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(74) Agent: **ANASTASI, John, N.**; Lowrie, Lando & Anastasi, LLP, Suite 1100, One Main Street, Cambridge, MA 02142 (US).

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(71) Applicant (*for all designated States except US*): **MASSACHUSETTS INSTITUTE OF TECHNOLOGY** [US/US]; 5 Cambridge Center, Kendall Square, Room NE25-230, Cambridge, MA 02142-1493 (US).

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(72) Inventors; and

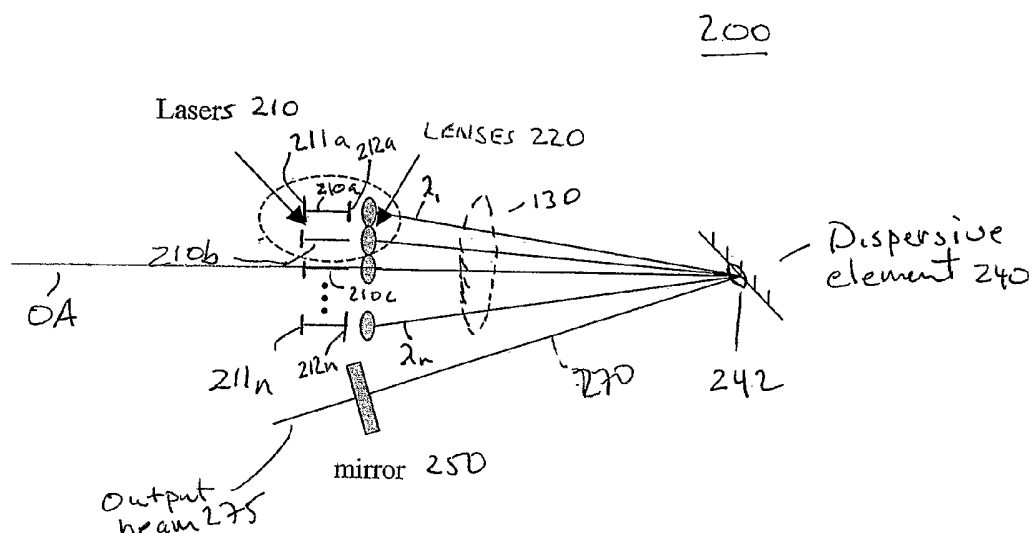
(75) Inventors/Applicants (*for US only*): **FAN, Tso, Yee** [US/US]; 32 Horace Road, Belmont, MA 02478 (US). **SANCHEZ, Antonio** [US/US]; 34 Taft Avenue, Lexington, MA 02173 (US). **CHANN, Bien** [US/US]; 30 Bey Ridge Drive, Apt. E, Nashua, NH 03062 (US).

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(54) Title: MULTI-WAVELENGTH BEAM COMBINER



(57) Abstract: Various embodiments of a multi-wavelength beam combiner are disclosed. Some embodiments comprise a plurality of lasers adapted to produce light and lenses arranged to receive and focus the light produced by each of the plurality of lasers. A wavelength dispersive element is arranged to receive the light produced by a combination of each of the plurality of lasers and the plurality of lenses, such that the light produced by each combination forms a region of overlap at the wavelength dispersive element. The wavelength dispersive element is configured to provide a multi-wavelength beam of light comprising the light produced by each combination of the plurality of lasers and the plurality of lenses. At least one partially reflective device is configured to receive at least a portion of the multi-wavelength light and to reflect a portion of the multi-wavelength light.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

MULTI-WAVELENGTH BEAM COMBINER

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BACKGROUND OF INVENTION

15 1. Field of Invention

The present invention is directed to beam combiners and, more particularly, to multi-wavelength beam combiners.

2. Discussion of Related Art

20 Multi-wavelength beam combiners that combine laser beams having different wavelengths to produce a single multi-wavelength laser beam are known. One example of such a conventional beam combiner is illustrated in FIG. 1. A multi-wavelength beam combiner 100 (illustrated in FIG. 1) includes an array of lasers 110, an array of microlenses 120, a converging lens 130, a diffraction grating 140, and a
25 partially reflective mirror 150. Each of the plurality of lasers 110 has a rear surface 111a-111e, a partially-reflective front surface 112a-112e, and a gain medium disposed therebetween.

In beam combiner 100, light is produced by each of the lasers in array of lasers 110 and light from each of said lasers is collimated by a corresponding one of the
30 array of lenses 120 to form a plurality of beams 125a-125e. After collimation, each beam 125a-125e travels substantially parallel to the remaining beams 125a-125e

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toward converging lens 130. Converging lens 130 is typically located a distance equal to the focal length of converging lens 130 away from array of lasers 110, and a distance equal to the focal length of converging lens 130 away from diffraction grating 140. Converging lens 130 converges the beams so that they form a region of overlap 142 on a surface of diffraction grating 140. By appropriately selecting and arranging diffraction grating 140 and partially reflective mirror 150, a single beam 145 can be produced.

Partially reflecting mirror 150 receives light in beam 145 and reflects a portion of the light back toward the region of overlap 142, and diffraction grating 140 then reflects light back to the plurality of lasers 110. A resonant cavity is thereby formed between partially reflecting mirror 150 and each of the rear surfaces 111a-111e of the plurality of lasers 110, provided that the reflectivity of the partially-reflective, forward surface 112a-112e is selected to be suitably low compared to the reflectivity of partially reflective mirror 150. Typically, output beam 145 is incident normal to the partially reflecting mirror 150. Partially reflecting mirror 150 combined with the diffraction grating 140, forces each laser of plurality of lasers 110 to lase at a unique, but controlled, wavelength. A portion of beam 145 transmitted by partially reflecting mirror 150 forms output beam 160.

SUMMARY OF INVENTION

The size of conventional multi-wavelength beam combiners as described above has increased as the number of lasers in the laser arrays has been increased to achieve high power output beams. In particular, in some beam combiners, the converging lens has become larger and correspondingly more expensive as the number of lasers has increased to collect and converge light from all of the lasers in the laser array. Aspects of the present invention are directed toward reducing or eliminating the above disadvantage of conventional multi-wavelength beam combiners.

According to some aspects of the invention the beam of light from the plurality of lasers are separated (i.e., diverged) prior to converging the beams to

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generate the region of overlap. For example, the separation may provide an opportunity to process one or more of the beams prior to combining the beams.

In some conventional multi-wavelength beam combiners, it is advantageous to reduce the number of components to reduce cost and/or complications of alignment.

5 Accordingly, aspects of the present invention are directed to eliminating the partially reflective mirror.

An aspect of the present invention is directed to a multi-wavelength beam combiner, comprising a plurality of lasers disposed at a first pitch, each of the plurality of lasers adapted to produce light, a plurality of lenses disposed at a second
10 pitch, the second pitch being different than the first pitch, arranged to receive the light produced by each of the plurality of lasers, a wavelength dispersive element arranged to receive the light produced by each of the plurality of lasers from the plurality of lenses, the wavelength dispersive elements being disposed at a location such that the light produced by each of the plurality of lasers forms a region of overlap at the
15 wavelength dispersive element, the wavelength dispersive element being configured to form a beam of light comprising the light produced by each of the plurality of lasers, and a partially reflective mirror configured to receive the beam from the wavelength dispersive element and to reflect a portion of the beam back to the region of overlap at the surface of the wavelength dispersive element.

