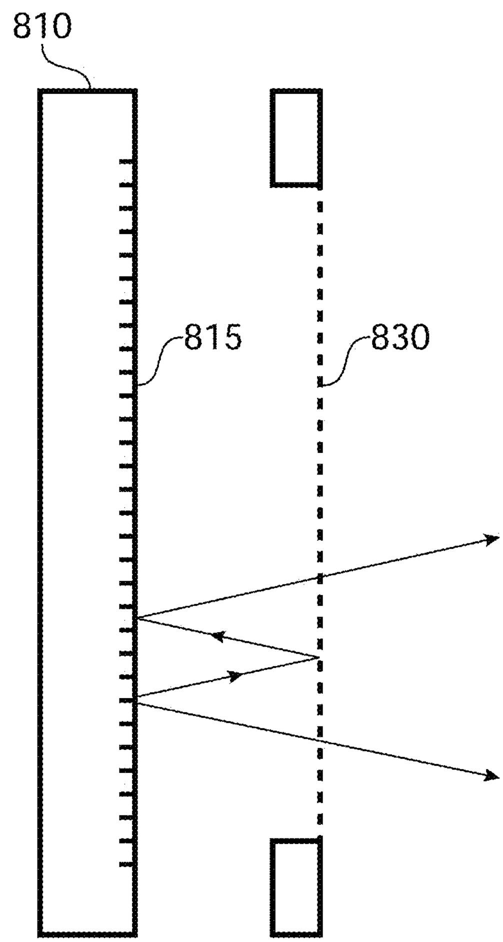
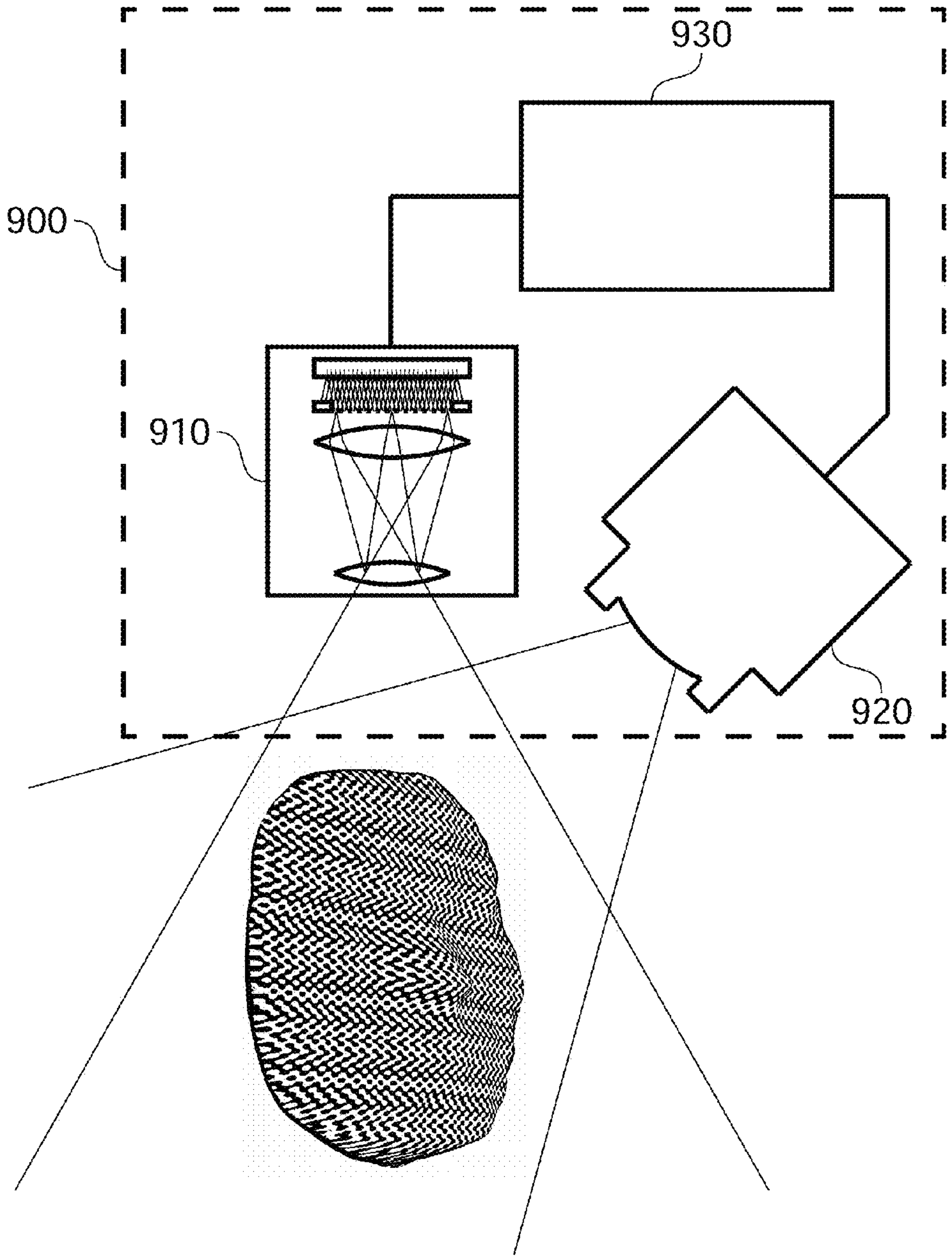


FIG. 9



STRUCTURED LIGHT PROJECTOR

RELATED APPLICATION DATA

[0001] The present application is a continuation of U.S. patent application Ser. No. 13/847,895, filed Mar. 20, 2013, which in turn claims priority from U.S. Provisional Patent Application No. 61/615,554, filed Mar. 26, 2012. Both of the aforementioned applications are hereby incorporated by reference.

FIELD

[0002] The present invention is in the field of pattern projection, in particular for three dimensional imaging.

SUMMARY

[0003] Many of the functional components of the presently disclosed subject matter can be implemented in various forms, for example, as hardware circuits comprising custom VLSI circuits or gate arrays, or the like, as programmable hardware devices such as FPGAs or the like, or as a software program code stored on an intangible computer readable medium and executable by various processors, and any combination thereof. A specific component of the presently disclosed subject matter can be formed by one particular segment of software code, or by a plurality of segments, which can be joined together and collectively act or behave according to the presently disclosed limitations attributed to the respective component. For example, the component can be distributed over several code segments such as objects, procedures, and functions, and can originate from several programs or program files which operate in conjunction to provide the presently disclosed component.

