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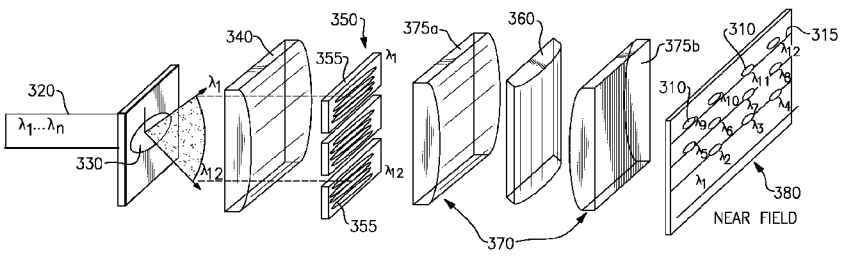


FIG.3

(57) Abstract: A method and apparatus for two-dimensional wavelength beam combining of laser sources. In one example, an external cavity multi- wavelength laser includes an array of laser emitters each producing an optical beam having a specified wavelength, a grating stack comprising a plurality of first-order diffraction gratings arranged linearly in a first dimension, and a dispersive element. The laser further includes a cylindrical telescope that images the optical beams from the array of laser emitters onto the grating stack. A first cylindrical transform lens spatially overlaps the optical beams in a second dimension forming a first region of overlap at the grating stack. A second cylindrical transform lens spatially overlaps the optical beams from the grating stack in the first dimension forming a second region of overlap at the dispersive element. The dispersive element transmits a multi-wavelength output beam comprising the spatially overlapped optical beams from the array of laser emitters.

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TWO-DIMENSIONAL WAVELENGTH-BEAM-COMBINING OF LASERS USING FIRST-ORDER GRATING STACK

FEDERALLY SPONSORED RESEARCH

This invention was made with government support under Grant No FA8721-05-C-0002 awarded by the United States Air Force. The U.S. government has certain rights in this invention.

BACKGROUND

Field of Invention

The present invention relates generally to the field of lasers and, more particularly, to methods and apparatus for wavelength beam combining using laser arrays.

Discussion of Related Art

High-efficiency multi-wavelength external-cavity laser sources that use laser arrays are utilized for a variety of applications including machining, material processing, laser pumping and numerous medical procedures. Two-dimensional (2-D) wavelength-beam-combining (WBC) of laser sources has been as a technique to enhance the power and brightness of 2-D laser sources.

A two-dimensional wavelength beam combining system generally comprises a plurality of multi-wavelength laser elements and two-dimensional dispersive elements. The two-dimensional dispersive elements generally include a diffraction grating/prism and an Echelle grating operating in high diffracting orders. One example of a two-dimensional wavelength beam combining system including the use of high-order gratings is disclosed in US 6,327,292 to Sanchez-Rubio et al. filed on June 21, 1999.

SUMMARY OF INVENTION

Aspects and embodiments are directed to a method and apparatus for two-dimensional wavelength beam combining in which a first-order grating stack is used instead of an Echelle grating. In particular, aspects and embodiments relate to methods and apparatus for generating high-power, high-brightness, multi-wavelength laser sources

using two-dimensional laser arrays by wavelength beam combining. According to one aspect, since all the gratings in the system may be first order gratings, embodiments of the system may have high wavelength beam combining efficiency, as discussed further below.

According to one embodiment, a multi-wavelength laser comprises an array of laser emitters arranged in a two-dimensional pattern, each laser emitter producing an optical beam having a wavelength, a grating stack comprising a plurality of first-order diffraction gratings arranged linearly in a first dimension, and a dispersive element. The multi-wavelength laser further comprises a cylindrical telescope positioned between the grating stack and the array of laser emitters and configured to image the optical beams from the array of laser emitters onto the grating stack, a first cylindrical transform lens positioned approximately a focal length from the array of laser emitters and configured to spatially overlap the optical beams in a second dimension forming a first region of overlap at the grating stack, and a second cylindrical transform lens positioned between the dispersive element and the grating stack and configured to receive the optical beams from the grating stack and to spatially overlap the optical beams in the first dimension forming a second region of overlap at the dispersive element, wherein the dispersive element transmits a multi-wavelength output beam comprising the spatially overlapped optical beams from the array of laser emitters.

In one example, the dispersive element is a first-order diffraction grating. In another example, the dispersive element is a prism. In one example, the first dimension is substantially perpendicular to the second dimension. In another example, the cylindrical telescope comprises a first lens element and a second lens element, and the first cylindrical transform lens is positioned between the first lens element and the second lens element. In one example, each of the first-order diffraction gratings of the grating stack has a unique groove density. In another example, the first-order diffraction gratings of the grating stack are arranged so that an angle of incidence of the optical beams on each of first-order diffraction grating of the plurality of first-order diffraction gratings is unique. In another example, the array of laser emitters comprises a plurality of laser emitters arranged in first number of rows, and the grating stack comprises the first number of first-order diffraction gratings. In another example, each of the first-order diffraction gratings

is constructed and arranged to transmit a beam comprising spatially overlapped optical beams from one row of laser emitters.

Another embodiment is directed to a method of two-dimensional wavelength beam combining in a laser system. The method comprises acts of spatially overlapping in a first dimension, optical beams from a plurality of laser emitters using a grating stack comprising a plurality of first-order diffraction gratings, imaging the optical beams onto the grating stack, and spatially overlapping in a second dimension the optical beams from the grating stack to generate a multi-wavelength output beam.

In one example of the method, imaging the optical beams onto the grating stack includes imaging the optical beams with a cylindrical telescope positioned between the grating stack and the plurality of laser emitters. In another example, spatially overlapping in the second dimension the optical beams from the plurality of laser emitters includes spatially overlapping the optical beams in the second dimension using a first cylindrical transform lens to form a first region of overlap at the grating stack. The method may further comprise an act of transmitting the multi-wavelength output beam with a dispersive element. In one example, spatially overlapping in the second dimension the optical beams from the grating stack includes spatially overlapping the optical beams in the second dimension using a second cylindrical transform lens to form a second region of overlap at the dispersive element.

According to another embodiment, a multi-wavelength laser comprises a master oscillator configured to generate a first plurality of optical beams, an amplifier array optically coupled to the master oscillator and comprising a plurality of laser elements arranged in a two dimensional array, the amplifier array configured to produce a second plurality of optical beams arranged in a two dimensional array having a first dimension and an orthogonal second dimension, a grating stack comprising a plurality of first-order diffraction gratings arranged linearly in the first dimension, and a dispersive element. The multi-wavelength laser further comprises a cylindrical telescope positioned between the grating stack and the amplifier array and configured to image the second plurality of optical beams from the amplifier array onto the grating stack, a first cylindrical transform lens optically coupled to the amplifier array and configured to spatially overlap the second

plurality of optical beams in a second dimension creating a first plurality of overlapped optical beams and forming a first region of overlap at the grating stack, and a second cylindrical transform lens positioned between the dispersive element and the grating stack and configured to receive the first plurality of overlapped optical beams from the grating stack and to spatially overlap the first plurality of overlapped optical beams in the first dimension forming a second region of overlap at the dispersive element, wherein the dispersive element transmits a multi-wavelength output beam comprising the spatially overlapped first plurality of overlapped optical beams.

