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Volodin

(10) **Patent No.: US 8,340,150 B2**
(45) **Date of Patent: Dec. 25, 2012**

(54) **HIGH-POWER, PHASE-LOCKED, LASER ARRAYS**

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(73) Assignee: **PD-LD, Inc.**, Pennington, NJ (US)

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(21) Appl. No.: **13/113,976**

(22) Filed: **May 23, 2011**

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Related U.S. Application Data

(63) Continuation of application No. 11/346,667, filed on Feb. 3, 2006, now Pat. No. 7,949,030.

(60) Provisional application No. 60/649,489, filed on Feb. 3, 2005.

(51) **Int. Cl.**
H01S 5/00 (2006.01)

(52) **U.S. Cl.** **372/50.123**; 372/29.014; 372/29.016; 372/29.023; 372/50.11; 372/50.12; 372/99; 372/102; 359/27; 359/337.21; 359/349; 359/583

(58) **Field of Classification Search** 372/29.014, 372/29.016, 29.023, 50.11, 50.12, 50.123, 372/99, 102; 359/27, 337.21, 349, 583
See application file for complete search history.

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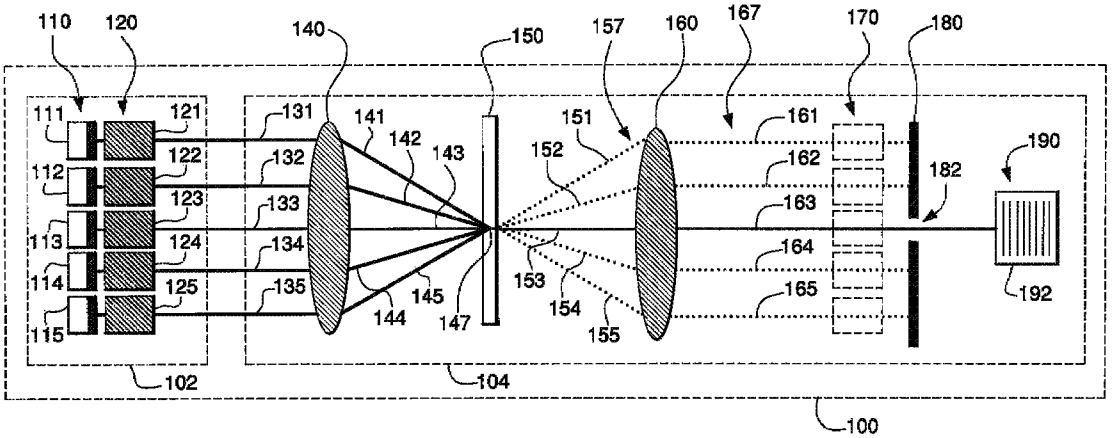
(57) **ABSTRACT**

High-power, phased-locked, laser arrays as disclosed herein utilize a system of optical elements that may be external to the laser oscillator array. Such an external optical system may achieve mutually coherent operation of all the emitters in a laser array, and coherent combination of the output of all the lasers in the array into a single beam. Such an "external gain harness" system may include: an optical lens/mirror system that mixes the output of all the emitters in the array; a holographic optical element that combines the output of all the lasers in the array, and an output coupler that selects a single path for the combined output and also selects a common operating frequency for all the coupled gain regions.

20 Claims, 9 Drawing Sheets



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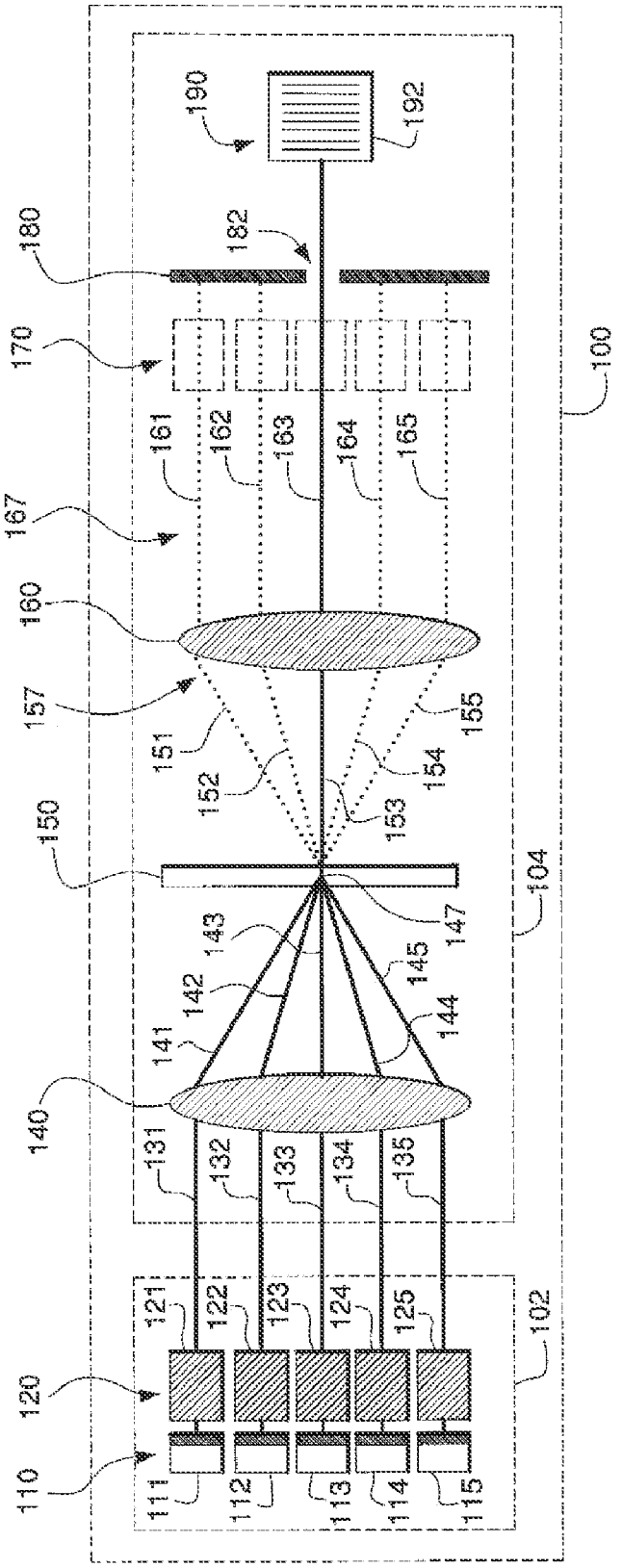
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FIG. 1A