[0004] In a similar manner, a presently disclosed component(s) can be embodied in operational data or operation data can be used by a presently disclosed component(s). By way of example, such operational data can be stored on tangible computer readable medium. The operational data can be a single data set, or it can be an aggregation of data stored at different locations, on different network nodes or on different storage devices.

[0005] The method or apparatus according to the subject matter of the present application can have features of different aspects described above or below, or their equivalents, in any combination thereof, which can also be combined with any feature or features of the method or apparatus described in the Detailed Description presented below, or their equivalents.

[0006] According to an aspect of the presently disclosed subject matter, there is provided a 3D imaging apparatus. According to examples of the presently disclosed subject matter, the 3D imaging apparatus can include a projector, an imaging sensor and a processor. The projector can include a laser array comprising a plurality of individual emitters, a mask for providing a structured light pattern, and projector optics. The distance between the laser array and the mask can be substantially minimized according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane. The projection optics can be configured to image the structured light pattern onto an object. The imaging sensor can be adapted to capture an image of the object with the structured light pattern projected thereon. The processing unit can be adapted to process the image to determine range parameters.

[0007] According to examples of the presently disclosed subject matter, the plurality of individual emitters can be characterized by substantially identical emitter size, substantially identical light divergence output, substantially identical light power output and substantially equal mutual spacing. The non-uniformity profile can be related to the light divergence output, and light power output of the individual emitters and can be related to the mutual spacing among the individual emitters.

[0008] According to further examples of the presently disclosed subject matter, the uniformity criterion can be further related to a target dynamic range.

[0009] According to still further examples of the presently disclosed subject matter, the uniformity criterion can be further associated with a relation between a density of the individual emitters in the laser array and a density of feature types in the structured light pattern.

[0010] In yet further examples of the presently disclosed subject matter, the mask can be sized according to a spatial intensity profile of the light emitted by the laser array.

[0011] In still further examples of the presently disclosed subject matter, the spatial intensity profile can define an area of uniform light of the laser array at the distance where the mask is positioned relative to the laser array.

[0012] In further examples of the presently disclosed subject matter, the mask can be sized further according to the uniformity criterion.

[0013] According to yet further examples of the presently disclosed subject matter, the mask can be sized further according to a light power transfer criterion.

[0014] According to examples of the presently disclosed subject matter, the laser array can be a VCSEL array.

[0015] According to examples of the presently disclosed subject matter, the laser array can be in compliance with a defective emitter criterion that is associated with a distribution and a ratio of individual defective emitters among the plurality of individual emitters.

[0016] According to examples of the presently disclosed subject matter, the laser array and the mask can be positioned with respect to one another at a distance that is less than 5 mm.

[0017] According to examples of the presently disclosed subject matter, the laser array and the mask can be positioned with respect to one another at a distance that is less than 2 mm.

[0018] According to a further aspect of the presently disclosed subject matter, there is provided a method of enabling 3D imaging. According to examples of the presently disclosed subject matter, the method of enabling 3D imaging can include: positioning a mask for providing a structured light pattern relative to a laser array that includes a plurality of individual emitters at a distance that is substantially minimal according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane; positioning projection optics in the optical path of light from individual emitters passing through the mask, to enable imaging of the structured light pattern onto an object; and positioning an imaging sensor in the optical path of reflected projected light to enable capturing of an image of the object with the structured light pattern projected thereon to further enable determining range parameters.

[0019] According to yet a further aspect of the presently disclosed subject matter there is provided a projector for three dimensional range finding. According to examples of the presently disclosed subject matter, the projector for three dimensional range finding can include a laser array, a mask and projection optics. The laser array can include a plurality of individual emitters. The mask can be configured to provide a structured light pattern. The distance between the laser array and the mask can be substantially minimized in the projector according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane. The projection optics can be adapted to image the structured light pattern onto an object.

[0020] A further aspect of the presently disclosed subject matter relates to a method of enabling 3D range finding that includes: positioning a mask for providing a structured light pattern relative to a laser array that includes a plurality of individual emitters at a distance that is substantially minimal according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane; and positioning projection optics in the optical path of light from individual emitters passing through the mask, to enable imaging of the structured light pattern onto an object.

[0021] A further aspect of the presently disclosed subject matter relates to a method of enabling 3D range finding that includes: positioning a mask for providing a structured light pattern relative to a laser array that includes a plurality of individual emitters at a distance where according to a non-uniformity profile of the plurality of individual emitters and according to a desired uniformity of light intensity distribution across the mask plane is achieved; positioning projection optics in the optical path of light from individual emitters passing through the mask, to enable imaging of the structured light pattern onto an object; and positioning an imaging sensor in the optical path of reflected projected light to enable capturing of an image of the object with the structured light pattern projected thereon to further enable determining range parameters.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

[0023] FIG. **1** is a block diagram illustration of a projector for 3D range finding, according to examples of the presently disclosed subject matter;

[0024] FIG. **2**A is an illustration of an example of the distribution of light at the plane of the emitters of the laser array or immediately adjacent to the emitting surfaces of the emitters;

[0025] FIG. **2**B is an illustration of an example of the distribution of light at an intermediate plane located between a plane that is immediately adjacent to the emitting surfaces of the emitters and a plane at a distance from the emitters which is defined at least by a non-uniformity profile of the emitters and a uniformity criterion related to a desired light intensity distribution across the mask plane;

[0026] FIG. **2**C is an illustration of an example of the distribution of the light intensity from a laser array's plurality of individual emitters having a certain non-uniformity profile at a minimal distance from the laser array where the distribution of light meets a uniformity criterion, according to examples of the presently disclosed subject matter;

[0027] FIG. **3**A-**3**C are schematic illustrations of the distributions of light intensity emitted by the laser array at the planes associated with FIGS. **2**A-**2**C, respectively;

[0028] FIG. **4** is a graphical illustration showing by way of example the effect of using different masks with a given light intensity distribution thereon and the resulting projected pattern, according to examples of the presently disclosed subject matter;

[0029] FIG. **5** is a graphical illustration of the effect of a certain relation among the density of the illumination pattern and the density of the mask's pattern on the resulting projected pattern, according to examples of the presently disclosed subject matter.