20 In some embodiments, the beam combiner may further comprise an optical element adapted to receive the light produced by each of the plurality of lasers from the plurality of lenses and to converge the light produced by each of the plurality of lasers to form the region of overlap

In some embodiments, the first pitch is larger than the second pitch. In other
25 embodiments, the second pitch is larger than the first pitch. In some embodiments, the combiner does not include converging optical element between the plurality of lenses and the dispersive element.

Another aspect of the present invention is directed to multi-wavelength beam combiner, comprising a plurality of lasers each of the plurality of lasers adapted to
30 produce light, a plurality of partially reflective regions, each region being configured and arranged to receive the light produced by a corresponding one of the lasers, and to

reflect light of a selected wavelength back to the corresponding one of the plurality of lasers, the wavelength reflected by each region being different than the other regions, an optical element adapted to receive the light produced by each of the plurality of lasers from plurality of partially reflective regions and to converge the light produced
5 by each of the plurality of lasers to form a region of overlap, and a wavelength dispersive element arranged to receive the light produced by each of the plurality of lasers from the optical element, the wavelength dispersive element being disposed at a location such that the region of overlap is projected at the wavelength dispersive element, the wavelength dispersive element being configured to form a beam of light
10 comprising the light produced by each of the plurality of lasers.

In some embodiments, the plurality of partially reflective regions constitute regions of a volume Bragg grating (VBG). In such embodiments, the plurality of lasers may constitute the laser diodes of a single linear laser diode bar. It is to be appreciated that using laser diodes constituting a single linear laser diode bar provides
15 advantages including but not limited to reducing the cost of the laser diodes and reducing time and effort related to alignment of individual lasers elements.

BRIEF DESCRIPTION OF DRAWINGS

The accompanying drawings are not intended to be drawn to scale. In the
20 drawings, 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 drawing. In the drawings:

FIG. 1 is a schematic illustration of a related art conventional beam combiner;

FIG. 2A is a schematic illustration of one embodiment of a multi-wavelength
25 beam combiner according to aspects of the present invention;

FIG. 2B is an expanded schematic illustration of lasers and lenses comprising the beam combiner of FIG. 2A;

FIG. 3A is a schematic illustration of another embodiment of a multi-wavelength beam combiner according to aspects of the present invention;

30 FIG. 3B is an expanded schematic illustration of lasers and lenses comprising the beam combiner of FIG. 3A;

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FIG. 4A is a schematic illustration of another embodiment of a multi-wavelength beam combiner according to further aspects of the present invention;

FIG. 4B is a schematic illustration of an example of a volume Bragg grating (VBG) having a grating period that varies along the direction x ;

5 FIG. 5 is a schematic illustration of an embodiment of a multi-wavelength beam combiner according to further aspects of the present invention in which a plurality of multi-wavelength output beams are formed;

FIG. 6 is a schematic illustration of another example of a multi-wavelength beam combiner according to still further aspects of the present invention;

10 FIG. 7 is a schematic illustration of another embodiment of a multi-wavelength beam combiner according to the invention; and

FIG. 8 is a schematic illustration of another embodiment of a multiple output beam, multi-wavelength beam combiner of the invention.

15 DETAILED DESCRIPTION

This invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, the phraseology and terminology used
20 herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having," "containing", "involving", and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

FIG. 2A is a schematic illustration of an example of a multi-wavelength beam
25 combiner according to aspects of the present invention. Multi-wavelength beam combiner 200 comprises a plurality of lasers 210, a plurality of lenses 220, a wavelength dispersive element 240, and a partially reflective mirror 250. As described below, plurality of lenses 220 are disposed at a pitch that is smaller than the pitch at which plurality of lasers 210 are disposed, thus causing the beams from the
30 plurality of lasers to converge. As discussed in greater detail below, in some embodiments of the present invention, by selecting a suitable difference in the pitch of

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plurality of lasers 210 and the pitch of plurality of lenses 220, converging lens 130 can be reduced in size or can be eliminated. Plurality of lasers 210 may comprise any suitable number of lasers.

The plurality of lasers 210 comprising lasers 210a, 210b are disposed at a first
5 pitch P_1 (see FIG. 2B). Each of the lasers comprising plurality of lasers 210 is configured and arranged to produce a corresponding light beam. In some embodiments, the plurality of lasers may constitute the laser diodes of a single linear laser diode bar. It is to be appreciated that using laser diodes constituting a single
10 linear laser diode bar provides advantages including but not limited to reducing the cost of the laser diodes and reducing time and effort related to alignment of individual lasers elements.

In one embodiment of beam combiner 200, plurality of lasers 210 comprises a conventional array of substantially identically constructed semiconductor lasers diodes. However, the invention is not so limited. It is to be appreciated that any laser
15 or array of lasers can be used. Typically, such lasers will have a relatively large gain-bandwidth product to permit each laser to lase at a unique wavelength. Typically, such lasers are tunable lasers. For example, the lasers may be gas lasers, dye lasers, Ti:Sapphire lasers, fiber lasers or any other suitable laser. Further, in a given embodiment, the lasers need not be identically constructed, for example, the
20 wavelength of maximum gain may vary monotonically across the array.

The lenses comprising plurality of lenses 220 are disposed at a second pitch P_2 (see FIG. 2B), the second pitch being smaller than the first pitch. It is to be appreciated that as a result of the pitch of the lenses being smaller than the pitch of the plurality of lasers, the beams ($\lambda_1, \lambda_2 \dots \lambda_n$) emitted by the lasers can be made to
25 converge.

In some embodiments, the laser at the center of the plurality of lasers 210c (i.e., located along the optical axis OA of beam combiner 200) is aligned with the center of the lens 220c located at the center of the plurality of lenses 220 such that the light from laser 210c passes through lens 220c without deviation in its direction. It is
30 to be appreciated that in this embodiment the lens 220c may focus the beam from laser 210c, but will not deviate the direction of the beam relative to the optical axis

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OA. In such embodiments, while the laser 210c and the lens 220c are aligned, because pitch $P_2 < P_1$, other lenses comprising the plurality of lenses 220 will not align with their corresponding laser, and as a result, light from each of the other beams emitted by the respective lasers will be deviated in a direction toward the optical axis OA. It is to be appreciated that, in embodiments where the pitches P_1 and P_2 for all lenses in the array, the offset between the center of the laser 210n and the center of its corresponding lens 220n will be larger the further from the optical axis OA that the laser and lens are located (i.e., the offset will be zero for the lens along optical axis OA and maximum at the periphery of the array). Accordingly, light from each of the plurality of lasers will be made to converge toward the optical axis OA to form a region of overlap 242.