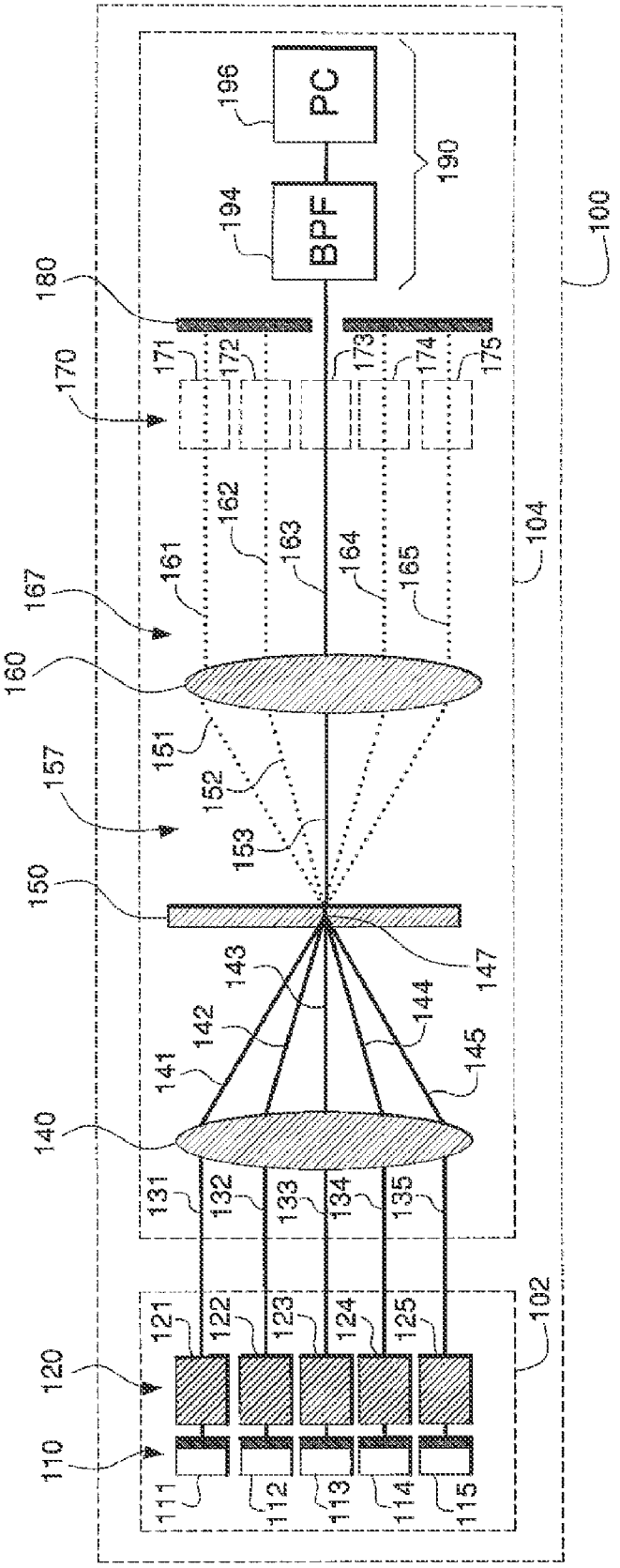
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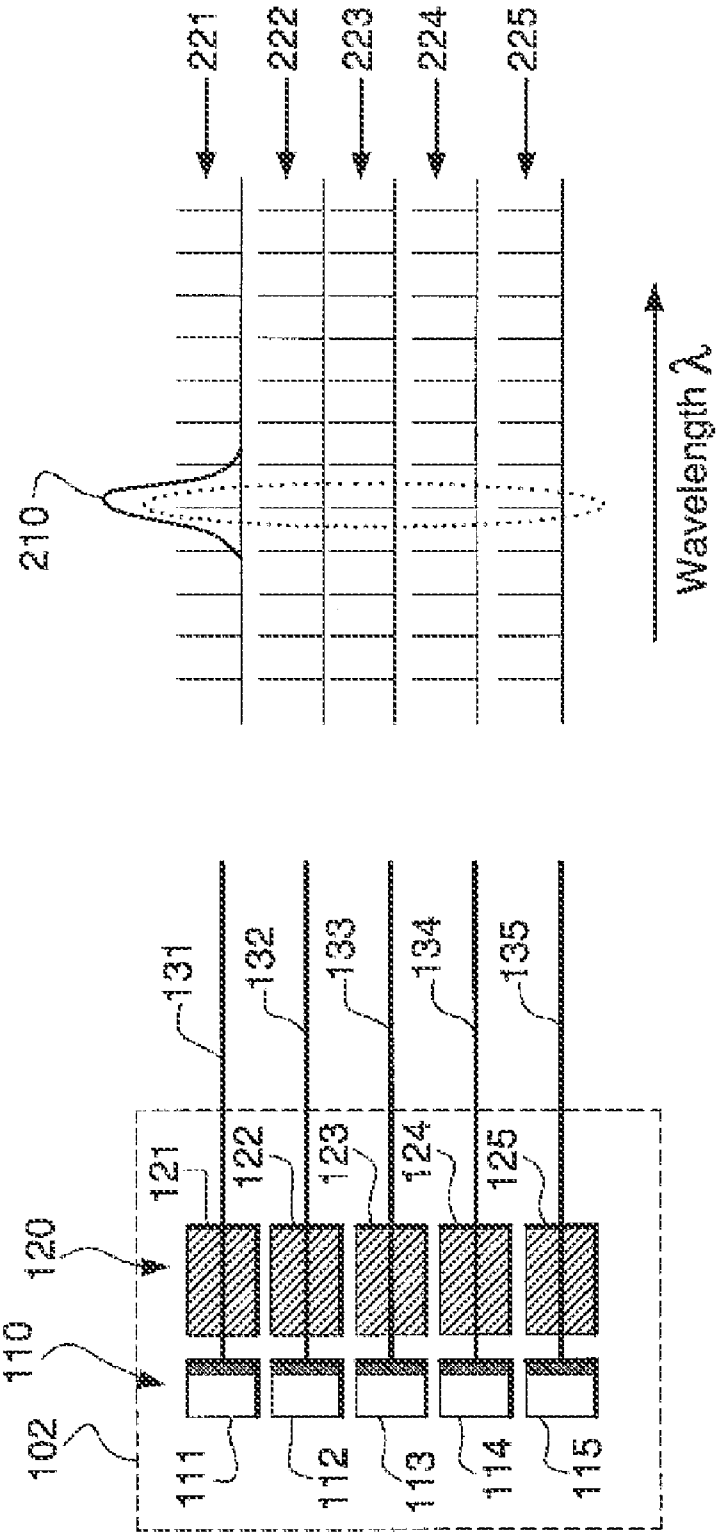
FIG. 1B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Wavelength λ
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FIG. 2