In one example, the first cylindrical transform lens is positioned approximately a focal length from the amplifier array. In another example, the master oscillator is configured to seed the amplifier array. The dispersive element may be, for example, one of a first-order diffraction grating and a prism. In one example, each of the first-order diffraction gratings of the grating stack has a unique groove density. In another example, the first-order diffraction gratings of the grating stack are arranged so that an angle of incidence of the second plurality of optical beams on each of first-order diffraction grating of the plurality of first-order diffraction gratings is unique.

Still other aspects, embodiments, and advantages of these exemplary aspects and embodiments, are discussed in detail below. Any embodiment disclosed herein may be combined with any other embodiment in any manner consistent with at least one of the objects, aims, and needs disclosed herein, and references to "an embodiment," "some embodiments," "an alternate embodiment," "various embodiments," "one embodiment" or the like are not necessarily mutually exclusive and are intended to indicate that a particular feature, structure, or characteristic described in connection with the embodiment may be included in at least one embodiment. The appearances of such terms herein are not necessarily all referring to the same embodiment. The accompanying drawings are included to provide illustration and a further understanding of the various aspects and embodiments, and are incorporated in and constitute a part of this specification. The drawings, together with the remainder of the specification, serve to explain principles and operations of the described and claimed aspects and embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects of at least one embodiment are discussed below with reference to the accompanying figures, which are not intended to be drawn to scale. Where technical features in the figures, detailed description or any claim are followed by references signs, the reference signs have been included for the sole purpose of increasing the intelligibility of the figures, detailed description, and claims. Accordingly, neither the reference signs nor their absence are intended to have any limiting effect on the scope of any claim elements. In the figures, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every figure. The figures are provided for the purposes of illustration and explanation and are not intended as a definition of the limits of the invention. In the figures:

FIG. 1 is a schematic diagram of one example of a one-dimensional array of optical elements;

FIG. 2 is a schematic diagram of one example of a two-dimensional array of optical elements;

FIG. 3 is a schematic diagram of one example of two-dimensional wavelength beam combining system in an open-loop configuration according to aspects of the invention;

FIG. 4 is an enlarged view of an example of a grating which may be used in the system of FIG. 3;

FIG. 5 is an enlarged view of an example of a grating stack which may be used in the system of FIG. 3;

FIG.6 is a schematic diagram of an example of a two-dimensional wavelength beam combining system in a closed-loop configuration according to aspects of the invention;

FIG. 7 is a flow diagram of one example of a method of two-dimensional wavelength beam combining according to aspects of the invention;

FIG. 8 is a schematic diagram of an example of a master-oscillator power amplifier implementation using a two-dimensional wavelength beam combining system according to aspects of the invention; and

FIG. 9 is a schematic diagram of an example of a master-oscillator power amplifier implementation according to aspects of the invention.

DETAILED DESCRIPTION

Aspects and embodiments are directed to a two-dimensional (2-D) wavelength-beam-combining (WBC) implementation including 2-D laser sources and using first-order grating stacks as a technique to enhance the power and brightness. As discussed above, conventional two-dimensional wavelength beam combining systems rely on 2-D dispersive elements, typically including a diffraction grating/prism and an Echelle grating, operating in high diffracting orders. By contrast, embodiments include an implementation in which the 2-D dispersive elements comprise a first-order diffraction grating/prism and a stack of first-order gratings with selected groove densities and/or incidence angles, as discussed further below. Since the gratings may all be operating in the first order, the system may have a higher beam combining efficiency and smaller size than systems which use an Echelle grating operating in very high diffracting orders. Furthermore, first-order diffraction gratings that can handle high power are much more readily available.

It is to be appreciated that embodiments of the methods and apparatuses discussed herein are not limited in application to the details of construction and the arrangement of components set forth in the following description or illustrated in the accompanying drawings. The methods and apparatuses are capable of implementation in other embodiments and of being practiced or of being carried out in various ways. Examples of specific implementations are provided herein for illustrative purposes only and are not intended to be limiting. In particular, acts, elements and features discussed in connection with any one or more embodiments are not intended to be excluded from a similar role in any other embodiments. Furthermore, although the following discussion may refer primarily to fiber lasers as an example, the aspects and embodiments discussed herein are

applicable to any type of laser that is wavelength-selectable, including, but not limited to, semiconductor lasers, diode lasers and fiber lasers.

Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. Any references to embodiments or elements or acts of the systems and methods herein referred to in the singular may also embrace embodiments including a plurality of these elements, and any references in plural to any embodiment or element or act herein may also embrace embodiments including only a single element. References in the singular or plural form are not intended to limit the presently disclosed systems or methods, their components, acts, or elements. The use herein of "including," "comprising," "having," "containing," "involving," and variations thereof is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. References to "or" may be construed as inclusive so that any terms described using "or" may indicate any of a single, more than one, and all of the described terms. Any references to front and back, left and right, top and bottom, upper and lower, and vertical and horizontal are intended for convenience of description, not to limit the present systems and methods or their components to any one positional or spatial orientation.

In practice, there are limits to the number of elements that can be wavelength-beam-combined in a wavelength beam combining system including, for example, the gain-bandwidth of the laser elements to be combined and practical limits imposed by size of the system. For a one-dimensional wavelength beam combining cavity, to a first order approximation, the size of the system is proportional to the number of laser elements used. As a result, for large numbers of elements, practical limits to the size of the system may present an issue, particularly for systems including fiber lasers/amplifiers in which it may be more difficult to densely pack many elements per unit length as compared with systems using diode lasers.

Referring to FIG. 1, there is illustrated a schematic diagram of a one-dimensional linear laser array 100 comprising a plurality of fiber laser/amplifier elements 110. Assuming a 1.5 millimeter (mm) pitch between the fiber laser elements 110, the linear dimension 120 of the fiber laser array 100, for a one dimensional wavelength beam

combining system, is 1.5 meters (m) for 1000 elements. Thus, the size of the transform optics in such a system would be at least 1.5 meters. Fabrication of such large optics with low aberrations is expensive and difficult. The size of the optics can be dramatically reduced if a two-dimensional wavelength beam combining cavity is used instead of a one-dimensional wavelength beam combining cavity. In general, the size of a two-dimensional wavelength beam combining system is proportional to $N^{1/2}$, where N is the number of laser elements. Referring to FIG. 2, there is illustrated a schematic diagram of a two-dimensional linear laser array 200 comprising a plurality of fiber laser elements 210. Assuming again a 1.5 mm pitch between elements, an approximate equivalent to the cavity of the 1000-fiber laser one-dimensional system may become roughly a two-dimensional array of 32 x 32 elements (a total of 1024 elements) or 48 mm by 48 mm. Thus, the size of the transform optics for the two-dimensional cavity may be on the order of about 5 centimeters (cm) compared to 1.5 m or larger for the one-dimensional cavity. Thus, two-dimensional wavelength beam combining may provide significant size and cost advantages. However, conventional two-dimensional wavelength beam combining systems that use high-order echelle gratings may suffer from reduced efficiency. Furthermore, since echelle-based two-dimensional wavelength beam combining systems use multiple diffraction orders, there is significant unused frequency/wavelengths, which may be inefficient and/or undesirable and also increases the size of the system. In addition, for high power applications first-order gratings that can handle high power are well developed and are readily available, providing cost and practicality benefits over systems using echelle gratings.