[0030] FIG. **6** is a block diagram illustration of part of the projector for 3D range finding shown in FIG. **1**, further including a diffuser positioned between the laser array and the mask, according to examples of the presently disclosed subject matter;

[0031] FIG. **7** is a block diagram illustration of part of the projector for 3D range finding shown in FIG. **1**, further including a micro lens array positioned between the laser array and the mask, according to examples of the presently disclosed subject matter;

[0032] FIG. **8** is a graphical illustration of a segment of the projector for 3D range finding shown in FIG. **1**, wherein the laser array has a reflective surface in the spacing in between the individual emitters, according to examples of the presently disclosed subject matter; and

[0033] FIG. **9** is a block diagram illustration of a 3D imaging apparatus, according to examples of the presently disclosed subject matter.

[0034] It will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity. Further, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements.

GENERAL DESCRIPTION

[0035] In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the presently disclosed subject matter. However, it will be understood by those skilled in the art that the presently disclosed subject matter may be practiced without these specific details. In other instances, well-known methods, procedures and components have not been described in detail so as not to obscure the presently disclosed subject matter.

[0036] Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions various functional terms refer to the action and/or processes of a computer or computing device, or similar electronic computing device, that manipulate and/or transform data represented as physical, such as electronic, quantities within the computing device's registers and/or memories into other data similarly represented as physical quantities within the computing device's memories, registers or other such tangible information storage, transmission or display devices.

[0037] Provided below is a list of conventional terms in the field of image processing and in the field of digital video content systems and digital video processing. For each of the terms below a short definition is provided in accordance with each of the term's conventional meaning in the art. The terms provided below are known in the art and the following definitions are provided as a non-limiting example only for convenience purposes. Accordingly, the interpretation of the corresponding terms in the claims, unless stated otherwise, is not limited to the definitions below, and the terms used in the claims should be given their broadest reasonable interpretation.

[0038] According to an aspect of the presently disclosed subject matter, there is provided a three dimensional ("3D") imaging apparatus. According to examples of the presently disclosed subject matter, the 3D imaging apparatus can include a projector, and imaging sensor and a processing unit. The projector can include a laser array, a mask and projections optics. The laser array can include a plurality of individual emitters. The mask can be adapted to provide a structured light pattern (when illuminated). The projection optics can be configured to image the structured light pattern onto an object. The distance between the laser array and the mask can be minimized according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane. The imaging sensor can be adapted to capture an image of the object with the structured light pattern projected thereon. The processing unit can be configured to process the image to determine range parameters.

[0039] According to a further aspect of the presently disclosed subject matter, there is provided a three dimensional ("3D") imaging apparatus. According to examples of the presently disclosed subject matter, the 3D imaging apparatus can include a projector, and imaging sensor and a processing unit. The projector can include a laser array, a mask and projections optics. The laser array can include a plurality of individual emitters. The mask can be adapted to provide a structured light pattern (when illuminated). The projection optics can be configured to image the structured light pattern onto an object. The laser array and the mask can be located at a minimal distance from one another where, according to a non-uniformity profile of the plurality of individual emitters, a desired uniformity criterion related to the light intensity distribution across the mask plane is met. The imaging sensor can be adapted to capture an image of the object with the structured light pattern projected thereon. The processing unit can be configured to process the image to determine range parameters.

[0040] According to a further aspect of the presently disclosed subject matter, there is provided a method of enabling 3D imaging. According to examples of the presently disclosed subject matter, the method of providing a 3D camera can include: positioning a mask for providing a structured light pattern relative to a laser array that includes a plurality of individual emitters at a distance that is substantially minimal according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane; positioning projection optics in the optical path of light from individual emitters passing through the mask, to enable imaging of the structured light pattern onto an object; positioning an imaging sensor in the optical path of reflected projected light to enable capturing of an image of the object with the structured light pattern projected thereon to further enable determining range parameters.

[0041] According to a further aspect of the presently disclosed subject matter there is provided a projector for 3D range finding. According to examples of the presently disclosed subject matter, the projector can include: a laser array, a mask and projections optics. The laser array can include a plurality of individual emitters. The mask can be adapted to provide a structured light pattern. The projection optics can be configured to image the structured light pattern onto an object. The distance between the laser array and the mask can be minimized according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane.

[0042] According to a further aspect of the presently disclosed subject matter there is provided a projector for 3D range finding. According to examples of the presently disclosed subject matter, the 3D range finding device can include a projector, and imaging sensor and a processing unit. The projector can include a laser array, a mask and projection optics. The laser array can include a plurality of individual emitters. The mask can be adapted to provide a structured light pattern (when illuminated). The projection optics can be configured to image the structured light pattern onto an object. The laser array and the mask can be located at a minimal distance from one another where, according to a non-uniformity profile of the plurality of individual emitters, a desired uniformity criterion related to the light intensity distribution across the mask plane is achieved.

[0043] According to yet a further aspect of the presently disclosed subject matter there is provided a method of providing a projector for 3D range finding. According to examples of the presently disclosed subject matter, the method can include: positioning a mask for providing a structured light pattern relative to a laser array that includes a plurality of individual emitters at a distance where according to a non-uniformity profile of the plurality of individual emitters and according to a desired uniformity of light intensity distribution across the mask plane is achieved; positioning projection optics in the optical path of light from individual emitters passing through the mask, to enable imaging of the structured light pattern onto an object; positioning an imaging sensor in the optical path of reflected projected light to enable capturing of an image of the object with the structured light pattern projected thereon to further enable determining range parameters.

[0044] Reference is now made to FIG. **1**, which is a block diagram illustration of a projector for 3D range finding, according to examples of the presently disclosed subject matter. According to examples of the presently disclosed subject matter, as will be further explained below, the projector **100** shown in FIG. **1** can be part of a 3D camera.

[0045] According to examples of the presently disclosed subject matter, the projector can include: a laser array **110**, a mask **130** and projection optics **160**. The laser array can include a plurality of individual emitters **112**A-**112**N. According to examples of the presently disclosed subject matter, the plurality of individual emitters **112**A-**112**N in the laser array **100** are substantially non-coherent with one another.