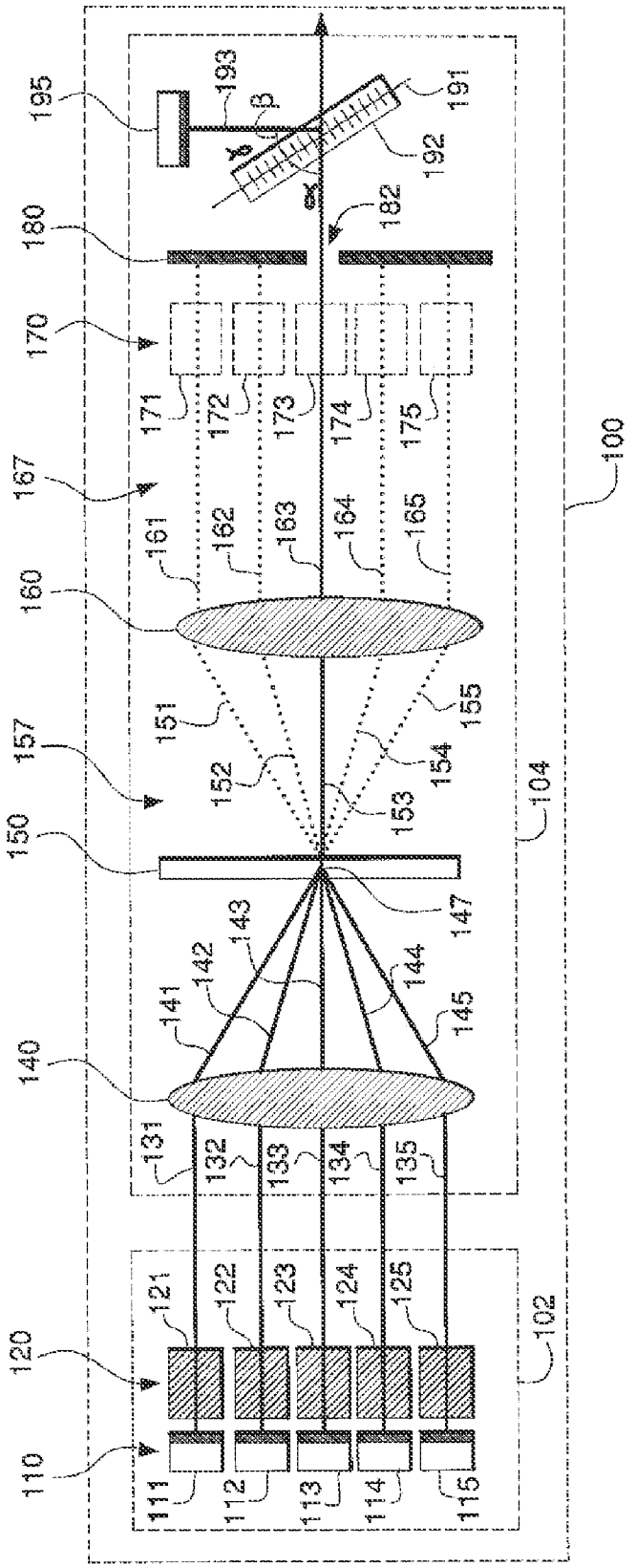
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FIG. 3A

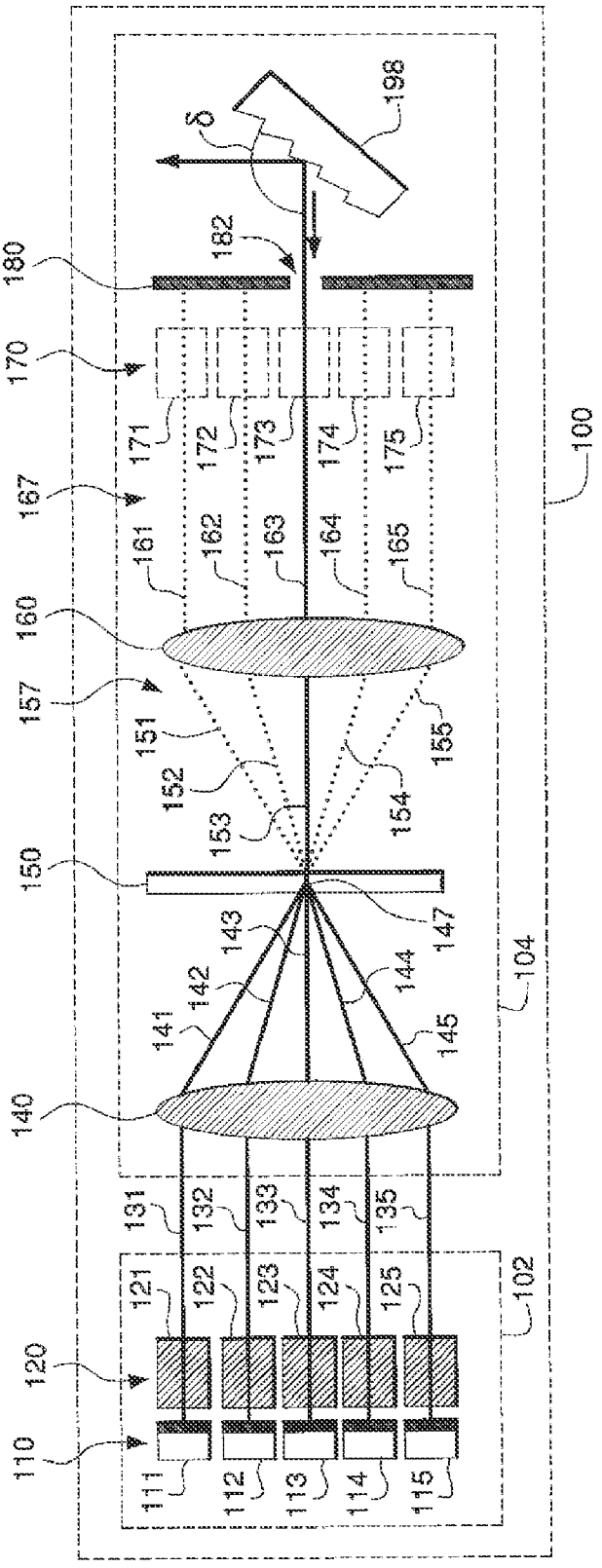
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FIG. 3B

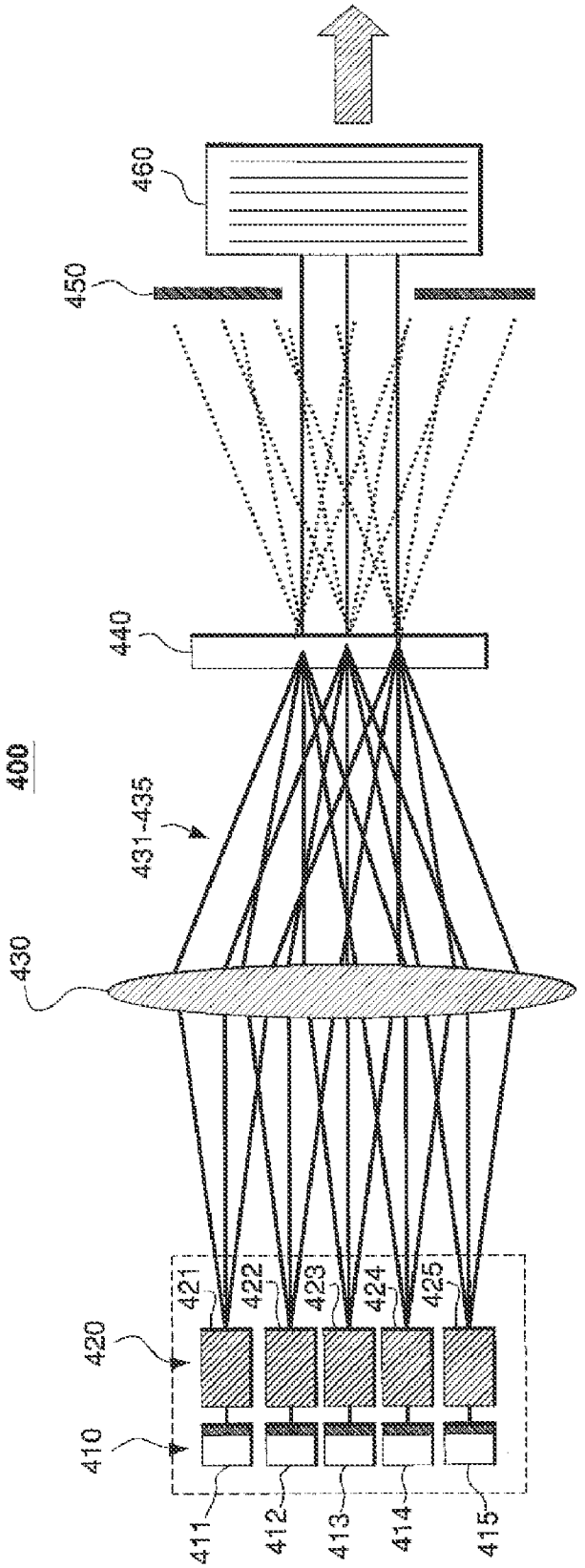
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FIG. 4A