Referring to FIG. 3, there is illustrated one example of a two-dimensional multi-wavelength optical system according to one embodiment in an open-loop configuration. The system 300 comprises a plurality of optical gain media 310, also referred to as laser elements 310, each of which emits a beam of optical radiation at a unique wavelength. In the open-loop configuration, the laser elements emit at a predetermined wavelength, and may be self wavelength-stabilized using an internal grating, external volume Bragg grating or amplifier seeded by a master oscillator (not shown). The optical gain media 310 are positioned in plurality of rows and may be positioned on equal or unequal center-

to-center spacing. It is to be appreciated that the row(s) may or may not be straight, depending on the optical system. The optical gain media may include, for example, a plurality of discrete single-mode or multi-mode semiconductor amplifiers or a plurality of fiber amplifiers, and may preferably have sufficient gain and sufficient gain bandwidth to overcome optical losses at the desired lasing wavelengths.

In one example, each of the laser elements 310 in the two-dimensional wavelength beam combining cavity has a unique wavelength. As a result, the two-dimensional wavelength beam combining system comprises optics that spectrally disperses light in two orthogonal dimensions. For ease of explanation of the optics of the two-dimensional wavelength beam, the following discussion assumes a multi-wavelength beam 320 propagating from the left (in reverse), as shown in FIG. 3. The multi-wavelength beam 320 is dispersed into its spectral components along the vertical dimension by a first dispersive element 330. The first dispersive element 330 may be, for example, a first-order diffraction grating or a prism. In one example, the first grating 330 is a slow-dispersion grating with dispersion in the vertical plane in FIG. 3. A cylindrical transform lens 340 maps each spectral component onto a grating stack 350 at its Fourier (focal) plane. In one example, the dispersion of the grating stack 350 is orthogonal to that of the first grating 330. In one example, the grating stack 350 comprises a plurality of fast-dispersion gratings 355, with dispersion in the horizontal direction, as discussed further below. Along the dispersion axis of the grating stack 350, each spectral component diffracts at a certain angle in the horizontal plane in FIG. 3, as discussed further below. In the horizontal plane, a second cylindrical transform lens 360 brings each spectral component to a focus at its Fourier plane. In the vertical dimension, a cylindrical telescope 370 re-images the beams on the grating stack 350 onto the Fourier plane of the second cylindrical transform lens 360. Thus, each spectral component of the multi-wavelength beam 320 comes to a focus at the Fourier plane in both the horizontal and vertical dimensions. As the wavelength is changed, the focus describes a line 315 in the Fourier plane (image plane 380), as shown in FIG. 3.

According to one embodiment, in order to map the entire spectral content in multiple lines 315, as shown by the "raster scan" pattern on the image plane 380 in FIG. 3,

the grating stack 350 comprises multiple individual first-order gratings 355, each grating 355 responsible for generating one of the lines 315 in the image plane 380. For example, assume the multi-wavelength beam 320 comprises 12 unique wavelengths, λ_1 through λ_{12}, and assume that these 12 wavelengths are to be partitioned into 3 rows, as illustrated in FIG. 3. In this example, the grating stack 350 comprises three individual high dispersion gratings 355 stacked in the vertical dimension, as shown and discussed further below.

Referring to FIG. 4, there is illustrated an enlarged view of a portion 400 of the first grating 330. As discussed above, the first (slow) grating 330 may disperse the 12 wavelengths into the spectral components along the vertical dimension. As illustrated in FIG. 4, the grating 330 comprises a plurality of grooves 410 arranged in the vertical dimension to disperse the multi-wavelength beam 320 into the 12 individual wavelengths. As discussed above, the cylindrical transform lens 340 images the 12 wavelengths along the vertical dimension onto the grating stack 350, as shown in FIG. 3.

Referring to FIG. 5, there is illustrated an enlarged view 500 of one example of the grating stack 350. In one example, each individual first-order grating 355 of the grating stack 350 intercepts 4 of the 12 wavelengths. Each individual grating 355 comprises a plurality of grooves to disperse the wavelengths in the horizontal dimension, as shown in FIG. 5. Thus, the top grating 355a of the grating stack 350 may disperse wavelengths λ_1 - λ_4 along the horizontal dimension. Wavelength λ_5 may be on the second grating 355b of the grating stack 350. If the second grating 355b has the same groove density and angle of incidence as the top grating 355a, then λ_5 will disperse along the same line 315 (see FIG. 3) as the wavelengths λ_1 - λ_4. However, in one example, the system is configured to make λ_5 the first wavelength of a new row in the image plane 380. This may be achieved in several different ways. For example, assuming that the second grating 355b has the same groove density as the top grating 355a, the second grating 355b may be slightly rotated such that the diffracted angle of λ_5 is the same as that of wavelength λ_1. As a result, λ_5 may be imaged onto the image plane 380 beneath λ_1, as shown in FIG. 3. Alternatively, the angle of incidence and diffraction on second grating 355b may be the same as for the top grating 355a, but the groove density may be made slightly different. Similarly, the same principles can be applied to the bottom grating 355c relative to the top

and middle gratings 355a and 355b. Thus, N discrete wavelengths are mapped to a two-dimensional pattern of beams in the image plane 380, as shown in FIG. 3. To operate as a two-dimensional wavelength beam combining laser system, the system 300 uses the above-discussed optics and principles in reverse.

Referring to FIG. 6, there is illustrated an example of a two-dimensional wavelength beam combining system in a closed-loop configuration. In the example of FIG. 6, the wavelength of each laser element 310 is stabilized by a partially reflecting mirror 610.

FIG. 7 illustrates a flow diagram of one example of a method of two-dimensional wavelength beam combining using the system shown in either FIG. 3 or FIG. 6. Referring to FIGS. 3 and 6, an array of laser elements 310, for example, fiber laser elements, is positioned such that the fibers have their end-facets at the image plane 380. Each fiber 310 generates a beam at a specified wavelength and in the appropriate location in the array. Thus, the two-dimensional pattern (array) of beams is generated by the plurality of fibers 310. For example, an array of 12 fibers, positioned in three rows 315 of four elements per row, may generate an array of beams with 12 discrete wavelengths, λ_1 - λ_{12}. Accordingly, in FIG. 7, step 710 comprises generating a plurality of beams, each with a particular wavelength, using a corresponding plurality of laser elements 310, as discussed above.

As shown in FIGS. 3 and 6, the two-dimensional wavelength beam combining system may comprise a cylindrical transform lens 360, which may be positioned a focal length from the image plane 380. The beams from the array of laser elements 310 may be spatially combined in the horizontal dimension by the cylindrical transform lens 360, with the region of overlap formed at the surface of the grating stack 355. Each of the first order gratings 355 in the grating stack 350 spectrally combines the beams from a row of emitters 310, in the reverse of the operation discussed above. Thus, referring again to FIG. 7, step 720 may include spatially overlapping the beams in the horizontal dimension. In step 730, the optical beams may be imaged onto the grating stack 355 in the vertical dimension using the cylindrical telescope 370. As shown in FIGS. 3 and 6, in one example, the cylindrical telescope 370 comprises two elements, 375a and 375b positioned

on either side of the cylindrical transform lens 360. The cylindrical telescope 370 collimates the optical beams from the emitters 310 to reduce optical losses caused by divergence in the optical beams produced by the emitters 310. It is to be appreciated that steps 720 and 730 may occur substantially simultaneously, rather than sequentially.