A suitable difference in pitch of the plurality lasers 210 and the pitch of plurality of lenses 220 to achieve a suitable convergence may be determined using a conventional geometric ray trace program. It is to be appreciated that the difference in pitches P_2 and P_1 is determined at least in part by the distance between the plurality of lenses 220 and dispersive element 240, and the number of lasers to be included in array of lasers 210. The difference in pitch P_1 can be as much as approximately two times as large as pitch P_2 (i.e., for an array of three lasers) to a fraction of a percent for arrays having hundreds of lasers. It is to be further appreciated, as stated above, that in some embodiments, the convergence of the beam can be caused to occur without the use of a converging lens 130.

Although beam combiner 200 is illustrated as comprising refractive elements (i.e., plurality of lenses 220) disposed at second pitch P_2 , any suitable optical element or elements capable of causing convergence of the beams emitted by the plurality of lasers toward the optical axis OA, may be used, and in particular to cause the plurality of beams to overlap at the dispersive element. For example, beam combiner 200 may comprise reflective elements (mirrors having suitable curvatures) or diffractive elements.

Wavelength dispersive element 240 is arranged to receive light produced by each of the plurality of lasers 210 from the plurality of lenses 220. The wavelength dispersive element 240 is disposed at a location such that a region of overlap 242 is

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formed at the wavelength dispersive element. As discussed above, the region of overlap 242 is caused, at least in part, as a result of the difference in pitches P_1 and P_2 . It is to be appreciated that the term "at the wavelength dispersive element" includes, for example, on a surface of a reflective dispersive element or inside a transmissive dispersive element or any other suitable location relative to a dispersive element.

It is to be appreciated that dispersive element 240 can comprise any suitable dispersive element. The dispersive element can be, for example, transmissive or reflective. For example, dispersive element 240 may comprise a prism, a reflective diffraction grating or a transmissive diffraction grating.

In embodiments in which dispersive element 240 is a diffraction grating, the angle at which the grating is disposed relative to the optical axis OA and the incident beams ($\lambda_1, \lambda_2 \dots \lambda_n$), the size of the grating elements and the pitch of the grating elements can be selected such that the wavelength dispersive element forms a single beam of light comprising the wavelengths of light 270 produced by each of the plurality of lasers.

Partially reflective mirror 250 is configured to receive beam 270 from wavelength dispersive element 240 and to reflect a portion of the beam back to the region of overlap 242 to the wavelength dispersive element thus providing feedback to form a resonant cavity for each of the beams ($\lambda_1, \lambda_2 \dots \lambda_n$). A portion of beam 270 transmitted by partially reflective mirror 250 forms output beam 275. It is to be appreciated that the reflectivity of the partially reflective mirror, as well as other characteristics of the partially reflective mirror (e.g., flatness), are selected according to a desired performance. In some embodiments, the reflectivity of partially reflective mirror 250 is selected to be greater than the reflectivity of front surfaces 212a-212n of the lasers such that a resonant cavity is formed between the mirror 250 and the rear surfaces 211a-211n of the lasers. For example, the front surface 212a-212n of the lasers may have a reflectivity in a range of 0-5% and the partially reflective mirror may have a reflectivity in a range of 1-90%.

The wavelength dispersive element 240 and partially reflecting mirror 250 are configured and arranged such that beams ($\lambda_1, \lambda_2 \dots \lambda_n$) are combined to form a single co-propagating output beam of light 270 after the beams ($\lambda_1, \lambda_2 \dots \lambda_n$) impinge on the

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wavelength dispersive element 240. Partially reflective mirror 250 is configured and arranged such that its surfaces are perpendicular to the beam from the dispersive element. The angle of the wavelength dispersive element 240 relative to the beams from plurality of lasers 210 is selected such that, after reflection of light from partially reflective mirror 250, appropriate wavelengths are fed back to the plurality of lasers.

It is to be appreciated that the output beam 275 may have some divergence, including divergence caused by the light from beams $\lambda_1, \lambda_2 \dots \lambda_n$ propagating at slightly different angles. The amount of divergence that is present in the output beam generated is at least partially determined by the amount of divergence that is tolerable in a given application in which the beam combiner is to be employed. Any suitable beam shaping techniques may be used to shape beam 275 output by the beam combiner. The beam shaping techniques may affect the size, shape and divergence of the beam.

U.S. Patent No. 6,192,062, titled BEAM COMBINING OF DIODE LASER ARRAY ELEMENTS FOR HIGH BRIGHTNESS AND POWER, to Sanchez-Rubio, et al. (hereinafter Sanchez-Rubio) discloses beam combiner arrangements having aspects in common with the present beam combiner. It is to be appreciated that, according to some embodiments of the invention, aspects of the present invention, including providing a lens array 220 having a pitch P_2 that is different than the pitch P_1 of plurality of lasers 210, can be applied to beam combiner arrangements as disclosed in Sanchez-Rubio. The Sanchez-Rubio patent is hereby incorporated by reference in its entirety.

Example – The following are exemplary dimensions of an example of an embodiment of a multi-wavelength beam combiner as described with reference to FIG. 2A.

An exemplary embodiment of a beam combiner comprises a laser diode array including 100 substantially identically constructed semiconductor laser diodes. The laser diodes are conventional semiconductor laser diodes adapted to produce light at 915 nanometers. The reflectivity of the back surface of the laser diodes is approximately 95% and the reflectivity of the front surface of the laser diodes is less

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than 1%. The lasers diodes are disposed at a 100 micrometer pitch, and the emitted beam of each laser diode has a diameter of approximately 4 micrometers.

5 Microlenses having a pitch that is 1% less than the pitch of lasers (i.e., 99 micrometers), and each having a focal length of 150 micrometers are disposed relative to the plurality of lasers to collimate the light from the plurality of lasers. A holographic diffraction grating having 1800 grooves/mm is located 15 cm from each of the plurality of lenses along the optical axis. The diffraction grating is disposed such that its normal forms an angle of 60 degrees with respect to the optical axis. A partially-reflective, dielectric mirror having a reflectivity of 10% is located 10 cm
10 away from the diffraction grating, as measured along the optical axis. It is to be appreciated that the dispersive element and the partially reflective mirror are located to form resonant cavities that, in combination with the back surfaces of the plurality of lasers, support resonance of wavelengths approximately equal to 915 nm (e.g. wavelengths in the band 905-923 nm).

15 The 100 lasers comprising a beam combiner configured as described above will form a region of overlap on the diffraction grating having a diameter of 3-4 mm and produce light in the band 905 nm to 923 nm. As a result, the output beam of the beam combiner will produce a single beam including light at 100 discrete wavelengths in the range 905-923 nm (i.e., one wavelength corresponding to each of
20 the laser diodes in the laser diode array). This exemplary embodiment beam combiner does not include a converging lens.

FIG. 3A is a schematic illustration of another example of a multi-wavelength beam combiner 300 according to aspects of the present invention. Beam combiner 300 is substantially the same as combiner 200 discussed above with reference to FIGs.
25 2A and 2B, other than combiner 300 also includes a converging optical element 330. Because beam combiner 300 includes a converging optical element 330, the difference in pitch P_2 between lenses 320 may be larger or smaller than the pitch P_1 between lasers 210. In embodiments where P_1 is greater than P_2 , the light produced by the lasers that are not located on the optical axis OA will be directed toward the
30 optical axis in the manner discussed above with reference to FIG. 2A. In such embodiments, the presence of converging lens 330 provides the ability to converge

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the light from the lasers more quickly than the plurality of lenses 320 alone, and dispersive element 240 may therefore be located correspondingly closer to the plurality of lenses 320.