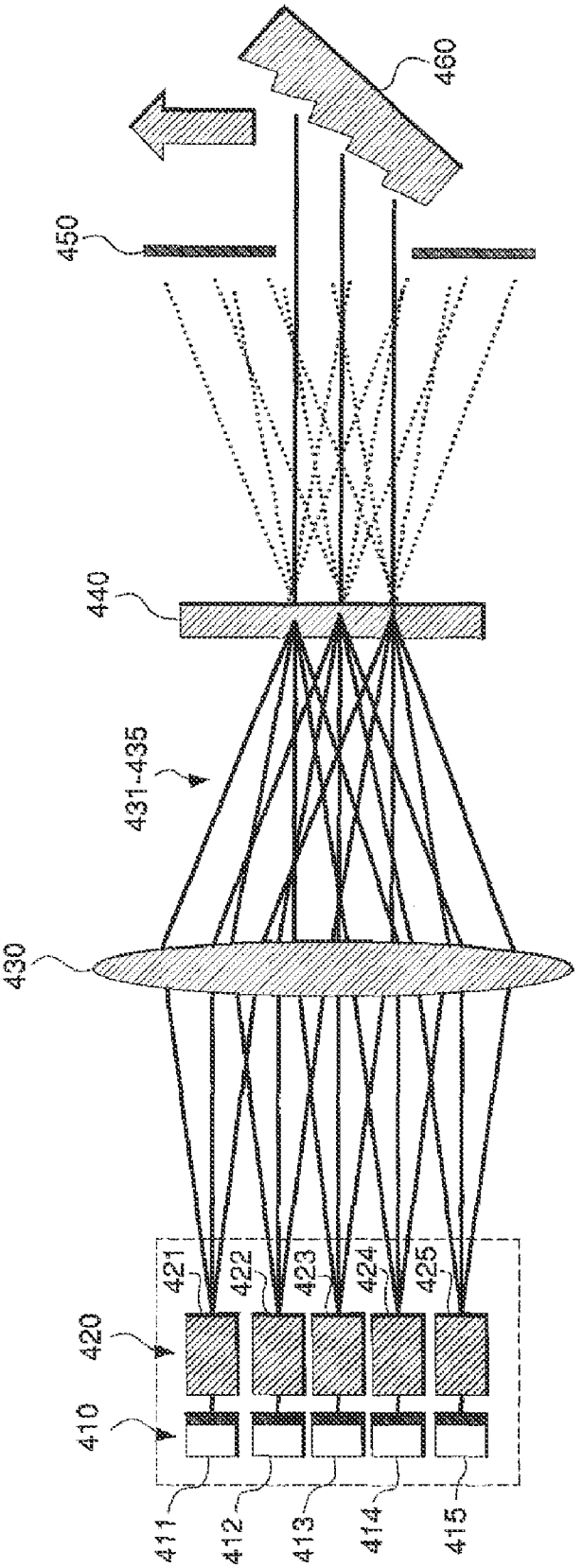
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FIG. 4B

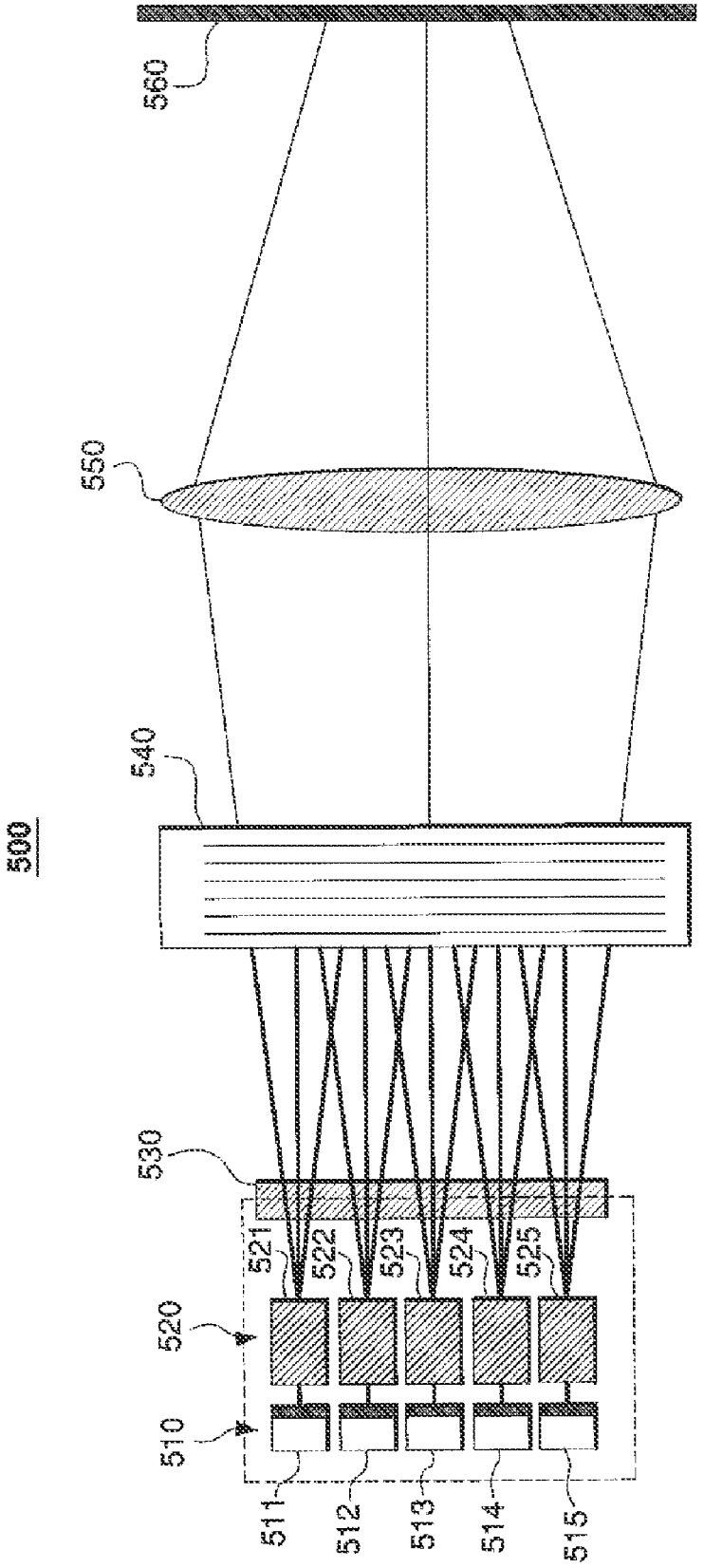
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FIG. 5