[0046] By way of example, the laser array **110** shown in FIG. **1** is an array of vertical-cavity surface-emitting lasers ("VCSEL"). By way of non-limiting examples, a VCSEL array with an effective emitting area of 2.6×2.6 mm^2 can be used. Further by way of example, the VCSEL array can be adapted to produce peak power outputs of approximately 30 watts, when operated in pulsed mode. Each emitter in the VCSEL array can be configured to deliver a peak power in the order of 10 mW. For a VCSEL array having about 3000 emitters, the total power can be in the order of about 30 watts. It would be appreciated that the above VCSEL array can be used to provide a large range of working distances, thanks to its relatively high power output. It would be further appreciated that the working distance can further depend on, inter-alia, the sensor sensitivity, camera optics and typical imaged objects (i.e. architecture modeling can be reliable at higher distances than human modeling, because the human skin reflects less than typical construction materials).

[0047] It would be appreciated that other types of laser array can be used as part of examples of the presently disclosed subject matter, and that a VCSEL is just one example of a possible type of laser arrays that can be used. Another example of a laser array that can be used as part of a projector for 3D range finding, according to examples of the presently disclosed subject matter, is an incoherent bundle of laser coupled optical fibers.

[0048] According to examples of the presently disclosed subject matter, the laser array **110** (e.g., a VCSEL array) can be configured such that each individual emitter **112**A-**112**N emitter lasers independently. Hence, there is (generally) no coherence between the individual emitters **112**A-**112**N. It would be appreciated that using a laser array which has a plurality of individual emitters that are substantially not coherent with one another as a light source for a structured light pattern can reduce the speckle in the resulting projected pattern.

[0049] As will be described in further detail below, the light that is emitted by the laser array **110** is characterized by some non-uniformity profile of the plurality of individual emitters. The non-uniformity profile represents the changing distribution of light from the individual emitters **112**A-**112**N of the laser array **110** with distance from the laser array.

[0050] In this regard it would be appreciated that at the plane of the laser array emitters **112**A-**112**N, or immediately adjacent to the emitting surfaces of the emitters **112**A-**112**N, the distribution of light is a result of the layout of the individual emitters **112**A-**112**N. Since the individual emitters **112**A-**112**N are spaced apart from one another, the light intensity distribution is highly non-uniform. For example, the individual emitter spot diameter can be about 12 μm, and between the centers of each light spot there can be a spacing of about 50 μm.

[0051] However, as can be seen by way of example in FIG. **1**, each one of the individual emitters **112**A-**112**N naturally emits light in a cone-like shape **120**. Therefore, the distribution of the light intensity provided by the laser array **110** changes as the light propagates from the individual emitters **112**A-**112**N. The changing light distribution is represented by the non-uniformity profile.

[0052] It would be appreciated that according to examples of the presently disclosed subject matter, different laser arrays can have different non-uniformity profiles. For example, different laser arrays can be designed with different emitting diameter of the individual emitter and/or with different spacing between the emitters. It would be appreciated that changing the emitting diameter also changes the beam divergence. For example, a 12 μm emitter has a NA of 0.12, and a 6 μm emitter will have a numerical aperture ("NA") of 0.24. Different emitting diameter of the individual emitters and/or different spacing between the emitters yield different non-uniformity profiles. Accordingly, in examples of the presently disclosed subject matter, a laser array having a specific non-uniformity profile can be selected for use in the projector for 3D range finding.

[0053] The mask **130** is positioned at a distance **190** from the laser array **110**. The mask **130** can be adapted to provide a structured light pattern when illuminated. According to examples of the presently disclosed subject matter, the mask **130** can include a combination of absorbing and reflecting patterns, which manipulate the light impinging on the mask's surface or passing through the mask **130**, such that the light exiting the mask **130** provides a desired structured pattern of light. Those versed in the art would appreciate that other types of masks can be used for providing a desired structured pattern of light, for example, a holographic type micro lens array, and various types of gratings.

[0054] The projection optics **150** can be configured to image the structured light pattern onto an object, or onto an object plane **180**. By way of example, the projection optics **160** in FIG. **1** consist of a field lens **150** and a projection lens **170**. The field lens **150** can be used to manipulate the telecentric nature of the laser array emitter **110**. It would be appreciated that various projection optics are known in the art, including combinations of various types of lenses and other optical elements and can be used in combination with the laser array **110** and the mask **130** according to examples of the presently disclosed subject matter. Different projection optics may be appropriate for different needs and the projection optics can be selected according to a specific need. The parameters that define the actual projection lens used are specifications of the angular field of view, desired resolution and depth of field constraints.

[0055] It would be appreciated that for certain applications, it is necessary to achieve a substantially uniform illumination of the mask **130** plane.

[0056] Take for example a mask that is configured to provide the pattern described in US Patent Publication No. 2010/0074532 filed Nov. 20, 2007, which is hereby incorporated by reference. This mask is configured to provide an encoded bi-dimensional light pattern that includes a predefined array of a finite set of identifiable feature types. The projected pattern can take the form of monochromatic light beams of varying intensity, wherein combinations of adjacent light beams comprise encoded features or letters having bi-dimensional spatial formations.

[0057] When projected onto an imaged object, the light beams intersect the imaged object's surfaces at various reflection points. Thus, if conditions allow, it is possible to discern reflections of the projected features in an image (typically a 2D image) captured by a sensor.

[0058] In order to determine range parameters for different points (or areas) on the surface of the imaged object, it is necessary to determine the projection geometry, including inter-alia the relationship between the location of feature types in the pattern and the location in the image of respective projection points. It is thus desirable to be able to discern the feature types in the image. If the feature types cannot be identified in the image, determining range parameters based on correlation with the pattern can become difficult and even impossible.

[0059] It would be appreciated that for the pattern described in US Patent Publication No. 2010/0074532, uniform light intensity distribution across the mask **130** plane is required. With a uniform light intensity distribution across the mask **130** plane, the light intensity distribution coming out of the mask **130**, and the resulting projected pattern, can be closely correlated to the intended bi-dimensional light pattern.

[0060] As will be further discussed below, according to examples of the presently disclosed subject matter, the light intensity distribution on the object or scene for which range parameters are to be determined can be further influenced by certain characteristics of the mask **130** and of the structured light pattern which the mask **130** provides, and the uniformity criterion can relate to such characteristics of the mask **130**. According to further examples of the presently disclosed subject matter, the light intensity distribution on the object or scene for which range parameters are to be determined can be influenced by the dynamic range of the object or the scene in respect of which range parameters are to be determined, and the uniformity criterion can relate to the dynamic range of the object or the scene. According to still further examples of the presently disclosed subject matter, the light intensity distribution on the object or scene for which range parameters are to be determined can be influenced by the relation among the density of the light intensity distribution pattern of the light that impinges upon the mask **130** plane and the density of the mask's **130** pattern, and the uniformity criterion can relate to this relation.