According to one embodiment, from the grating stack 355, the optical beams (or at least the portion of the light therefrom) are transmitted to the other cylindrical transform lens 340. The cylindrical transform lens 340 is operative in the vertical dimension to spatially overlap the beams (spectral components) with the region of overlap forming at the grating 330, as shown in FIG. 6. Thus, referring again to FIG. 7, step 740 may include spatially overlapping the beams in the vertical dimension. The grating 330 acting in transmission provides the multi-wavelength beam to a partially reflecting output coupler 610. A portion of the laser light from each laser element 310 is reflected off the partially reflecting output coupler 610 to stabilize each laser element to a unique wavelength. The remaining light is transmitted as the multi-wavelength output beam 620 (step 750) and may provide usable output power.

Referring to FIG. 8, there is illustrated an example of a master-oscillator power amplifier implementation using a two-dimensional wavelength beam combining system according to one embodiment. The system include a master oscillator 810 which may comprise N laser elements (with N being an integer greater than or equal to one) each generating a unique wavelength λ_n. The N laser elements of the master oscillator 810 may be discrete elements, or elements arranged in bars and/or arrays, etc. or any form, provided only that the elements generate the desired wavelength(s). The master oscillator seeds a power amplifier implemented using a two-dimensional wavelength beam combining system such as that discussed above with reference to FIGS. 3 and 6. In one example, the wavelengths from the master oscillator 810 are coupled to an amplifier array 820. The master oscillator array 810 comprises a plurality of laser elements (not shown) which each lase at a unique wavelength. The output of the master oscillator array 810 is used to seed the amplifier array 820. As will be appreciated by those skilled in the art, given the benefit of this disclosure, there are many methods for seeding the amplifier array 820, one example of which is illustrated in FIG. 9 discussed below. The beams from the

amplifier array 820 are wavelength beam combined, as discussed above, to generate a multi-wavelength output beam 830. Although not illustrated in FIG. 8, the system may include an output coupler 610 as discussed above with reference to FIG. 6.

Another embodiment of a master-oscillator power amplifier implementation is illustrated in FIG. 9. In the example illustrated in FIG. 9, both the master oscillator 910 and the power amplifier 920 are implemented using the wavelength beam combining optics discussed above with reference to FIGS. 3 and 6. A multi-wavelength input beam 930 from a mirror or output coupler 940 propagates through the master oscillator system 910, as discussed above with reference to FIG. 3, and is dispersed into the individual wavelengths $\lambda_1 ... \lambda_n$ at the image plane 380. These wavelengths become the wavelengths provided by the master oscillator 910 (or 810 discussed above with reference to FIG. 8). The output beams are coupled, by example, via relay optics (not shown) to the amplifier array 810 in the power amplifier 920, thus becoming input beams to the amplifier. The beams are wavelength beam combined, and amplified, by the power amplifier 920, as discussed above with reference to FIG. 6, and the amplifier 920 produces a multi-wavelength output beam 950. This output beam 950 represents the usable power from the system.

Thus, there has been described a two-dimensional wavelength beam combining implementation of a two-dimensional array of laser sources. The wavelength beam combining may be used as a technique to enhance the power and/or brightness of the laser sources. As discussed above, prior two-dimensional wavelength beam combining systems rely on two-dimensional dispersive elements, such as an Echelle grating, operating in high diffracting orders. By contrast, according to one embodiment, the implementation uses two-dimensional dispersive elements that include a first-order diffraction grating or prism 330, and a stack 350 of first-order gratings 355. As discussed above, each of the first order gratings 355 in the grating stack 350 may have unique groove densities or incidence angles to combine the beams from the different laser elements 310 in the array, without requiring operation in high diffracting orders. As a result of using only first-order diffraction elements, a two-dimensional wavelength beam combining implementation may

have higher efficiency and be producible at lower cost than conventional two-dimensional wavelength beam combining cavities.

Any of the above-discussed embodiments of wavelength beam combining laser cavities may be incorporated into an associated laser system. Such a laser system may include, for example, the wavelength beam combining cavity, electrical, thermal, mechanical, electro-optical and opto-mechanical laser control equipment, associated software and/or firmware, and an optical power delivery subsystem. Embodiments of the wavelength beam combining laser cavities, and associated laser systems, can be used in applications that benefit from the high power and brightness of the embodied laser source produced using the wavelength beam combining cavity. These applications may include, for example, materials processing, such as welding, drilling, cutting, annealing and brazing; marking; laser pumping; medical applications; and directed energy applications. In many of these applications, the laser source formed by the wavelength beam combining cavity may be incorporated into a machine tool and/or robot to facilitate performance of the laser application.

Having thus described several aspects of at least one embodiment, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure and are intended to be within the scope of the invention. Accordingly, the foregoing description and drawings are by way of example only, and the scope of the invention should be determined from proper construction of the appended claims, and their equivalents.

CLAIMS

1. A multi-wavelength laser comprising:

an array of laser emitters arranged in a two-dimensional pattern, each laser emitter producing an optical beam having a wavelength;

a grating stack comprising a plurality of first-order diffraction gratings arranged linearly in a first dimension;

a dispersive element configured to transmit a multi-wavelength output beam comprising spatially overlapped optical beams from the array of laser emitters;

a cylindrical telescope positioned between the grating stack and the array of laser emitters and configured to image the optical beams from the array of laser emitters onto the grating stack;

a first cylindrical transform lens positioned approximately a focal length from the array of laser emitters and configured to spatially overlap the optical beams in a second dimension forming a first region of overlap at the grating stack; and

a second cylindrical transform lens positioned between the dispersive element and the grating stack and configured to receive the optical beams from the grating stack and to spatially overlap the optical beams in the first dimension forming a second region of overlap at the dispersive element.

2. The multi-wavelength laser as claimed in claim 1, wherein the dispersive element is a first-order diffraction grating.

3. The multi-wavelength laser as claimed in claim 1, wherein the dispersive element is a prism.

4. The multi-wavelength laser as claimed in claim 1, wherein the first dimension is substantially perpendicular to the second dimension.

5. The multi-wavelength laser as claimed in claim 1, wherein the cylindrical telescope comprises a first lens element and a second lens element; and

wherein the first cylindrical transform lens is positioned between the first lens element and the second lens element.

6. The multi-wavelength laser as claimed in claim 1, wherein each of the first-order diffraction gratings of the grating stack has a unique groove density.

7. The multi-wavelength laser as claimed in claim 1, wherein the first-order diffraction gratings of the grating stack are arranged so that an angle of incidence of the optical beams on each of first-order diffraction grating of the plurality of first-order diffraction gratings is unique.

8. The multi-wavelength laser as claimed in claim 1, wherein the array of laser emitters comprises a plurality of laser emitters arranged in first number of rows; and

wherein the grating stack comprises the first number of first-order diffraction gratings.

9. The multi-wavelength laser as claimed in claim 8, wherein each of the first-order diffraction gratings is constructed and arranged to transmit a beam comprising spatially overlapped optical beams from one row of laser emitters.

10. The multi-wavelength laser as claimed in claim 1, further comprising a partially reflecting output coupler optically coupled to the dispersive element and configured to receive the multi-wavelength output beam, to reflect a portion of multi-wavelength output beam to stabilize each laser emitter to produce the respective optical beam at the respective wavelength, and to transmit a remaining portion of the multi-wavelength output beam.