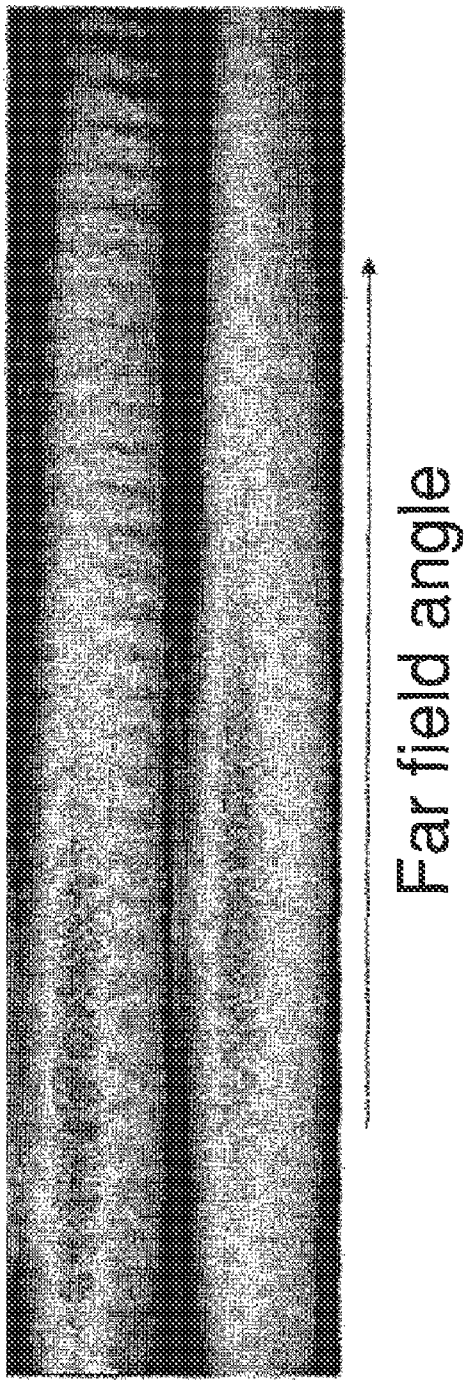

FIG. 6A

FIG. 6B

HIGH-POWER, PHASE-LOCKED, LASER ARRAYS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 11/346,667, filed Feb. 3, 2006, which claims benefit under 35 U.S.C. §119(e) of provisional U.S. patent application No. 60/649,489, filed Feb. 3, 2005, the contents of each of which are incorporated herein by reference.

BACKGROUND

Lasers are the brightest and, in many instances, some of the most efficient sources of light available today. Nevertheless, there is a constant need to increase their brightness and total power even further. There are, however, real barriers to increasing the brightness of a single laser source of any design that currently present some of the most difficult technological challenges. One of the best examples is semiconductor lasers. Semiconductor lasers provide the highest electrical-to-optical power-conversion efficiency, and achieve very high optical gain, but typically do not provide sufficiently high contiguous gain volume. As a result, optical power in excess of 10 W (i.e., continuous wave) can currently be extracted only from arrays of semiconductor laser diodes. Such ensembles of individual laser emitters, however, cannot readily provide a diffraction-limited or nearly diffraction-limited beam, even though they can deliver very impressive total output power (e.g., ~500 W/cm2 of array face area currently achieved). This results in poor brightness of otherwise highly efficient and powerful light sources.

The poor mode quality of laser diode arrays stems from the fact that the gain is extracted from physically separate pimp regions, essentially making them extended area light sources. However, if there was a technique to harness the gain of such separate gain regions and make them behave as parts of a contiguous gain medium with a constant phase difference between all the regions, then the light emitted by all such regions would be coherent and, as a result, could be efficiently combined into a single beam of much higher optical quality than that of the standard laser diode array. This problem is common to all laser types and, if solved, would allow for harnessing together the power of multiple laser sources with progressively increasing brightness, without having to deal with the problems of scaling up the power of each individual source.

Other methods of beam combination for increased brightness include polarization combining and spectral beam combining. Polarization beam combining, however, can only increase brightness by a factor of two. Spectral beam combining, on the other hand, does not increase spectral brightness.

SUMMARY

The approach disclosed herein utilizes a system of optical elements that may be external to the laser oscillator array. Such an external optical system may achieve: a) mutually coherent operation of all the emitters in a laser array; and b) coherent combination of the output of all the lasers in the array into a single beam.

An example embodiment of such an "external gain harness" system may include: 1) an optical lens/mirror system that mixes the output of all the emitters in the array in one region in space; 2) a beam combining element (BCE), positioned in the region of space that combines the output of all the lasers in the array; and 3) an output coupler, positioned after the BCE, that selects a single path for the combined output and also selects the common operating frequency for all the coupled gain regions.

The optical mixing system may be a single lens. It should be understood, however, that the optical mixing system may include any combination of one or more lenses, mirrors, and/or prisms. A BCE may be reflective or transmissive, and may be manufactured using three-dimensional, holographic Bragg grating technology, such as VBG™, which is developed, manufactured, and distributed by PD-LD, Inc. It should be understood that a BCE may be manufactured using other techniques. For example, the BCE may be a holographic optical element, a diffractive optical element, such as a Dammann grating or a spot array generator, or any other optical element with suitable functionality. The output coupler may be constructed from a reflective or transmissive Bragg grating element that provides wavelength-selective feedback for a single optical path of the BCE that forces coherent operation of all the emitters with a specific phase difference that will achieve constructive interference in that particular optical path. Other possible options include a phase-conjugate mirror used in combination with one or more optical etalons or other wavelength-selective elements.

A principle of operation of such a "gain harness laser (GHL)" is in mixing the output of all the individual emitters in the array, filtering the mixed output based on the relative phase of the light emitted by each of the separate gain regions, then further filtering the light based on wavelength in order to limit the number of longitudinal modes oscillating in the composite resonator. The mixed and filtered output is then fed back into the separate gain regions, each of the regions thus receiving seed light from all the others with appropriate wavelength and phase. When the returned light is filtered in the way described, the feedback from all the gain sections adds constructively at the front emitting-aperture of each of the gain regions and, therefore, creates a relatively strong feedback capable of locking the laser array into coherent operation.