[0061] Reference is now made to FIGS. **2**A-**2**C, are simplified illustrations of the distribution of light emitted by the laser array at respective planes located at different distances from the emitting surface of the laser array emitters. In FIG. **2**A, a distribution of light at the plane of the emitters of the laser array or immediately adjacent to the emitting surfaces of the emitters is shown by way of example. As can be seen in FIG. **2**A, the emitters **112**A-**112**N are spaced apart and therefore the light intensity distribution immediately adjacent to the emitting surface of the emitters **112**A-**112**N is in the form of relatively small (or focused) spots of light which are clearly distinct from one another, and in-between the spots of light, there are areas which are substantially not illuminated, or in other words, in between the spots of light there are substantially dark areas. For example, the individual emitter spot diameter can be about 12 μm, and between the centers of each light spot there can be a spacing of about 50 μm.

[0062] FIG. **2**B illustrates by way of example the distribution of light at an intermediate plane located between a plane that is immediately adjacent to the emitting surfaces of the emitters and a plane at a distance from the emitters which is defined at least by a non-uniformity profile of the emitters and a uniformity criterion related to a desired light intensity distribution across the mask plane. As can be seen in FIG. **2**B, at the intermediate plane, the light from individual emitters diverges, and the distribution of light has become more even across the intermediate plane, compared to the distribution of light at the plane that is immediately adjacent to the emitting surface of the emitters **112**A-**112**N (e.g., in FIG. **2**A).

[0063] Nonetheless, at least for some applications, the light distribution from the laser array **110** on the surface of the mask **130** at the intermediate point shown in FIG. **2**B may be inappropriate. For example, in 3D range finding applications, at the intermediate point, the light distribution at the intermediate point may not be suitable for structured light pattern projection, since the structured light pattern that is projected by a mask **130** positioned at the intermediate plane and is illuminated by a laser array **110** with the light intensity distribution shown in FIG. **2**B, could be degraded due to the non-uniform light projected onto the mask **130**, to a degree where at least some of the projected feature types become difficult or impossible to identify.

[0064] In FIG. **2**C there is shown by way of example, an illustration of the distribution of the light intensity from a laser array's plurality of individual emitters having a certain non-uniformity profile at a minimal distance from the laser array where the distribution of light meets a uniformity criterion, according to examples of the presently disclosed subject matter. As mentioned above, each one of the individual emitters **112**A-**112**N emits light in a cone-like shape **120**. As a result, light from individual emitters of the laser array **110** diverges according to a non-uniformity profile, and at some distance from the emitters **112**A-**112**N, rays from adjacent emitters begin overlap. At first, when rays from adjacent emitters overlap, the overlap produces a light distribution that is similar to that which is shown in FIG. **2**B. However, using the predefined non-uniformity profile, it is possible to find a minimal distance **190** at which a uniformity criterion that is related to the light intensity distribution from the laser array **110** is met. According to examples of the presently disclosed subject matter, positioning the mask **130** at the minimal distance **190** where, according to the non-uniformity profile of the laser array's light intensity distribution, the uniformity criterion is met can enable projection of a structured light pattern which is suitable for 3D range finding. This minimal distance **190** can depend and vary with factors such as a desired contrast, the desired application, the optical characteristics of the projected pattern, resolution, etc. According to examples of the presently disclosed subject matter, the minimal distance **190** where, according to the non-uniformity profile of the laser array's light intensity distribution, the uniformity criterion is met, can be determined empirically taking into account some or all of the factors mentioned above, and possibly also further on other factors. By way of non-limiting example, for certain 3D range finding applications and under certain conditions, an illumination profile of 12 μm diameter 0.12 NA emitters spaced 50 μm apart may become sufficiently uniform at a distance of 0.5 mm.

[0065] As mentioned above, and as will be further discussed below, additional factors can be taken into account when determining the minimal distance **190** between the laser array **110** and the mask **130**, where the laser array's light intensity distribution is appropriate for enabling projection of a structured light pattern that is suitable for 3D range finding.

[0066] As mentioned above, the distance between the laser array **110** and the mask **130** can be minimized according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane. However, due to design preferences and/or other preferences, the mask **130** and the laser array can be positioned relative to one another slightly further away from the minimal distance without hampering the performance of the projector for 3D range finding applications, or the performance of a 3D camera which the projector is part of.

[0067] In still further examples of the presently disclosed subject matter, there can be provided a maximal distance for positioning the mask **130** relative to the laser array **110**. By way of example, the maximal distance can be associated with predetermined minimum power transfer of the laser array source through the mask. Further by way of example the maximal distance can be associated with predetermined light intensity criterion across the mask surface. By way of one specific example the predetermined criteria can be a minimum power transfer of 85%, and the criterion that the light intensity at the edge of the mask does not drop below 80% of its value at the center of the mask illumination area.

[0068] According to examples of the presently disclosed subject matter, the mask **130** can be positioned within a certain range from the laser array **110**, wherein the range can be determined according to the minimal distance, which is in turn determined according to the non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane, and further according to the maximal distance.

[0069] For convenience, in the description of examples of the presently disclosed subject matter, reference is generally made to the minimal distance between the mask and the laser array or to the determination of the minimal distance. It should be appreciated however, that many of the examples presently disclosed herein can also relate to positioning of the mask and laser array within the range that is determined according to the minimal distance and according to the maximal distance described above. Likewise, instead of determining the minimal distance, a range can be determined based on the minimal distance and the maximal distance. Thus, it should be noted that the examples described herein with reference to the minimal distance can also be applied to the range associated with minimal distance and the maximal distance.

[0070] FIGS. **3**A-**3**C are schematic illustrations of the distributions of light intensity emitted by the laser array at the planes associated with FIGS. **2**A-**2**C, respectively. FIG. **3**A corresponds to FIG. **2**A, and provides a schematic illustration of the distribution of light intensity at the plane of the laser array **110** emitters **112**A-**112**N or immediately adjacent to the emitting surface of the emitters **112**A-**112**N. FIG. **3**B corresponds to FIG. **2**B, and provides a schematic illustration of the light intensity distribution at an intermediate plane located between a plane that is immediately adjacent to the emitting surfaces of the emitters **112**A-**112**N and a plane that is at a minimal distance where according to the non-uniformity profile of the light emitted by the laser array, the light intensity distribution meets a uniformity criterion. FIG. **3**C corresponds to FIG. **2**C, and provides a schematic illustration of the light intensity distribution at a plane located at a minimal distance from the laser array, where according to the non-uniformity profile of light emitted by the laser array, the light intensity distribution meets a uniformity criterion.