11. The multi-wavelength laser as claimed in claim 1, wherein the array of laser emitters comprises an array of fiber lasers.

12. The multi-wavelength laser as claimed in claim 1, wherein the array of laser emitters comprises an array of semiconductor diode lasers.

13. The multi-wavelength laser as claimed in claim 1, further comprising:

a master oscillator configured to generate a first plurality of optical rays; and

wherein the array of laser emitters is included in an amplifier array optically coupled to the master oscillator.

14. The multi-wavelength laser as claimed in claim 13, wherein the master oscillator is configured to seed the amplifier array.

15. A method of two-dimensional wavelength beam combining in a laser system, the method comprising:

spatially overlapping in a first dimension optical beams from a plurality of laser emitters using a grating stack comprising a plurality of first-order diffraction gratings;

imaging the optical beams onto the grating stack; and

spatially overlapping in a second dimension the optical beams from the grating stack to generate a multi-wavelength output beam.

16. The method as claimed in claim 15, wherein imaging the optical beams onto the grating stack includes imaging the optical beams with a cylindrical telescope positioned between the grating stack and the plurality of laser emitters.

17. The method as claimed in claim 15, wherein spatially overlapping in the second dimension the optical beams from the plurality of laser emitters includes spatially overlapping the optical beams in the second dimension using a first cylindrical transform lens to form a first region of overlap at the grating stack.

18. The method as claimed in claim 17, further comprising transmitting the multi-wavelength output beam with a dispersive element.

19. The method as claimed in claim 18, wherein spatially overlapping in the second dimension the optical beams from the grating stack includes spatially overlapping the optical beams in the second dimension using a second cylindrical transform lens to form a second region of overlap at the dispersive element.

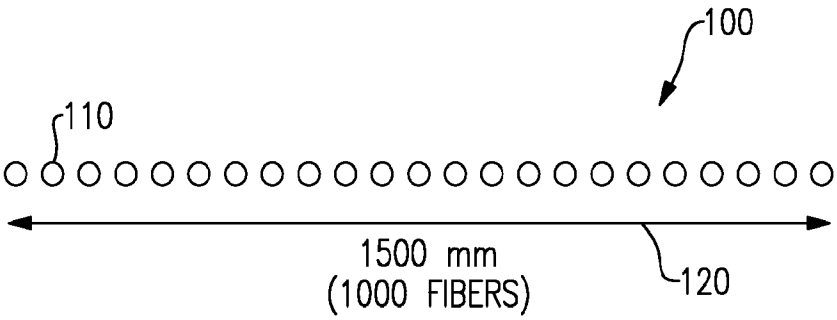

100
110
1500 mm
(1000 FIBERS)
120

FIG.1

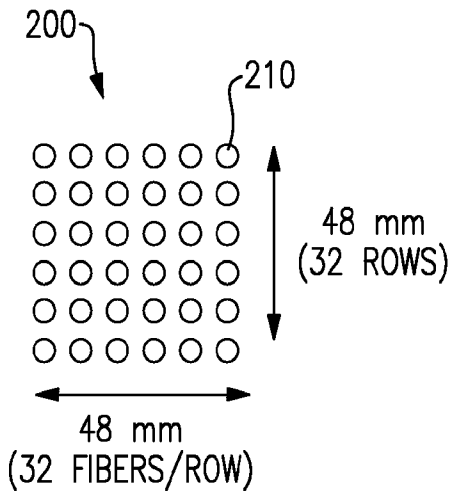

200
210
48 mm
(32 ROWS)
48 mm
(32 FIBERS/ROW)

FIG.2

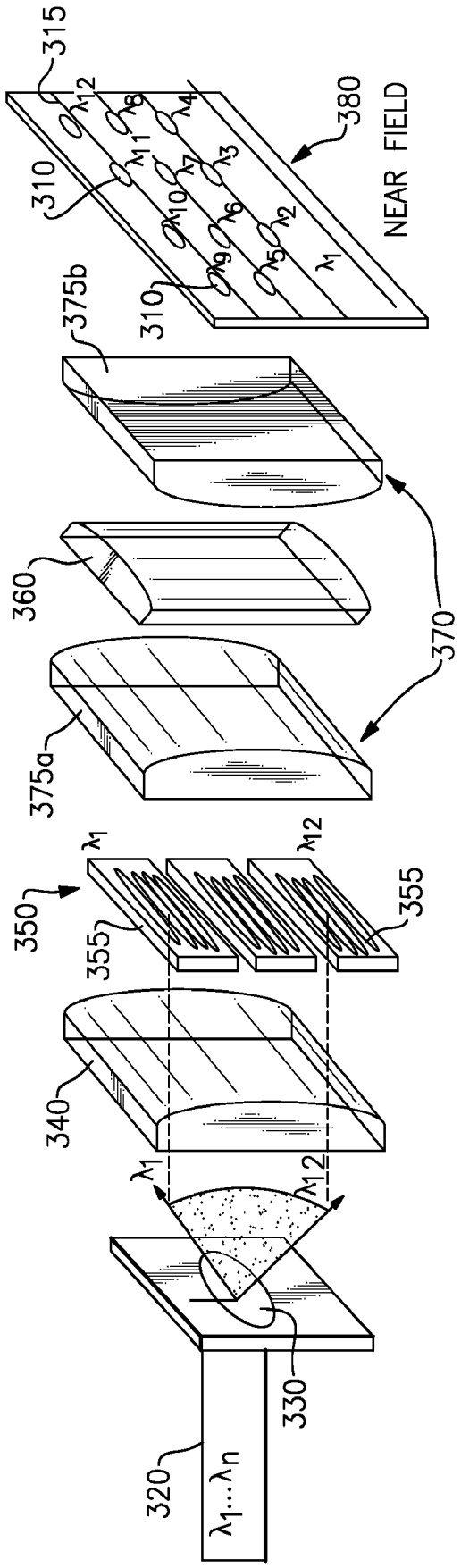

315
λ12
λ8
λ4
λ11
λ7
λ3
λ10
λ6
λ2
λ9
λ5
λ1
310
380
NEAR FIELD
310
375b
360
370
375a
λ1
λ12
350
355
355
340
λ1
λ12
330
320
λ1...λn