The approach described herein may achieve long range coupling between the members of a laser oscillator array, limiting the number of coupled modes by using wavelength-selective feedback from a Bragg grating element, and also limiting the coupling to a particular phase state of the emitter array by use of a BCE and an optical path selector.

The GHL concept is, in principle, rather similar to the injection seeding of a high-power slave laser with a lower-power master laser. However, unlike in the case of master/slave configuration, there is no need for active phase control of the seed light—the phase adjustment happens automatically due to the effect of the gain harness. Furthermore, in case of GHL, there is no need to cascade the slave lasers/amplifiers into multiple stages—the seed power scales directly with the number of lasers in the array. Nonetheless, the GHL itself can be used as a powerful seed source for a large super-array of semiconductor or other type lasers in order to achieve higher-level coherence and overall power.

The GHL approach described herein may provide for self-adjusting coherence (e.g., there may be no need for active phase control). There may be no need for an external seed source. There may be no need for modifying the high-power laser resonators, which allows the use of lasers with highest possible native efficiency. The approach provides for simplicity and robustness (e.g., minimum, number of optical components), and for scalability—via using the GHL as a seed source and via spectral combining. It should be understood

that spectral beam combining, which does not increase spectral brightness, may be employed as a complementary technique to the coherent beam combining described herein.

To understand the functionality of the BCE, consider the propagation of the laser light in reverse. For example, if one considers a diffraction-limited beam entering the gain harness block of the GHL counter-propagating with its output, that beam will pass through the Bragg grating output coupler, with a certain percentage of it being reflected back, and reach the BCE. The BCE will produce an image matching the laser array that will be projected onto the output apertures of the lasers by the Fourier-transform lens. Note that, for a properly constructed BCE, each laser emitter may receive the same proportion of light injected into the cavity. If the light returned from the laser cavities has the same phase difference between the different paths as the incident light, all the beams of light returning to the BCE will be recombined into a single diffraction-limited beam now counter-propagating with the imaginary injected beam of light, thus closing the cavity path.

The selection of the proper phase condition for the reconstruction of the output beam is likely to occur spontaneously in the GHL cavity due to the dense mode spacing of the external gain harness relative to the spectral width of the reflectivity envelope of the output coupler. Although the use of a Bragg grating as an output coupler represents the most convenient and simple method of completing the GHL cavity, a phase-conjugate mirror (in conjunction with an output path selector, which may be a simple aperture, and a band pass filter, which may be an optical etalon, thin film filter or other) may also yield good stability of the cavity.

The performance of the device may be related to the performance of the BCE. For example, the diffraction efficiency of the BCE and the amount of light leaking into higher orders may determine the total loss of the GHL cavity. The use of holographic Bragg grating elements for fabrication of a BCE may be desirable, therefore, as they afford the possibility of fabricating a true matching filter for a particular laser array, as opposed to a phase-only filter constructed using, for example, the techniques of binary digital holography employed for fabrication of surface-etched pattern generators. It should be understood, however, that such a BCE may be fabricated via techniques other than Bragg grating technology.

The technique described herein applies to many different kinds of laser oscillators and/or gain media: semiconductor laser diodes (both optically and electrically pumped, either single transverse mode or broad-area multi-mode), solid-state lasers, fiber lasers, gas and ion lasers, atomic vapor lasers, etc. It is not restricted to strictly TEM_{00} operation of the oscillators.

There are at least two possible regimes for the operation of laser arrays with external gain harness—i.e., weak and strong coupling regimes. In the case of weak coupling, the laser array is operating above threshold near its nominal output power and pump level. The feedback from the external gain harness acts as a weak perturbation to the array, just sufficiently strong enough to cause the spontaneous transition to the coherent operation. In the case of strong coupling, however, the laser array would not nominally reach the lasing threshold but, rather, would be operating as an amplifier or an active mirror with a faceted surface. In that case, the external gain harness may complete the cavity and reduce the intracavity losses to the level sufficient for stable lasing.

The GHL concept may be, in many respects, similar to self-mode-locking of ultra-fast lasers via the formation of a Kerr lens inside the gain medium. The concept may be referred to as Kerr Lens Mode locking or KLM. Similar to GHL, KLM relies on the fact that the cavity loss becomes significantly reduced for a particular phase difference between the longitudinal modes of the laser cavity, namely that which leads to the formation of a continuous train of short pulses. In the case of GHL the particular phase difference between the different gain paths leads to the constructive interference along the path selected by the output coupler/path selector.

The GHL approach offers a clear and simple path to further power scaling due to its inherent compactness and narrow-band operation. There are two possible routes for GHL power scaling: 1) using GHL as a seed for a larger array of coherent lasers; and 2) using spectral combining of the output of individual GHLs. The first approach, although feasible, may require active phase control on the separate injection paths and, therefore, may be rather complex. The second approach, on the other hand, is a very natural choice because the output of GHL tends to be very narrow spectrally. For this reason, a large number of GHLs can be combined spectrally within a spectral region of several nanometers.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A and **1**B depict a cavity with multiple gain paths phase-locked by use of a beam combining element (BCE), a path selector, and different types of output couplers.

FIG. **2** illustrates the role of a wavelength-selective output coupler.

FIGS. **3**A and **3**B depict laser cavities with phase locking of multiple-gain paths and different types of wavelength-selective, tunable output couplers.

FIGS. **4**A and **413** depict a gain harness laser with long-range coupling between the laser array elements.

FIG. **5** provides a schematic of a test setup for inducing cross-element coherence of a laser diode bar.

FIGS. **6**A and **6**B depict the results of a test on inducing cross-element coherence of a laser diode bar.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

FIGS. **1**A and **1**B depict example embodiments of systems and methods for achieving phase synchronization of multiple gain paths of a complex laser cavity. A composite resonator **100**, as shown, may include an internal part **102**, which may include those components that a typical laser cavity would have, and an external part **104**, which may include additional components that enable phase synchronization of multiple gain paths in the laser cavity. The internal part **102** may include an array **120** of gain section resonators **121-125**. Each gain section **121-125** may emit light, such as laser light, for example, along a respective optical path **131-135**.

In order to achieve the best phase-locking (i.e., coherence) between the several gain sections **121-125**, it may be desirable that coupling, preferably equally-strong coupling, is achieved between each emitter **121-125** in the array **120** and every other emitter **121-125** in the array **120**. In order to construct a complete laser cavity with the independent gain sections **121-125** of the array **120**, a plurality **110** of highly reflective mirrors **111-115** may be disposed proximate a first end of the gain sections **121-125**. The opposite ends of the gain section **121-125** may have partially reflective mirrors (not shown) or no mirrors at all (as shown).

In order to achieve coupling between the individual gain sections **121-125**, it may be desirable to mix the optical paths of the light beams **131-135** emitted by the gain sections **121-125**. That is, the optical paths may be caused to overlap one another in space. As shown in FIGS. **1**A and **1**B, this may be

accomplished by a Fourier transform (FT) lens **140** disposed to receive the light beams **131-135** emitted by the individual gain sections **121-125**. The lens **140** performs an optical Fourier transform on the received beams **131-135**, forming transformed beams **141-145**. Each of the transformed beams **141-145** corresponds to a respective one of the emitted beams **131-135**. The FT lens **140** focuses the transformed beams **141-145** onto its back focal plane. The transformed beams **141-145** are thereby mixed, in a location **147** in the back focal plane of the lens **140**.