[0071] Reference is now made to FIG. **4**, showing the effect which using different masks with a given light intensity distribution thereon can have on the resulting projected pattern, according to examples of the presently disclosed subject matter. As mentioned above, in accordance with examples of the presently disclosed subject matter, a laser array is comprised of a plurality of individual emitters which are spaced apart from one another. The individual emitters emit light (or radiation) in a cone-like shape **120**, and the light diverges from the individual emitters according to a non-uniformity profile. Very close to the emitting surface of the individual emitters the light intensity distribution appears as relatively focused spots of light separate by relatively large dark areas. The distribution of the light intensity provided by the laser array **110** changes according to the laser array's non-uniformity profile as the light propagates from the individual emitters. At some distance from the emitters, rays from adjacent emitters begin overlap, and the light intensity distribution gradually becomes more and more uniform.

[0072] The light intensity distribution **410** represents an intermediate level of light intensity distribution. In combination with the mask **420**, the non-uniformity of the light intensity distribution **410** appears as noise in the projected pattern **421**. In projection systems aimed for human viewing (e.g. video projectors), such non-uniformity can be undesired, for aesthetic reasons. However, the projected pattern **431**, which is a result of projecting the same light intensity distribution **410** onto structured light pattern **430** can be useful for 3D range finding applications, despite the added noise, since local features of the pattern are still distinguishable, and can be accurately localized. The differences between the projection masks **420** and **430** and the resulting projected patterns **421** and **431**, respectively, serves as a simplified example of the manner by which the light intensity distribution on the object or scene for which range parameters are to be determined can be further influenced by certain characteristics of the mask and of the structured light pattern which the mask provides. As mentioned above, according to examples of the presently disclosed subject matter, the uniformity criterion can relate to such characteristics of the mask.

[0073] In further examples of the presently disclosed subject matter, a tolerance specification can be provided, and determining the minimal distance between the laser array and the mask can be carried out according to a non-uniformity profile of the plurality of individual emitters, according to a uniformity criterion related to the light intensity distribution across the mask plane, and further according to the tolerance specification.

[0074] According to further examples of the presently disclosed subject matter, the tolerance specification can be related to characteristics of the mask and/or of the structured light pattern which the mask provides. In yet further examples of the presently disclosed subject matter, determining the minimal distance between the laser array and the mask can be carried out according to a non-uniformity profile of the plurality of individual emitters, according to a uniformity criterion related to the light intensity distribution across the mask plane, and further according to the tolerance specification related to characteristics of the mask and/or of the structured light pattern which the mask provides.

[0075] Reference is now made to FIG. **5**, which is an illustration of the effect which the relation among the density of the illumination pattern and the density of the mask's pattern can have on the resulting projected pattern, according to examples of the presently disclosed subject matter. The projected light pattern **521** is the result of illuminating mask **510** with light intensity distribution **520**. The light intensity distribution **520** is highly non-uniform and the resulting projected light pattern **521** is corrupted as a result (features types are difficult or impossible to identify in the projected light pattern **521**).

[0076] The light intensity distribution **530** is clearly more uniform compared to light intensity distribution **520**. However, although the intensity variance in light intensity distribution **530** is not as high as in light intensity distribution **520**, the feature types have become difficult or impossible to identify in the projected light pattern **531**, because the density of the peaks in the light intensity distribution **530** is of the same order as the features' density in the mask **510**, leading to undesired interferences, which distort the local features in the projected pattern **531**. The interference between the light intensity distribution pattern of the light that impinges upon the mask, and the masks' features, serves as a simplified example of the manner by which the density of the light intensity distribution pattern of the light that impinges upon the mask and the density of the mask's pattern can interact and cause interference in the local features in the projected pattern.

[0077] As mentioned above, according to examples of the presently disclosed subject matter, the uniformity criterion can relate to the density of the light intensity distribution pattern of the light that impinges upon the mask and the density of the mask's pattern.

[0078] In further examples of the presently disclosed subject matter, a constraint specification can be provided, and determining the minimal distance between the laser array and the mask can be carried out according to a non-uniformity profile of the plurality of individual emitters, according to a uniformity criterion related to the light intensity distribution across the mask plane, and further according to the constraint specification. In still further examples of the presently disclosed subject matter, determining the minimal distance between the laser array and the mask can be carried out according to a non-uniformity profile of the plurality of individual emitters, according to a uniformity criterion related to the light intensity distribution across the mask plane, according to the constraint specification, and further according to the tolerance specification.

[0079] According to further examples of the presently disclosed subject matter, the constraint specification can be related to a relation among the density of the light intensity distribution pattern of the light that impinges upon the mask and the density of the mask's pattern. In yet further examples of the presently disclosed subject matter, determining the minimal distance between the laser array and the mask can be carried out according to a non-uniformity profile of the plurality of individual emitters, according to a uniformity criterion related to the light intensity distribution across the mask plane, according to the constraint specification related to a relation among the density of the light intensity distribution pattern of the light that impinges upon the mask and the density of the mask's pattern, and further according to the tolerance specification related to characteristics of the mask and/or of the structured light pattern which the mask provides.

[0080] Having described various features of the projector and of the 3D imaging apparatus according to examples of the presently disclosed subject matter, which are associated with a minimal distance between a laser array and a mask for providing a projected light pattern for 3D range finding, additional features of the projector and of the 3D imaging apparatus according to further examples of the presently disclosed subject matter are now described.

[0081] According to examples of the presently disclosed subject matter, the mask, and the pattern provided by the mask, can be sized according to a spatial intensity profile of the light emitted by the laser array. Further by way of example, the mask, and the pattern provided by the mask, can be sized according to a spatial intensity profile of the light emitted by the laser array at the minimal distance where, according to the non-uniformity profile of the laser array's light intensity distribution, the uniformity criterion is met.

[0082] Turning back now to FIG. **1**, as mentioned above, according to examples of the presently disclosed subject matter, the mask **130** is located at a minimal distance **190** from the laser array **110**, where a desired uniformity criterion related to the light intensity distribution across the mask plane is met. As was also mentioned above, the minimal distance **190** can be determined further according to a constraint specification and according to a tolerance specification.