FIG.3

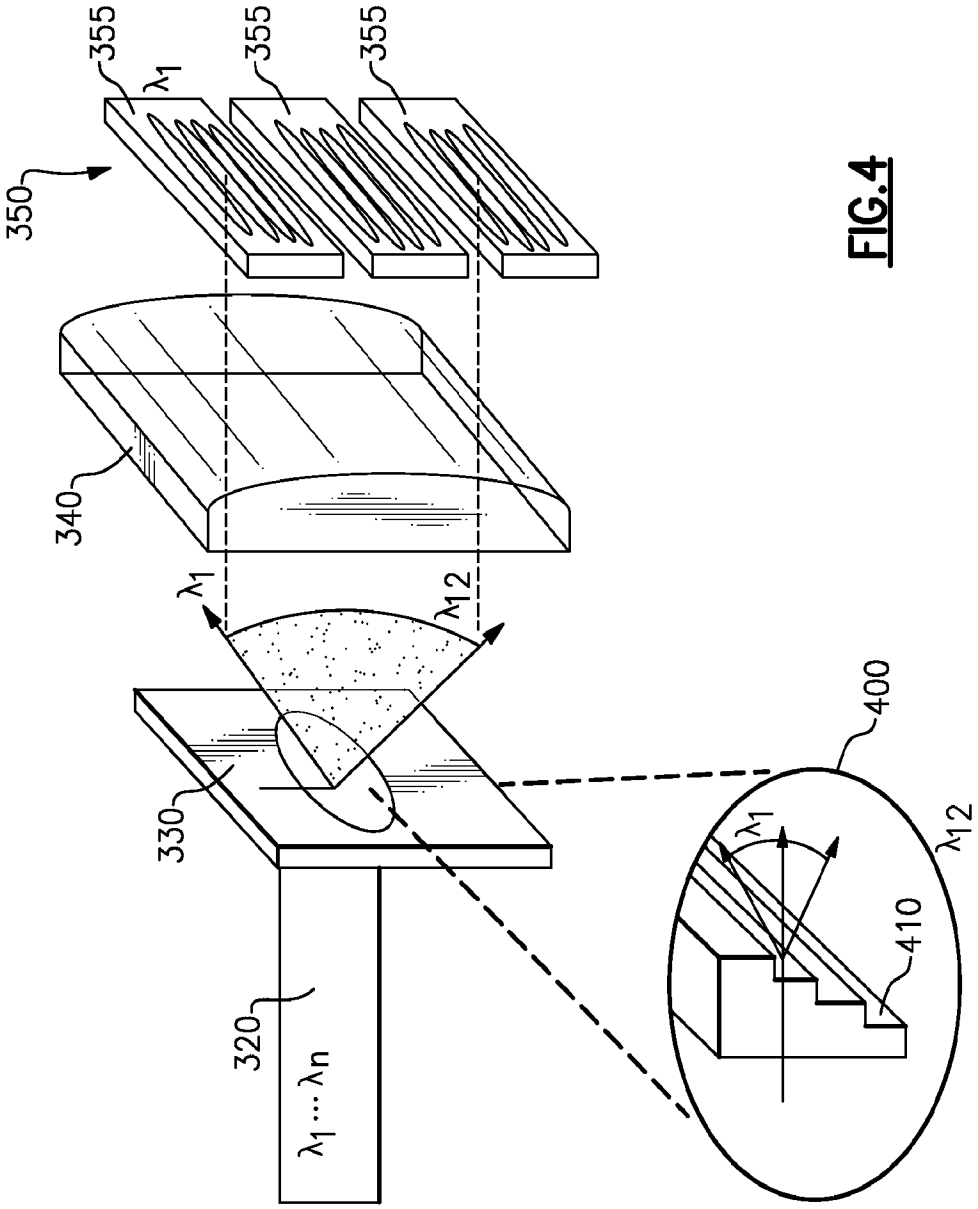


FIG.4

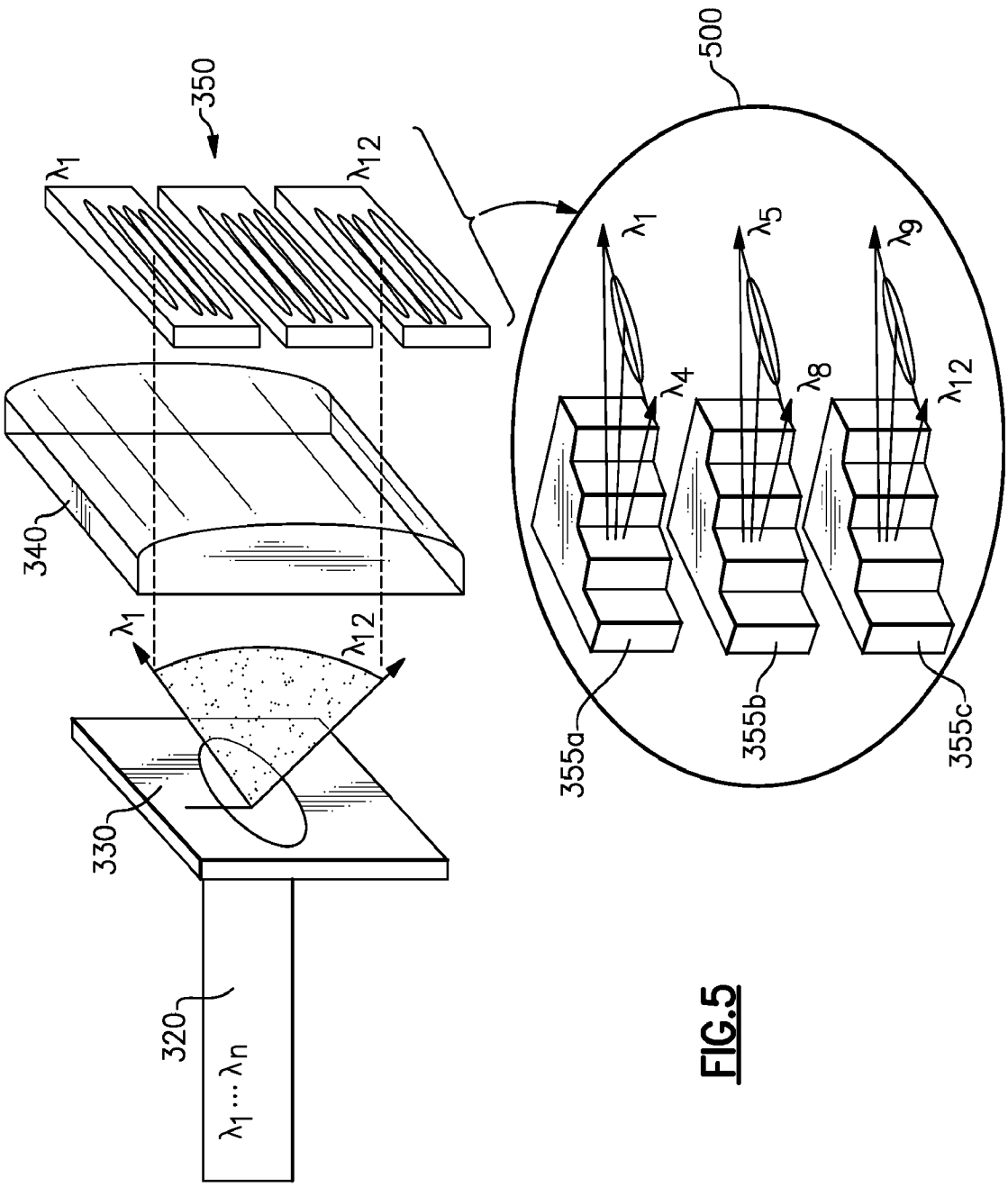

500
350
λ1
λ12
340
λ1
λ12
330
320
λ1 ... λn
λ1
λ5
λ9
λ4
λ8
λ12
355a
355b
355c

FIG.5

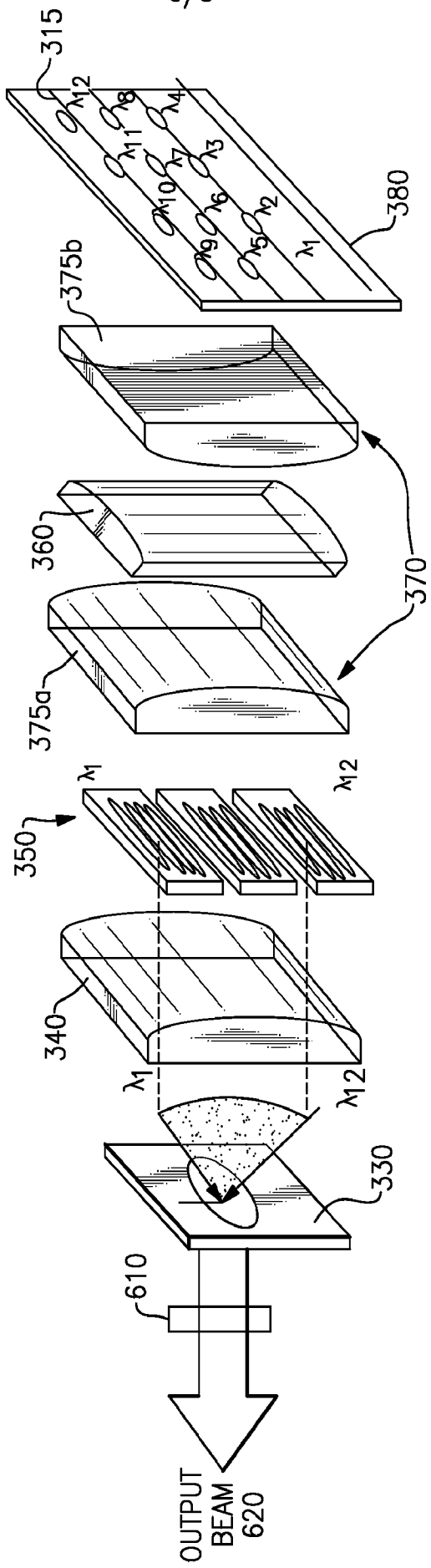

315
λ12
λ8
λ4
λ11
λ7
λ3
λ10
λ6
λ2
λ9
λ5
λ1
380
375b
360
370
375a
λ1
λ12
350
340
λ1
λ12
330
610