In embodiments where P_2 is greater than P_1 (not shown), the center of the plurality of lasers 210c (i.e., located along the optical axis OA of beam combiner 300) is aligned with the center of the lens 320c located at the center of the plurality of lenses 320, such that the light from laser 210c passes through lens 320c without deviation in its direction. However, because pitch $P_1 < P_2$, lenses adjacent lens 320c will not align with their corresponding lens, and will be deviated in a direction away from the optical axis OA, thus separating (i.e., diverging) the beams $\lambda_1, \lambda_2 \dots \lambda_n$. For example, separating the beams may provide space to locate a processor to process one or more of the beams prior to combining the beams. In such embodiments, converging optical element 330 can be selected to converge light from the plurality of lasers 210 to form a suitable region of overlap 242 at the dispersive element 240. It is to be appreciated that, in such embodiments, converging optical element 330 may be larger than it would be if the beams were not separated prior to convergence.

Optical element 330 is adapted to receive the light produced by each of the plurality of lasers from the plurality of lenses and to converge the light produced by each of the plurality of lasers to form a region of overlap 242 at the dispersive element 242. It is to be appreciated that, in embodiments where $P_2 < P_1$, convergence of the beams is caused by the pitch P_2 of the plurality of lenses being smaller than the pitch of the lenses P_1 , in combination with the converging optical element 330, and that for such case the converging optical element 330 may be selected to be smaller than lens 130 (shown in FIG. 1) for a given number of lasers 210.

It is to be appreciated that converging optical element 330 may comprise any suitable converging optical element capable of forming a region of overlap 242. For example, element 330 may comprise a refractive element, a reflective element, a diffractive element, a holographic elements or a combination of any of the above. It is to be appreciated the greater the power of the converging optical element, the shorter the system length of the resultant system.

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FIG. 4A is a schematic illustration of another example of a multi-wavelength beam combiner 400 according to aspects of the present invention. Beam combiner 400 comprises a plurality of lasers 210, a plurality of partially reflective regions 425a-425n, a converging optical element 330 and a wavelength dispersive element 240.

5 Each of plurality of lasers 210 and wavelength dispersive element 240 are configured and arranged to function in a manner as described above with reference to FIGs. 2A above; and converging optical element 330 operates as described with reference to FIG. 3 above. According to the aspects of the invention, a resonant cavity is formed between each of a plurality of partially reflective regions 425a-425n and a corresponding rear surface 211a-211n of a given one of plurality of lasers 210. It is to be appreciated that, according to this embodiment for reasons discussed in greater detail below, partially reflective mirror 250 is omitted from beam combiner 400.

Each region 425a-425n of plurality of partially reflective regions 420 is arranged to receive the light produced by a corresponding one of the lasers and to reflect a different wavelength than each of the other regions. Each region 425a-425n forms a resonant cavity with a corresponding one of the rear surfaces 211a-211n of the plurality of lasers 210a-210n. The wavelength of the light produced by a given resonant cavity is determined by the wavelength of the light that is reflected by the region 425a-425n that forms the given resonant cavity. According to this embodiment, because a laser cavity is formed between a region 425a-425n and a corresponding laser diodes diode 210a-210n, a partially reflective mirror 250 is unnecessary and is therefore omitted.

It is to be appreciated that regions 425 may be constructed in any suitable manner such that a selected wavelength of light is reflected back to each of the lasers. In some embodiments the regions 425 can form a single apparatus; and in some embodiments the regions are formed on an integrated substrate. For example, the regions may be regions of a single Volume Bragg Grating (VBG) having a linear, wavelength chirp. That is, as illustrated in greater detail in FIG. 4B, the VBG has a grating period that varies along the direction x. Accordingly, the VBG is configured to reflect different wavelengths of light at different locations along direction x.

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Alternatively, the regions may comprise dielectric filters configured to reflect the selected wavelengths, or the regions may comprise resonant grating filters. Typically, regions 425 are externally reflective. However, the invention is not so limited and regions 425 may be made of any suitable reflective apparatus.

5 As discussed above with reference to FIG. 3A, optical element 330 is selected such that it collects the light produced by each of the plurality of lasers 210 and converges the light to form a region of overlap 242 at wavelength dispersive element 240. In the manner discussed above, the wavelength dispersive element is configured and arranged to form an output beam 275 comprising co-propagating light produced
10 by each of the plurality of lasers 210.

 In some embodiments, a plurality of lenses 420 may be included between the plurality of lasers and the plurality of regions to collimate and/or suitably shape the beams of light emitted by the plurality of lasers 210. For example, the lenses comprising the plurality of lenses may be spherical, aspherical or cylindrical. In
15 embodiments in which the plurality of lenses 420 are cylindrical lenses, the lenses may be aligned to collimate light from the plurality of lasers 210 in the x direction or in the y direction. In embodiments where the light is collimated in the y-direction, the plurality of lenses may be replaced by a single cylindrical lens disposed in front of the plurality of lasers.

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Example - The following are exemplary dimensions of an example of an embodiment of a multi-wavelength beam combiner as described with reference to FIG. 4A.

 The exemplary embodiment of a beam combiner comprises a linear laser diode array including 100 substantially identically constructed semiconductor laser diodes.
25 That is, the laser diodes constitute the laser diodes of a linear laser diode bar. The laser diodes are conventional semiconductor laser diodes adapted to produce light at 915 nanometers. The reflectivity of the back surface of the laser diodes is approximately 95% and the reflectivity of the front surface of the laser diodes is less than 1%. The laser diodes are disposed at a 100 micrometer pitch, and the emitted
30 beam of each laser diode has a diameter of approximately 4 micrometers.

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Micro lenses having a pitch equal to the pitch of the laser diodes, and each of the lenses having a focal length of 150 micrometers, are disposed relative to the plurality of lenses to collimate the light from the plurality of lenses. A VBG is located 1 mm in front of the plurality of lenses. The VBG is 3 mm thick, and is adapted to reflect light in the range 905-920 nm across its length. That is, the VBG is configured such that the wavelength of light reflected varies continuously across the length of the VBG at rate of 15nm/cm. Thus, each laser element receives reflected light of a unique and controlled wavelength from the VBG. The reflectivity at each wavelength is approximately 10%. One of ordinary skill in the art would understand that, in such embodiments, the plurality of partially reflective regions are disposed at the locations where the laser light impinges on the VBG. Other regions are disposed continuously across the length of the VBG. A converging, biconvex lens having a 15 cm focal length is located 15 cm (i.e., one focal length) away from the VBG. A holographic diffraction grating having 1800 grooves/mm is located approximately 15 cm (i.e., one focal length) from the converging lens. The diffraction grating is disposed such that a normal to its front surface forms an angle of 66 degrees with respect to the optical axis.

The 100 lasers comprising a beam combiner configured as described above will form a region of overlap on the diffraction grating having a diameter of 3-4 mm and produce light in the band 905 nm to 920 nm. As a result, the output beam of the beam combiner will produce a single beam including light at 100 discrete wavelengths in the range 905-920nm (i.e., one wavelength corresponding to each of the laser diodes in the laser diode array).