A beam combining element (BCE) **150** may be positioned in the back focal plane of the FT lens **140**, and in the front focal plane of a second FT lens **160**. The BCE **150** may be designed to split a single beam of light (e.g., beam **143**) into a plurality of beams **151-155** in a controlled manner. The BCE may split each incident beam into the same number of beams as there are gain sections in the array **121-125**. At least one of the beams **151-155** output from the BCE should be a composite of all the beams **141-145** and, therefore, representative of a composite of all the beams **131-135**. The beams **151-155** are split out of the BCE in such a manner as to form a pattern **157** that corresponds to a spatial arrangement of the individual gain sections **121-125** of the system. That is, the pattern **157** represents how the emitters **121-125** are arranged relative to one another (e.g., the beams output from the BCE form an array that matches the array of beams output from the emitters).

The BCE may be designed to be made by using the techniques of three-dimensional Bragg gratings (described elsewhere), using surface diffractive optical elements, or any other suitable technique. The BCE may be made of an optical material with high transparency, high durability, and high optical damage threshold.

The second FT lens **160** performs an optical. Fourier transform on the beams **151-155** received from the BCE **150**, forming re-transformed beams **161-165**. At least one of the re-transformed beams **161-165** is a composite of all the beams **131-135**. Accordingly, after the optical Fourier transform is performed by the second FT lens **160**, a pattern **167** will appear that includes an image **170** of the array **120** of individual gain sections **121-125**. The images **171-175** of all the individual gain sections **121-125** will overlap at least on one of the images of the exit apertures of the individual gain sections.

A path selector **180** may be positioned after the second FT lens **160**. The path selector **180** may define an aperture **182** that allows light from one of the optical paths **161-165** (e.g., optical path **164**, as shown) through the path selector **180**. The path selector may be made of a non-transparent material that is robust enough to withstand the exposure to light at the operating power of the system. Thus, the path selector **180** may restrict the feedback into the gain regions to come only from a path containing overlapping beams from all the gain sections in the array. Together with the BCE **150**, the path selector **180** may force a particular phase state for the ensemble of phase-locked emitters that would produce constructive interference from all the emitters in the output of the system.

An output coupler **190** may be positioned behind the path selector **180**. The output coupler **180** may reflect back some or all of the light propagating along the optical path **164** selected by the path selector **180**, thus completing the external portion **104** of the composite cavity **100**. As shown in FIG. **1**A, the output coupler **190** may include a three-dimensional, Bragg grating element **192**, which may be formed of a three-dimensional, transparent material (e.g. glass, crystal, polymer) having a Bragg grating recorded therein. Such a Bragg grating element may have a spectrally-narrow reflectivity band that tends to restrict the number of longitudinal modes oscillating in the composite cavity **100** and, as a result, tends to achieve stable phase locking between the individual gain sections **121-125** of the array **120**.

The BCE **150** re-maps the light returned by the output coupler **190** (along the optical path **164** selected by the path selector **180**) back onto the array **120** of gain sections **121-125**. As an array **120** of individual gain sections **121-125** will have a fill factor of less than one (and very likely much less than one), it may be desirable that the light returned, by the external part **104** of the composite cavity **100** does not fall in between the front emitting apertures of the individual gain sections **121-125**. This may be accomplished by a properly-designed BCE **150** that insures minimal possible loss inside the composite cavity.

The mixed and filtered output (reflected from the Bragg grating element along optical path **164**) is thus fed back into each of the gain regions **121-125**. Each of the gain regions **121-125** thus receives "seed" light from all the others (because the composite beam is fed back to each) with appropriate wavelength, selected by the output coupler, and phase, selected by the BCE and the path selector. When the returned light is filtered as described above, the feedback from all the gain sections **121-125** adds constructively at the front emitting apertures of the several gain regions **121-125** and, therefore, creates a relatively strong feedback capable of locking the laser array **120** into coherent operation. Thus, the Bragg grating element provides feedback for a single optical path of the BCE that forces coherent operation of all the emitters with a specific phase difference that will achieve constructive interference in that particular optical path.

As shown in FIG. **1**B, the output coupler **190** may include a bandpass filter **194** that allows a selected wavelength or band of light through to a mirror **196**, which may be a phase-conjugate mirror or an ordinary mirror, for example. The mirror **196** reverses the phase of the light incident upon it. Such an output coupler may be used in conjunction with other wavelength-selective elements or band-pass filters such as, for example, optical etalons, Bragg gratings, diffraction gratings, etc.

Note that, although FIGS. **1**A and **1**B depict five separate gain sections **121-125** arranged in a one-dimensional array **120**, it should be understood that the techniques described herein apply, without restriction, to larger-sized one-dimensional and two-dimensional arrays of emitters.

FIG. **2** illustrates the role of a wavelength-selective output coupler. The individual gain sections **121-125** of the emitter array **120** may have internal resonators formed by the highly reflective mirrors **111-115** near the respective back apertures of the gain sections **121-125** and partially reflective mirrors (not shown) near the respective front apertures of the gain sections **121-125**. In general, each of the internal resonators may have a slightly different mode comb **221-225**. When a wavelength-selective output coupler is used, it may restrict the number of internal resonator modes to a single mode or a few close modes, as shown by the dashed ellipse in FIG. **2**, thus increasing the coherence between the light **131-135** emitted by the individual gain sections **121-125**. Note that the lower the reflectivity of the partial reflector in the front part of the gain section (not shown), the wider will be the broadening of the modes within the mode comb of the internal resonators. This may facilitate better phase locking of the individual gain sections **121-125**.

FIG. **3**A depicts a tunable, wavelength-selective output coupler **190** using a transmissive Bragg grating element **192**. If wavelength tuning is desired in an array **120** of coherent

emitters **121-125**, it can be accomplished via angular adjustment of the transmissive Bragg grating element **192**. Adjusting the angle of incidence α of light onto a transmissive Bragg grating **194** changes the Bragg matching condition and, therefore, changes the wavelength for which maximum diffraction efficiency is achieved. Thus, the Bragg grating element **192** can provide wavelength-selective feedback for a single optical path **164** of the BCE **150** that forces coherent operation of all the emitters **121-125** with a specific phase difference that will achieve constructive interference in that particular optical path **164**.

As shown in FIG. **3**B, a diffraction grating **196** can be used in well-known Littrow (as shown in FIG. **3**B), Littman-Metcalf, or other configurations, in order to provide wavelength-selective feedback back into the emitters.