OUTPUT BEAM 620

FIG.6

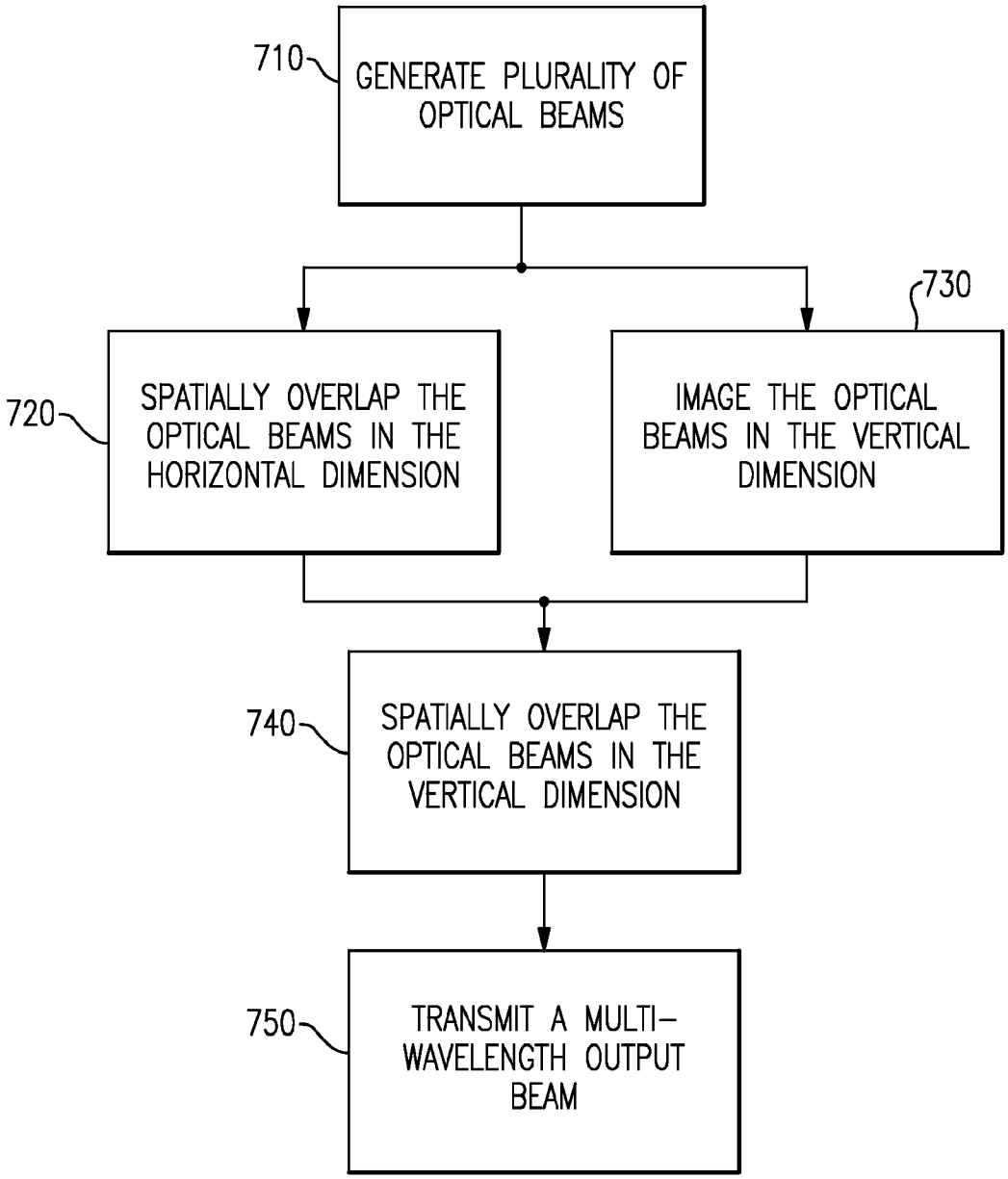

710
GENERATE PLURALITY OF OPTICAL BEAMS
720
SPATIALLY OVERLAP THE OPTICAL BEAMS IN THE HORIZONTAL DIMENSION
730
IMAGE THE OPTICAL BEAMS IN THE VERTICAL DIMENSION
740
SPATIALLY OVERLAP THE OPTICAL BEAMS IN THE VERTICAL DIMENSION
750
TRANSMIT A MULTI-WAVELENGTH OUTPUT BEAM