FIG. 7 illustrates a schematic illustration of another embodiment of a multi-wavelength beam combiner 700 according to the present invention, in which the lasers 210 of the embodiment of FIG. 4A comprise two or more diode arrays 210A and 210B as illustrated in FIG. 7. In addition, the beam combiner 700 of FIG. 7 comprises two or more partially reflective regions 425A and 425B, which can be, for example, VBG's with a linear wavelength chirp. Otherwise, beam combiner 700 is substantially similar to the beam combiner discussed above and illustrated with respect to FIG. 4A. In the embodiment of FIG. 7, a resonant cavity is formed between

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each of the plurality of diode arrays 210A, 210B and each of the partially reflective devices 425A and 425B, to provide light reflected by the diode arrays and the partially reflective regions at a plurality of different wavelengths for each diode array and reflective region combination. It is to be appreciated that the diode arrays 210A and 210B and the partially reflective devices 425A and 425B can be any of the devices described above. It is also to be appreciated that according to this embodiment, because the resonant cavities are formed between each of the diode arrays and the corresponding partially reflective surface, the partially reflective mirror 250 as illustrated, for example in FIG. 2A, is not needed and is therefore omitted.

Otherwise, operation of the beam combiner 700 of FIG. 7 is substantially as discussed above with respect to FIG. 4A. Namely, the optical element 330 is selected such as it collects the light produced by each combination of a diode array and a partially reflective device, and the optical element 330 converts the light from each such combination to a region of overlap 242 at the wavelength dispersive element 240. In addition, the cylindrical microlenses 420A, 420B are optional. It is to be appreciated that the optical element 330 can be any of the optical elements discussed above. It is also to be appreciated that the wavelength dispersive element 240 can be any of the elements discussed above and that, in the manner discussed above, the optical element 330 and the wavelength dispersive element act to provide an output beam 275 comprising light produced by each combination of a diode array and partially reflective device.

FIG. 5 is a schematic illustration of an example of a multi-wavelength beam combiner 500 according to further aspects of the present invention in which a plurality of multi-wavelength output beams 275_A, 275_B are formed. Beam combiner 500 is substantially similar to the beam combiner discussed above with reference to FIG. 4A, except that a plurality of linear laser diode bars 210_A, 210_B are used and a cylindrical lens 530 is used to combine the plurality of wavelengths provided by each of the plurality of laser diode bars 210_A, 210_B. Each output beam 275_A, 275_B is formed using the light from each laser diode 210_{A 1-N}, 210_{B 1-N} of a corresponding one of a plurality of linear laser diode bars 210_A, 210_B. It is to be appreciated that, although the beam combiner 500 is illustrated with a single cylindrical lens 220_A, 220_B in front

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of each laser diode bar 210_A, 210_B, the invention is not so limited and, as discussed above with reference to FIG. 4B, for example, a plurality of spherical or cylindrical lenses may be used.

FIG. 6 is a schematic illustration of another example of a multi-wavelength beam combiner 600 according to aspects of the present invention. Beam combiner 600 includes aspects of beam combiner 200 discussed above with reference to FIG. 2A and aspects of beam combiner 400 discussed above with reference to FIG. 4A.

In particular, similar to beam combiner 200 discussed above, plurality of lasers 210 are disposed at a first pitch P_1 and the lenses 220 comprising plurality of lenses are disposed at a second pitch P_2 , the second pitch being smaller than the first pitch. Accordingly, the beams ($\lambda_1, \lambda_2 \dots \lambda_n$) emitted by the lasers can be made to converge, and therefore according to some embodiments converging lens 130 (as shown in phantom in FIG. 2A) may be omitted.

In addition, similar to beam combiner 400 illustrated in FIG. 4A, this embodiment comprises a resonant cavity that is formed between each of a plurality 425 of partially reflective regions 425a-425n and a corresponding rear surface 211a-211n of a given one of plurality of lasers 210, and therefore the partially reflective mirror 250 is omitted from beam combiner 600.

Referring now to FIG. 8, there is illustrated another embodiment 800 of a multi-wavelength beam combiner 800, in which a plurality of multi-wavelength output beams 275A and 275B are formed. Beam combiner 800 is substantially similar to the beam combiners discussed above with respect to FIG. 7, except that each diode array 210A and 210B comprises a two-dimensional diode array and the partially reflective elements can comprise a single partially reflective element or can comprise a plurality of partially reflective elements 425A, 425B, 425C and 425D that together make up a two-dimensional partially reflective element, such as linear chirped VBG that corresponds to each diode array. It is to be appreciated that the beam combiner 800 is otherwise substantially similar to the beam combiners discussed above with respect to FIG. 7 except that the partially reflective elements 425A and 425C act to form respective resonant cavities with two-dimensional diode array 210A and partially reflective elements 425B and 425D combined with

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respective two-dimensional diode array 210B to provide respective resonant cavities, thereby providing two output beams 431 and 432 which are converged by optical element 330 to dispersive element 240 to provide two regions of overlap 242A and 242B. Accordingly, in the manner discussed above, the beam combiner is configured and arranged to provide two output beams 275A and 275B comprising co-propagating light produced by each of the two-dimensional diode arrays 210A, 210B and the corresponding two-dimensional partially reflective devices 425A, 425C and 425B, 425D. It is also to be appreciated that the embodiment of FIG. 8 can optionally include a plurality of cylindrical lenses 820A, 820B, 820C and 820D. It is also to be appreciated that the diode arrays 210A, 210B, cylindrical lenses 820A-D, the partially reflective surfaces 425A, 425B, 425C, 425D, the optical element 330, and the wavelength dispersive element 240 can be any of the above described devices.

Having thus described several aspects of at least one embodiment of this invention, 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 spirit and scope of the invention. Accordingly, the foregoing description and drawings are by way of example only.

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CLAIMS

1. A multi-wavelength beam combiner, comprising:
a plurality of lasers disposed at a first pitch, each of the plurality of lasers
5 adapted to produce light;
a plurality of lenses disposed at a second pitch, the second pitch being
different than the first pitch, arranged to receive and focus the light produced by each
of the plurality of lasers;
a wavelength dispersive element arranged to receive the light produced by a
10 combination of each of the plurality of lasers and the plurality of lenses, the
wavelength dispersive element being disposed at a location such that the light
produced by each combination forms a region of overlap at the wavelength dispersive
element, the wavelength dispersive element being configured to form a multi-
wavelength beam of light comprising the light produced by each combination of the
15 plurality of lasers and the plurality of lenses; and
a partially reflective mirror configured to receive the multi-wavelength beam
from the wavelength dispersive element and to reflect a portion of the multi-
wavelength beam back to the region of overlap on the surface of the wavelength
dispersive element.
20
2. The beam combiner of claim 1, further comprising an optical element adapted
to receive the light produced by each combination of the plurality of lasers and
plurality of lenses and to converge the light produced by each combination to form the
region of overlap
- 25
3. The beam combiner of claim 2, wherein the first pitch is larger than the second
pitch.
4. The beam combiner of claim 2, wherein the second pitch is larger than the first
30 pitch.