[0083] It would be appreciated that the uniformity of the light intensity distribution from the laser array at the minimal distance **190** is achieved thanks to the emission profile of adjacent individual emitters in the laser array **110**, and the overlap among rays from adjacent emitters. The emission profile of individual emitters in the laser array **110** was described above, by way of example, as having a cone-like shape **120**, and in FIG. **1** it can be seen that the light from individual emitters spreads out with distance from the emitters. At some point the light cones **120** of adjacent emitters begin to overlap. The extent of overlap increases with distances from the emitters.

[0084] However, at the edges of the spatial intensity profile, in particular at the minimal distance **190**, the edge emitters are not surrounded by neighboring emitters, and therefore the light intensity is weaker at the edges of the light from the laser array **110**. This can be seen for example in FIG. **2**C and in the diagram of FIG. **3**C.

[0085] According to examples of the presently disclosed subject matter, the mask **130** can be sized according to the spatial intensity profile of the light that is emitted by the laser array **110**. In further examples of the presently disclosed subject matter, the mask **130** can be truncated to cover substantially the entire area of the light produced by the laser array **110** at the minimal distance **190**, except for the periphery where the light intensity distribution is substantially less uniform.

[0086] According to further examples of the presently disclosed subject matter, determining the minimal distance **190** can be further determined according to a periphery specification. The periphery specification can be used to specify a periphery of the light produced by the laser array, which can be disregarded when determining the minimal distance where the light from the laser array **110** complies with the uniformity criterion. The periphery can be specified as that region where the light intensity drops below a certain percentage (e.g., 80%) of its value at the center of the illumination area.

[0087] In still further examples of the presently disclosed subject matter, the mask **130** can be sized according to a light power transfer criterion. In yet further examples of the presently disclosed subject matter, the light power transfer criterion can be used in conjunction with the periphery specification to determine the size of the mask **130**. As mentioned above, the light intensity at the periphery of the light that is emitted by the laser array **110** is substantially less uniform, and in some examples of the presently disclosed subject matter, it is therefore desirable to have a mask which is truncated to maintain uniform light intensity distribution across the mask **130**. However, reducing the mask's **130** size reduces the overall light power transfer. Accordingly, in some examples of the presently disclosed subject matter, a light power transfer criterion can be used to constrain the truncation of the mask, e.g., according to the spatial intensity profile, and can protect against over-truncation of the mask **130**. The light power transfer criterion can be used together with the periphery specification to determine the mask's **130** size.

[0088] According to examples of the presently disclosed subject matter, the mask's **130** size can be evaluated according to the relevant conditions when the mask **130** is positioned at the minimal distance **190** from the laser array **110**.

[0089] According to further examples of the presently disclosed subject matter, determining the minimal distance **190** can be further determined according to a periphery specification. The periphery specification can be used to specify a periphery of the light produced by the laser array, which can be disregarded when determining the minimal distance where the light from the laser array **110** complies with the uniformity criterion

[0090] According to examples of the presently disclosed subject matter, a defective emitter criterion can be provided. The defective emitter criterion can be used to specify a distribution and/or a ratio of individual defective emitters among the plurality of individual emitters **112**A-**112**N which is considered to qualify the emitter as an appropriate light source of the projector **100**. As mentioned above, the projector **100** is intended to be used for providing a structured light pattern for 3D range finding applications. Accordingly, if the light source (the laser array **110**) has too many individual defective emitters, the output of the light source can be too low and the structured light pattern cannot be projected far enough to enable broad range 3D range finding. Thus, according to examples of the presently disclosed subject matter, a defective emitter criterion can be provided and can be used to reject laser arrays that include a number of defective individual emitters that is greater than some threshold. It would be appreciated that the threshold is not necessarily a fixed number, but rather can be some ratio of the total number of individual emitters in the laser array, or any other appropriate measure.

[0091] Furthermore, as was mentioned above, the non-uniformity profile of the plurality of individual emitters of the projector's laser array source (a laser array) can be used to determine a minimal distance where the mask can be positioned relative to the light source, on that the light intensity distribution across the mask plane meets a uniformity criterion. Accordingly, if the light source has relatively large clusters of defective emitters, the light from the light source would have significant dark spots, and the uniformity of the light intensity distribution can be hampered, causing the projected light pattern to become corrupted. Thus, according to examples of the presently disclosed subject matter, a defective emitter criterion can be provided and can be used to reject laser arrays that include a relatively large cluster(s) of defective individual emitters. It would be appreciated that the defective criterion can relate to number of defective emitters (or a similar measure of the rate of defective emitters) or to the extent (size, ratio, etc.) of clusters of defective individual emitters, or to both.

[0092] According to examples of the presently disclosed subject matter, the projection lens **170** can be selected such that the entrance pupil **175** is matched to the divergence of the light from the laser array **110**, or vice-versa.

[0093] Reference is now made to FIG. **6**, where there is shown a block diagram illustration of part of the projector for 3D range finding shown in FIG. **1**, further including a diffuser positioned between the laser array and the mask, according to examples of the presently disclosed subject matter. According to examples of the presently disclosed subject matter, a diffuser **615** can be positioned between the laser array **610** and the mask **630** to shorten the minimal distance between the laser array **610** and the mask **630**, where given the non-uniformity profile of the laser array's **610** light intensity distribution, the uniformity criterion is met.

[0094] Referring now to FIG. **7**, there is shown a block diagram illustration of a segment of the projector for 3D range finding shown in FIG. **1**, further including a micro lens array positioned between the laser array and the mask. According to examples of the presently disclosed subject matter, a micro lens array **715** can be positioned between the laser array **710** and the mask **730** to shorten the minimal distance between the laser array **710** and the mask **730**, where given the non-uniformity profile of the laser array's **710** light intensity distribution, the uniformity criterion is met.

[0095] According to examples of the presently disclosed subject matter, the laser array can have a reflective surface in the spacing in between the individual emitters. Reference is now made to FIG. **8**, which is a graphical illustration of a segment of the projector for 3D range finding shown in FIG. **1**, wherein the laser array has a reflective surface in the spacing in between the individual emitters, according to examples of the presently disclosed subject matter. The mask **830** that is used to provide the desired projected light pattern can use reflective and transmissive areas to selectively transmit the light from the laser array **810**, and thus produce the desired projected light pattern. According to examples of the presently disclosed subject matter, since the area of the spacings between the individual emitters of the laser array **810** is substantially greater than the area of the emitters themselves, a substantial portion of the light that is reflected by the reflective portions of the mask **830** is likely to be reflected back by the reflective surface **815** in between the emitters. Consequently, the light that is reflected from the mask **830** back towards the reflective surface **815**, would be reflected once more. This reflection cycle can occur until the light reflected from the reflective surface **815** impinges upon a transmissive area of the mask **830**, and is emitted out of the projector.