FIG.7

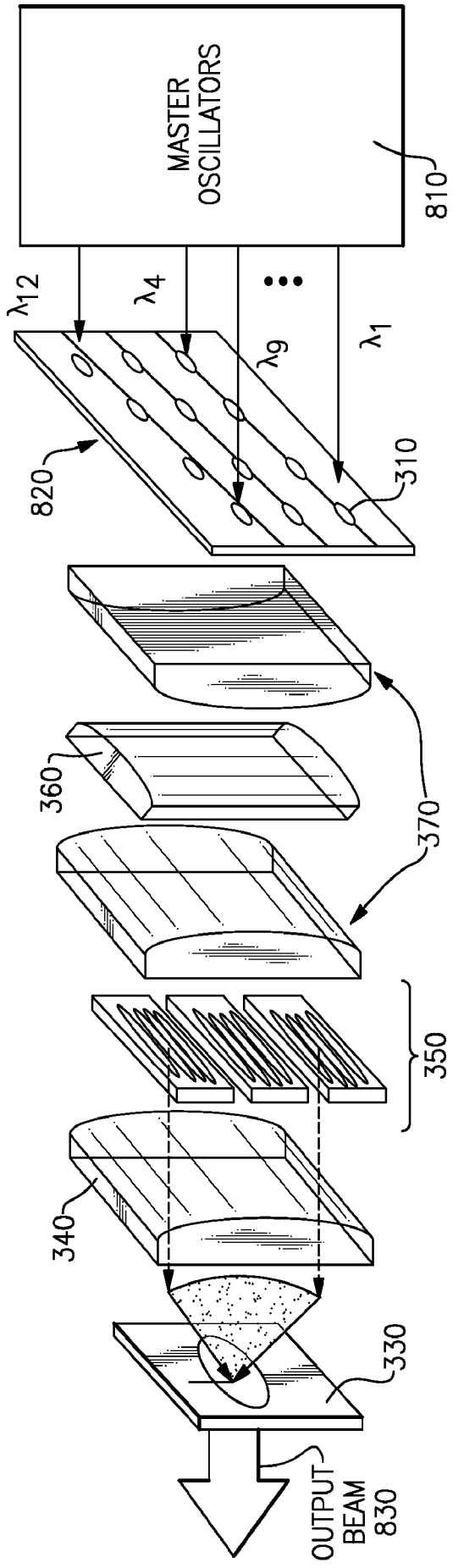

MASTER OSCILLATORS
810
λ12
λ4
λ9
λ1
820
310
360
370
350
340
330
OUTPUT BEAM
830

FIG.8

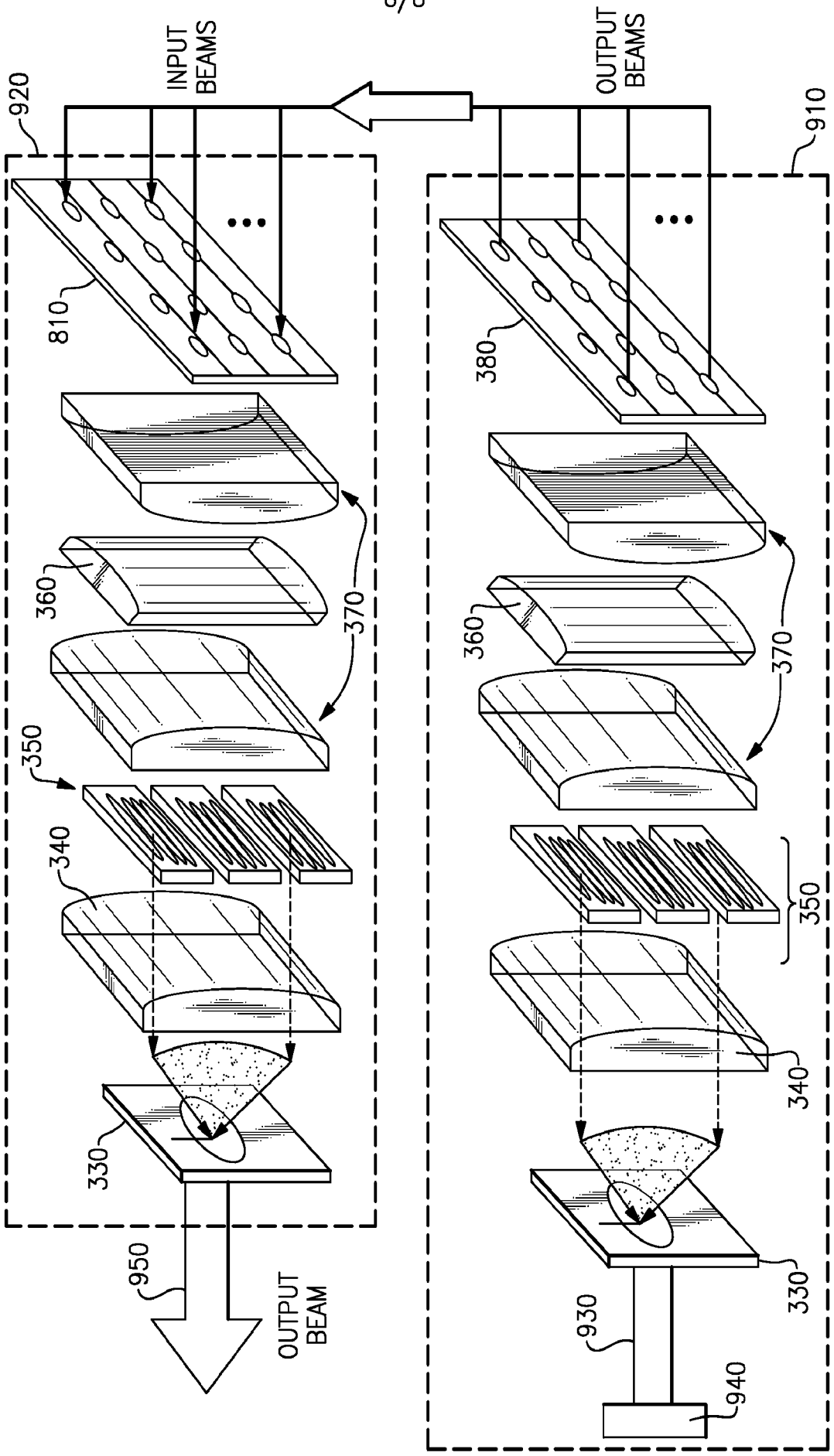

INPUT BEAMS
OUTPUT BEAMS
920
910
810
380
360
370
350
340
330
950
OUTPUT BEAM
930
940

FIG.9

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/026246

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B27/10 G02B27/44 G02B27/09 H01S5/40
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2006/012463 A2 (MASSACHUSETTS INST TECHNOLOGY [US]; HORNUNG THOMAS [US]; VAUGHAN JOSHU) 2 February 2006 (2006-02-02) page 8, line 2 - page 15, line 26; figures 1-3	1-19
Y	WO 02/071119 A1 (ZOLO TECHNOLOGIES INC [US]; SAPPEY ANDREW D [US]; HUANG PEI [US]; MURP) 12 September 2002 (2002-09-12) page 15, line 27 - page 16, line 5; figure 8 page 17, line 10 - line 13	1-19
Y	US 6 763 054 B2 (WHITLEY RICHARD M [US]) 13 July 2004 (2004-07-13) column 3, line 65 - column 8, line 2; figures 1,2	1-19

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 July 2011	02/08/2011

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	P Theopistou-Bertram

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/026246

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CHANN B ET AL: "Frequency narrowed external cavity diode laser array bar", OPTICS LETTERS, OSA, OPTICAL SOCIETY OF AMERICA, WASHINGTON, DC, US, vol. 25, no. 18, 15 September 2000 (2000-09-15), pages 1352-1354, XP002605185, ISSN: 0146-9592, DOI: DOI:10.1364/OL.25.001352 page 1352 - left-hand column; figure 1	1-19
A	US 2006/171428 A1 (VOLODIN BORIS L [US] VOLODIN BORIS LEONIDOVICH [US]) 3 August 2006 (2006-08-03) paragraph [0007] - paragraph [0008] paragraph [0025] - paragraph [0042]; figures 1-4	1-19

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2011/026246

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WO 02071119 A1	12-09-2002	NONE	
US 6763054 B2	13-07-2004	US 2004095983 A1	20-05-2004
US 2006171428 A1	03-08-2006	NONE	