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5. The beam combiner of claim 1, wherein the first pitch is larger than the second pitch.

6. The beam combiner of claim 5, wherein the combiner does not include
5 converging optical element between the plurality of lenses and the wavelength dispersive element.

7. A multi-wavelength beam combiner, comprising:
a plurality of lasers, each adapted to produce light;
10 a plurality of partially reflective regions, each partially reflective region being configured and arranged to receive the light produced by a corresponding one of the lasers, and to reflect a portion of light of a selected wavelength back to the corresponding one of the plurality of lasers, and to transmit a portion of the light at the selected wavelength, the wavelength reflected and transmitted by each region
15 being different than the other regions;
an optical element adapted to receive the light produced by each combination of the plurality of lasers and partially reflective regions, and to converge the light produced by each combination to form a region of overlap; and
a wavelength dispersive element arranged to receive the light produced by
20 each combination from the optical element, the wavelength dispersive element being disposed at a location such that the region of overlap is formed at the wavelength dispersive element, the wavelength dispersive element being configured to form a multi-wavelength beam of light comprising the light produced by each of the plurality of lasers.

25

8. The beam combiner of claim 7, wherein the plurality of partially reflective regions constitute regions of a volume Bragg grating.

9. The beam combiner of claim 8, wherein the volume Bragg grating is
30 configured to vary the wavelength of reflection at each region.

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10. The beam combiner of claim 7, wherein the plurality of lasers constitute a linear bar of lasers diodes.
11. The beam combiner of claim 7, wherein the plurality of lasers comprise more
5 than one plurality of laser sources.
12. The beam combiner of claim 11, wherein the plurality of partially reflective regions comprises more than one plurality of partially reflective regions.
- 10 13. The beam combiner of claim 7, wherein the plurality of lasers are disposed at a first pitch and further comprising a plurality of lenses disposed at a second pitch, arranged to receive light produced by each of the plurality of lasers.