[0096] According to an aspect of the examples of the presently disclosed subject matter, a 3D imaging apparatus can be provided, which includes a projector for 3D range finding according to the examples of the subject matter that were described above. FIG. **9**, to which reference is now made, is a block diagram illustration of a 3D imaging apparatus, according to examples of the presently disclosed subject matter. According to examples of the presently disclosed subject matter, the 3D imaging apparatus **900** can include an imaging sensor **920**, a processing unit **930** and a projector **910**.

[0097] The projector **910** can include a laser array comprising a plurality of individual emitters, and a mask, wherein a distance between the laser array and the mask is substantially minimized according to a non-uniformity profile of the plurality of individual emitters and according to a uniformity criterion related to the light intensity distribution across the mask plane. The projector **910** can be implemented in accordance with the examples of the projector described hereinabove, including but not limited to with reference to FIGS. **1-8**.

[0098] The imaging sensor **920** can be adapted to capture an image of the object with the structured light pattern projected thereon. There is a variety of imaging sensors which can be used for capturing an image of the object with the structured light pattern projected thereon and to provide an image that is suitable for 3D range finding applications. Any suitable imaging sensor that is currently available or that will be available in the future can be used for capturing an image of the object with the structured light pattern projected thereon.

[0099] According to examples of the presently disclosed subject matter, the imaging sensor **920** can be positioned relative to the projector **910** in a manner to provide a specific imaging geometry that is appropriate for 3D range finding applications. In further examples of the presently disclosed subject matter, the imaging sensor can be operatively connected to the projector **910** and the operation of the imaging sensor **920** and of the projector **910** can be synchronized, for example, in order to achieve better power efficiency for the 3D imaging apparatus **900**.

[0100] According to examples of the presently disclosed subject matter, the processing unit **930** can be adapted to process an image that was captured by the imaging sensor **920**, and can provide range parameters. Various algorithms which can be used to extract range parameters from an image of an object having projected thereupon a pattern can be implemented by the processing unit **930**.

1. A structured light intensity projector, the projector comprising:

an emitters array comprising a plurality of individual light emitters, wherein the emitters array is configured such that when the emitters array is activated, light from each of the plurality of individual emitters diverges, and in association with the divergence of light from the plurality of individual emitters, a light intensity distribution of the emitters array changes with distance from the emitters array; and

a mask configured to provide a light pattern wherein the mask is positioned at a distance relative to the emitters array where, when the emitters array emits light, rays from adjacent emitters overlap, and where such overlaps provide uniform light intensity distribution across a mask plane.

2. The projector according to claim **1**, wherein the light pattern is comprised of features encoded by adjacent light beams forming predefined spatial intensity formations.

3. The projector according to claim **1**, wherein light intensity distribution across the mask plane is uniform when a reflected portion of a projection of the light pattern is compatible with optical requirements of a decoder associated with the structured light projector.

4. The projector according to claim **2**, wherein light intensity distribution across the mask plane is uniform, when a decoder of the light pattern decodes an image of a reflected portion of the light pattern, the decoder can localize features of the light pattern.

5. The projector according to claim **2**, wherein the relative distance is associated with a density of the light pattern features.

6. The projector according to claim **5**, wherein the relative distance is associated with mutual spacing between the individual light emitters.

7. The projector according to claim **6**, wherein the wherein the relative distance is further associated with a light power output of the emitters.

8. The projector according to claim **1**, wherein the mask comprises reflective and transmissive areas to selectively transmit the light from the emitters array, when the projector is activated.

9. The projector according to claim **1**, wherein the relative distance is not less than a minimal distance, where the minimal distance is a shortest relative distance where the light intensity distribution across the mask plane is uniform, when the mask is illuminated.

10. The projector according to claim **1**, wherein the relative distance is not more than a maximal distance, where the maximal distance is associated with a light intensity at an edge of the mask relative to a light intensity at a center of the mask and a predetermined minimum power transfer value, when the mask is illuminated.

11. A depth sensing device, the device comprising:

an emitters array comprising a plurality of individual light emitters, wherein the emitters array is configured such that when the emitters array is activated, where light from each of the plurality of individual emitters diverges, and in association with the divergence of light from the plurality individual emitters, a light intensity distribution of the emitters array changes with distance from the emitters array:

a mask configured to provide a light pattern, wherein the mask is positioned at a distance relative to the emitters array where, when the emitters array emits light, rays from adjacent emitters overlap, and where such overlaps provide uniform light intensity distribution across a mask plane;

projection optics configured to receive light passing through the mask and configured to image a structured light pattern onto an object; and

an imaging sensor configured to generate an image of the object with the structured light pattern projected thereon from a reflected portion of the projected structured light pattern; and

a decoder configured to decode the image of the reflected portion of the projected structured light pattern to extract depth information therefrom.

12. The device according to claim **11**, wherein the pattern is comprised of features encoded by adjacent light beams forming predefined spatial intensity formations.

13. The device according to claim **11**, wherein light intensity distribution across the mask plane is uniform when a reflected portion of a projection of the structured light pattern is compatible with optical requirements of a decoder associated with the structured light projector.

14. The device according to claim **12**, wherein light intensity distribution across the mask plane is uniform, when the decoder of the structured light pattern decodes an image of a reflected portion of the structured light pattern, the decoder can localize features of the pattern.

15. The device according to claim **12**, wherein the relative distance is associated with a density of the structured light pattern features, with mutual spacing between the individual light emitters and with a light power output of the emitters.

16. The device according to claim **11** wherein the mask comprises reflective and transmissive areas to selectively transmit the light from the emitters array.

17. The device according to claim **11**, wherein the relative distance is not less than a minimal distance, where the minimal distance is a shortest relative distance where the light intensity distribution across the mask plane is uniform, when the mask is illuminated.

18. The device according to claim **11**, wherein the relative distance is not more than a maximal distance, where the maximal distance is associated with a light intensity at an edge of the mask relative to a light intensity at a center of the mask and a predetermined minimum power transfer value, when the mask is illuminated.

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