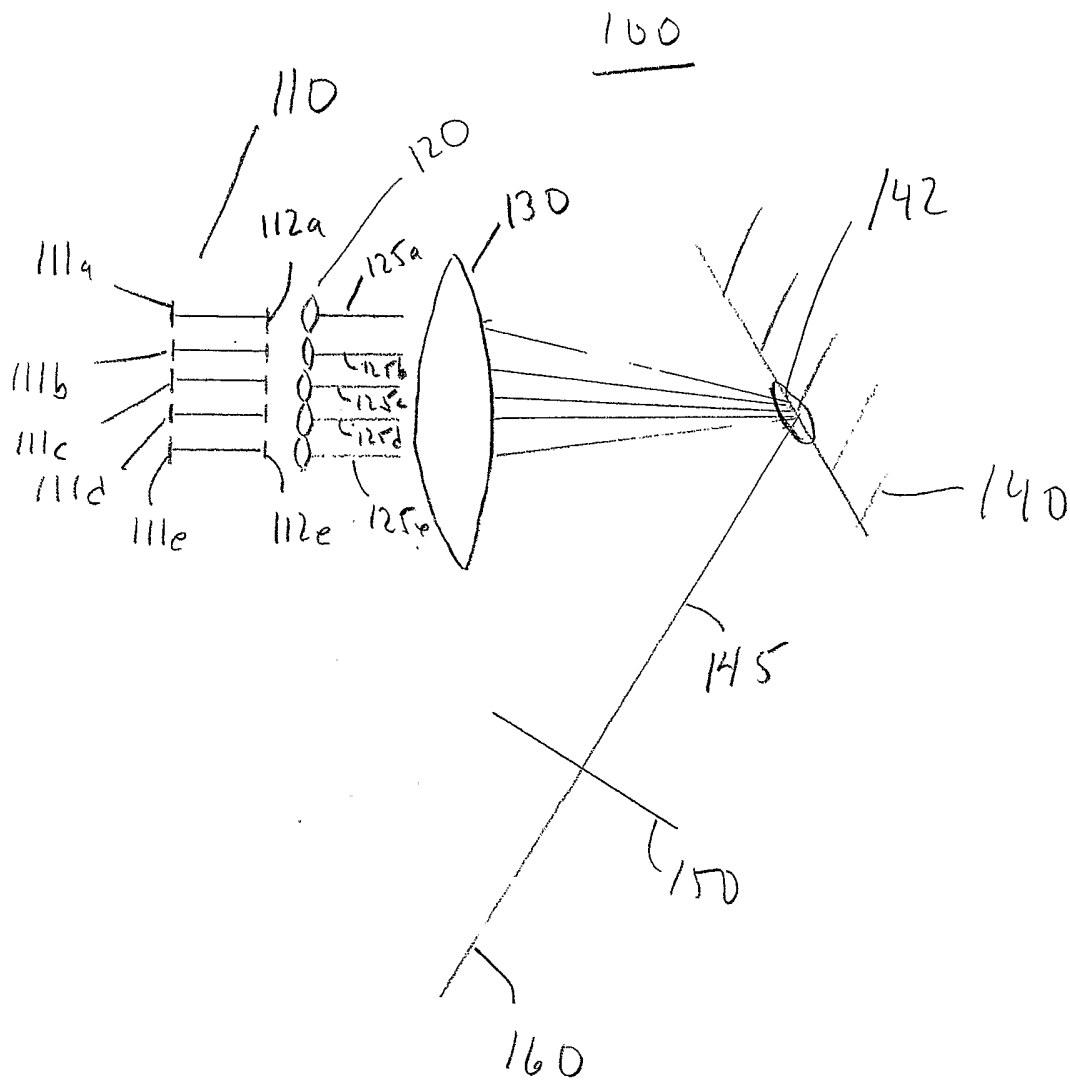


FIG. 1

Related Art

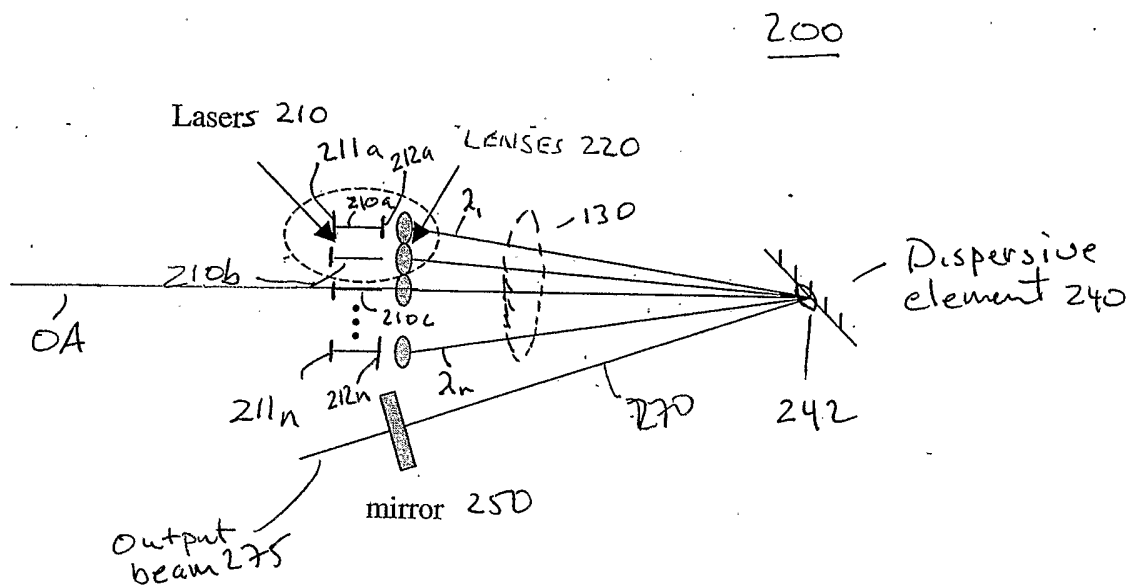


FIG. 2A

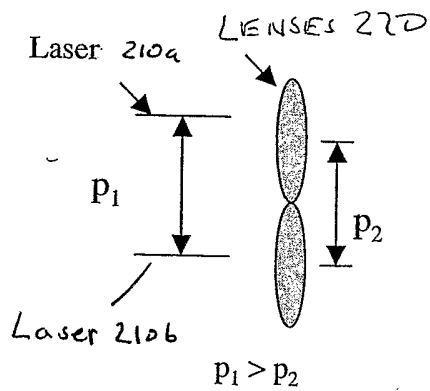


FIG. 2B

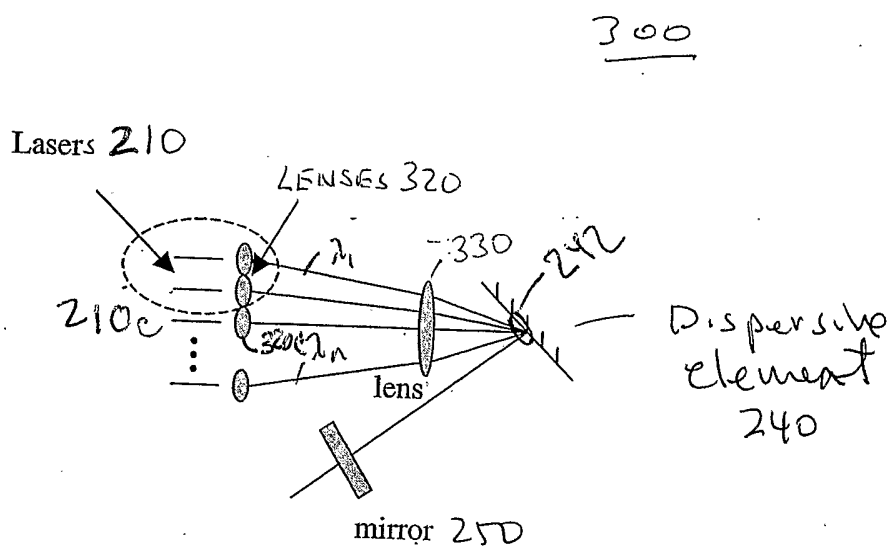


FIG. 3A

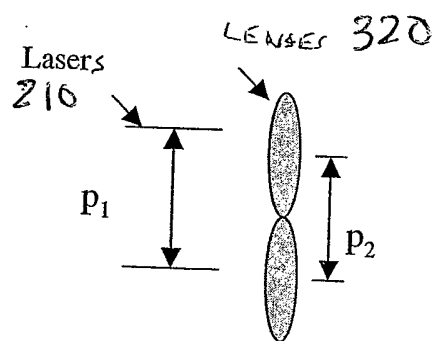
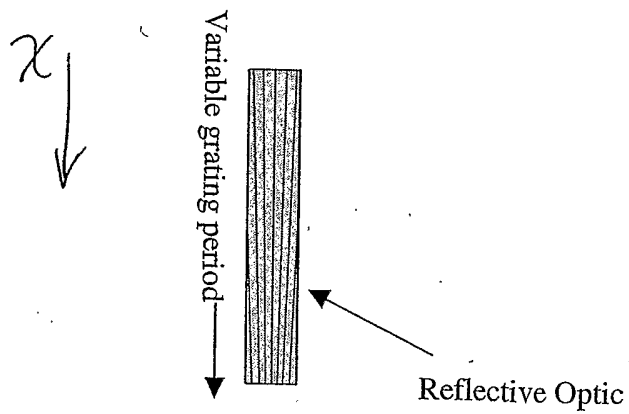
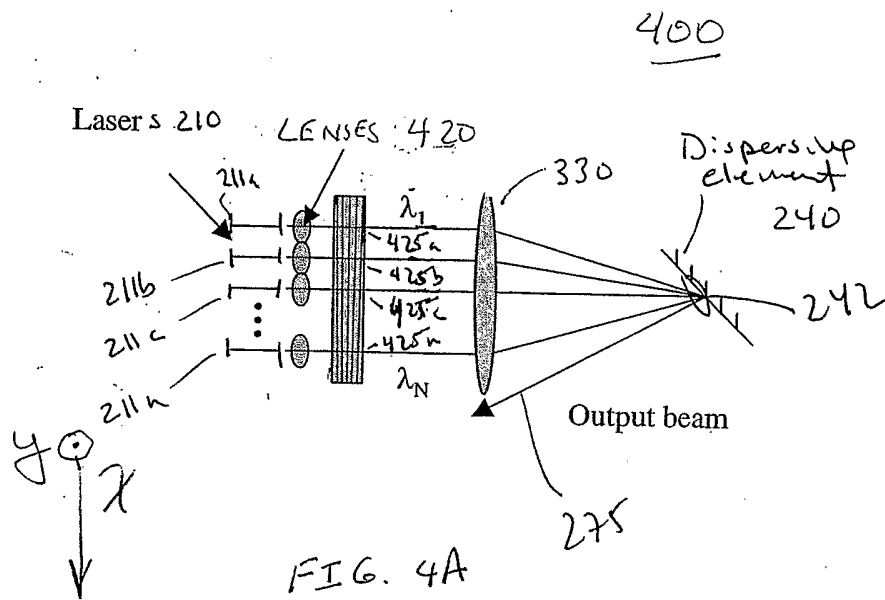
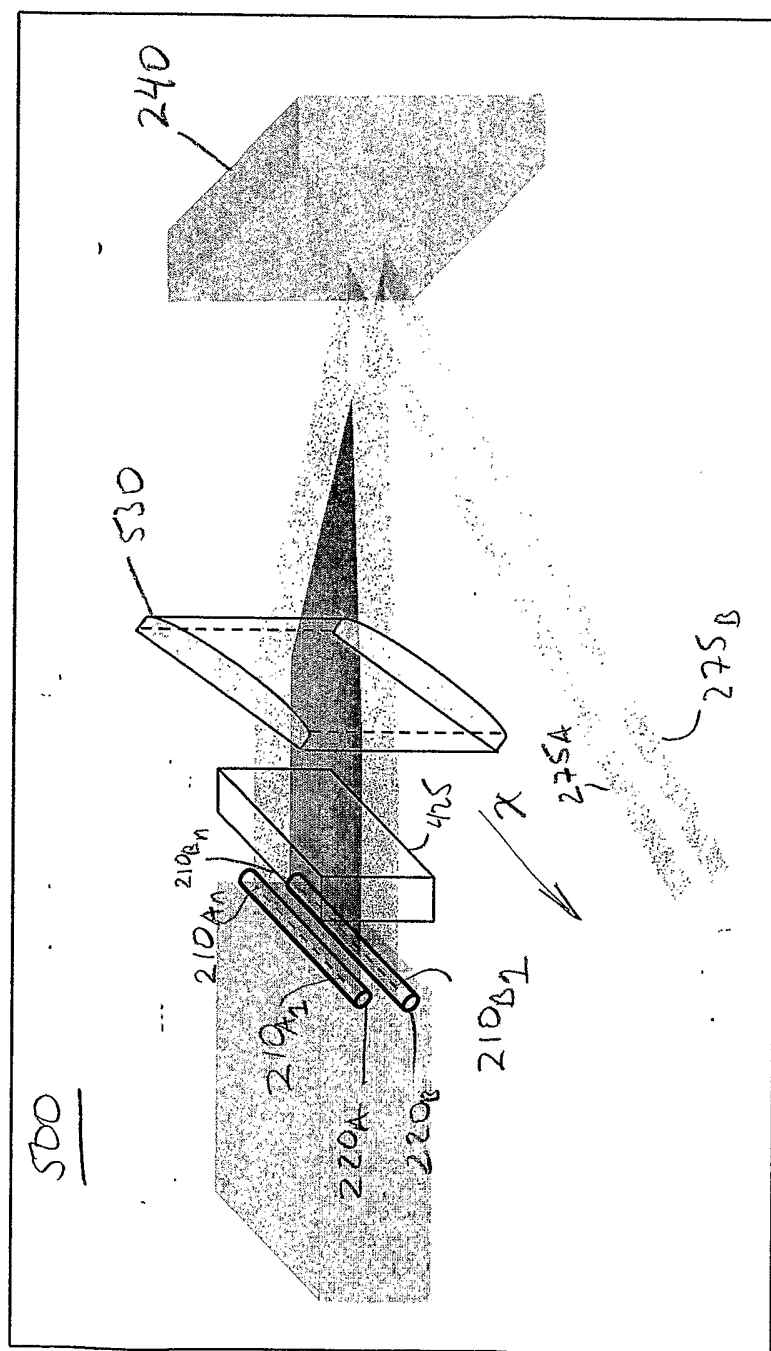


FIG. 3B





LIHG 5

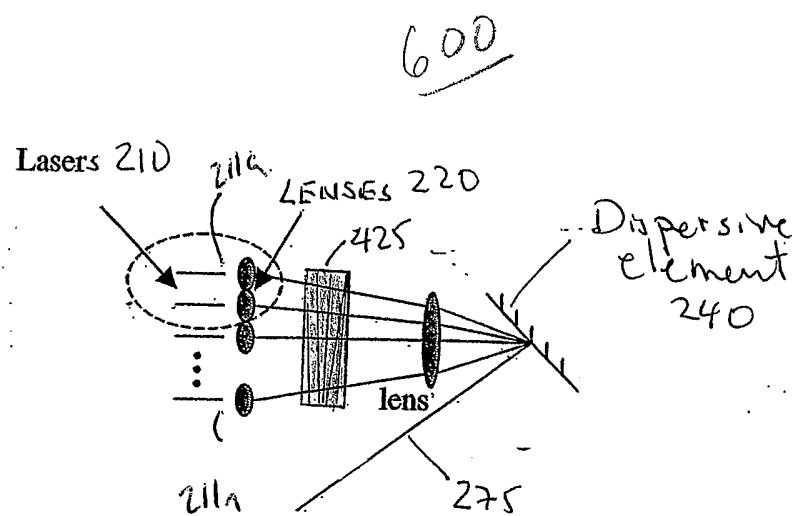


FIG. 6

Fig 7

700

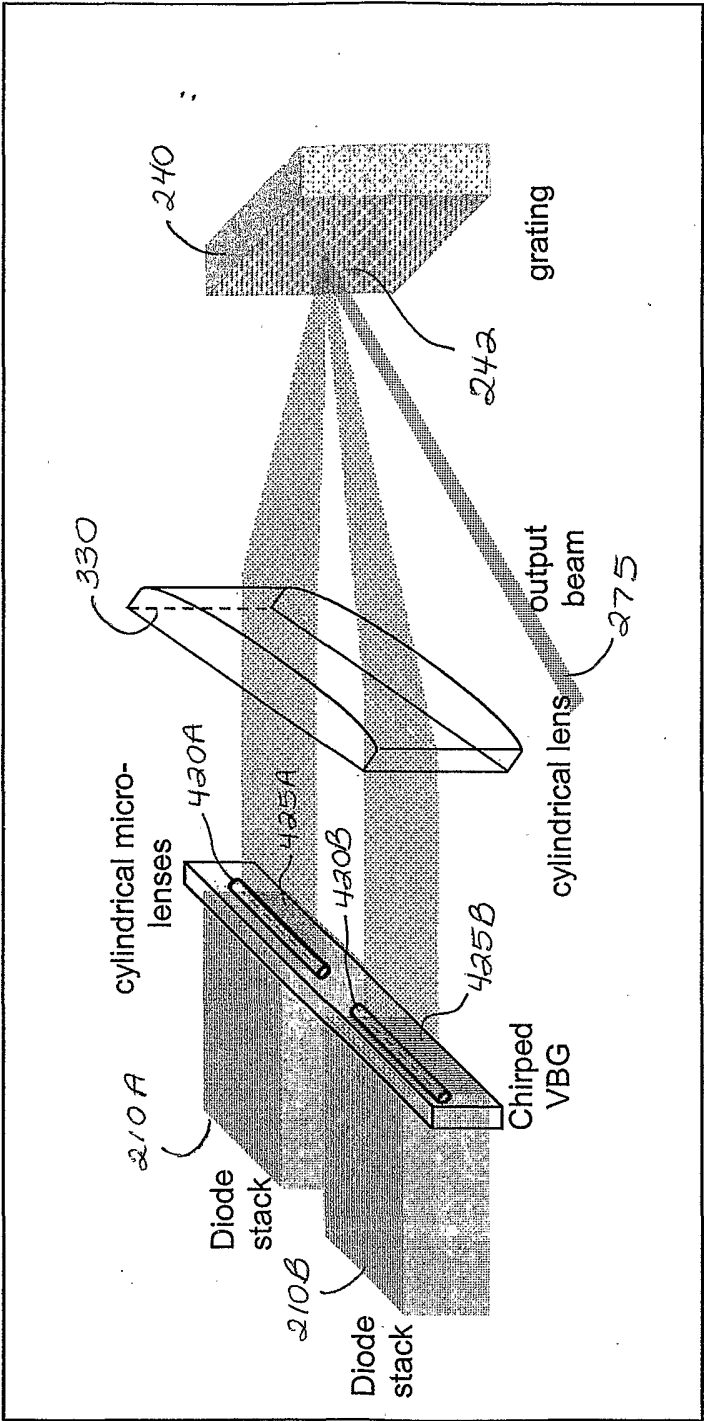


Fig 8

800