As shown in FIGS. **3**A and **3**B, the light **131-135** emitted by the individual gain sections **121-125** is mixed in the back focal plane of the first FT lens **140**, where a BCE **150** is positioned. The BCE **150** mixes the optical paths **141-145** of all of the gain sections **121-125**. A second FT lens **160** may be used in order to produce mixed images **171-175** of the individual gain sections **121-125** in its back focal plane. A path selector **180** may be positioned in the back focal plane of the second FT lens **160**. The path selector **180** selects a single common optical path **164** for all light-emitting sections. A transmissive Bragg grating element **192** diffracts the mixed light at a certain diffraction angle β according to particular design conditions. A partially or fully reflective output coupler **194** is positioned in the path of the diffracted beam **193**. The output coupler **194** reflects the light incident upon it back on its path **164**, thus completing the external part **104** of the composite resonator **100**. Wavelength tuning is achieved by adjusting the angle α between the Bragg grating element **192** and the beam incident upon it.

Similarly, as shown in FIG. **3**B, a diffraction grating **196** can be rotated, which adjusts the wavelength of the light returned onto the emitters. Thus, the diffraction grating **196** can be used as a wavelength-selective element that can achieve wavelength tuning via adjustment of the incident angle δ. The diffraction grating **196** may be reflective, as shown in FIG. **3**B, or transmissive. It may be a surface diffraction grating or a volume holographic grating. The diffraction grating **196** can be manufactured by any of a number of techniques, such as, for example, surface ruling, holographic techniques, etching, etc. The wavelength-selective feedback may be produced in the 1^{st} or higher diffraction order of the diffraction grating, and the output of the system may be produced in the 0^{th} order of the diffraction grating.

FIGS. **4**A and **4**B depict a gain harness laser (GHL) **400** with long-range coupling between the laser array elements **421-425**. The GHL **400** may include an array **420** of individual gain sections/emitters **421-425**, which may be an array **420** of laser diodes. It may also include a Fourier transform (FT) lens **430**, a BCE **440**, a path selector **450**, and a wavelength-selecting element **460**, such as a three-dimensional Bragg grating element (as shown in FIG. **4**A) or a diffraction grating (as shown in FIG. **4**B) as an output coupler. The FT lens **430** collimates and overlaps the outputs of the individual emitters **121-125** in a certain location in space. The BCE **440** may be positioned in that location and receives the focused optical paths **421-425**. The BCE **440** mixes the focused optical paths **431-435** of all of the gain sections **421-425** into a common path. As shown in FIGS. **4**A and **4**B, a path selector **450** is positioned behind the BCE **440**, without the use of a second FT lens (as described above). The light allowed through the path selector **450** is reflected back by a three-dimensional Bragg grating (as shown in FIG. **4**A) or a diffraction grating (as shown in FIG. **4**B) that serves as a wavelength-selective output coupler **460** due to its narrow reflectivity spectrum. The diffraction grating may be reflective, as shown in FIG. **4**B, or transmissive. It may be a surface diffraction grating or a volume holographic grating. The diffraction grating can be manufactured by any of a number of techniques, such as, for example, surface ruling, holographic techniques, etching, etc. it may be used in any well-known arrangements, such as Littrow, Littman-Metcalf, or any other suitable configuration.

FIG. **5** is a schematic diagram of a test setup **500** for inducing cross-element coherence of a laser diode bar using a Talbot cavity. As shown, the test setup **500** may include an array **520** of individual gain sections/emitters **521-525**, a collimating lens **530** or lens array, and a three-dimensional Bragg grating element **540** that reflects some of the light back into the individual emitters **521-525**.

An experiment was conducted using the test setup shown in FIG. **5**. The Bragg grating element **540** was positioned at a particular distance from the face of the laser diode bar **520** so that, upon reflection from the Bragg grating element **540**, the diffraction pattern on the face of the laser diode bar **520** would repeat or nearly repeat the arrangement of the emitters **521-525** and, therefore, maximize the coupling in the composite cavity. A Fourier-transform lens **550** was used to produce the far field pattern of the array, which was observed on a screen **560**. If coherence between the emitters **521-525** in the laser diode array **520** is achieved, the far field pattern will show clear signs of coherent interference (i.e., fringes).

FIGS. **6**A and **6**B provide far field patterns observed during the experiment. FIG. **6**A provides a far field pattern for a situation wherein the Bragg grating element **540** is aligned to reflect the incident light back on its path. FIG. **6**B provides a far field pattern for a situation wherein the Bragg grating element **540** is iris-aligned and, therefore, does not reflect the incident light back on its path. The results show an apparently stable interference pattern in the far field of the laser diode array **520**, which is only possible if there exists a constant and stable phase difference between the modes of the several emitters **521-525** in the array **520**. If the phase difference between the individual emitters **521-525** in the array **520** is not constant, then the interference pattern loses it stability and visibility (i.e., no periodic dark fringes are observed).

It should be understood that the systems and methods described and claimed herein may be applied to, among other things: apparatus and methods using reflective and transmissive holographic Bragg grating elements as a feedback element to achieve coherence; systems using coherently combined laser arrays that use Bragg grating elements; systems that perform spectral beam combining of the coherently combined laser arrays using Bragg grating elements; coherently combined systems using Bragg grating elements as wavelength selector that are used for second harmonic generators or optical parameteric oscillators or parameteric amplification; coherent combining of laser diodes, solid-state lasers, fiber lasers, gas lasers, ion lasers, alkali vapor lasers, and the like; coherent combining of lasers with TEM_{00} output; coherent combining of lasers with multi-mode output; and using phase conjugate mirrors for coherent beam combining.

The advantages of laser systems constructed according to the approaches described herein can be exploited in any application that benefits from laser sources with increased brightness and power. Such applications include, but are not limited to, laser pump sources, direct material processing, military applications (e.g., directed energy weapons, target designators, laser range finders, etc.), laser radars, optical communications, spectroscopy (including differential absorption spec-

troscopy, Raman spectroscopy, different other nonlinear spectroscopy techniques), medical applications (e.g., therapeutic, surgical, diagnostic, etc.), remote sensing, security applications, etc.

What is claimed:

1. A method for producing mutually-coherent operation of a plurality of light emitters, each of the emitters outputting a respective power and brightness, the method comprising:

mixing respective beams received from each of the plurality of emitters;

combining the mixed beams in a beam-combining element to form a composite beam containing a respective contribution from each of the emitters; and

feeding back through the beam-combining element at least a portion of the light containing the respective contribution from each of the emitters, the portion having a selected wavelength,

wherein the portion is fed back into the emitters in such a way that each of the emitters receives narrowband light from every other emitter, and

wherein mutually coherent operation of the plurality of emitters is achieved such that each of the emitters lases at the selected wavelength with a phase difference that results in a coherent output beam that effectively combines the powers from each of the emitters such that the output beam has a brightness that is greater than the brightnesses of the individual emitters.

2. The method of claim **1**, further comprising:

mixing the beams received from the emitters by overlapping the received beams in a focal plane of a lens.

3. The method of claim **2**, wherein the lens performs an optical Fourier transform on the beams received from the emitters.

4. The method of claim **2**, wherein the beam-combining element is positioned in the focal plane of the lens.

5. The method of claim **4**, wherein the beam-combining element is a diffractive optical element.

6. The method of claim **4**, wherein the beam-combining element is a digital optical element.

7. The method of claim **4**, wherein the beam-combining element is a holographic optical element.

8. The method of claim **2**, wherein the beam-combing element is positioned in a focal plane of a second lens.

9. The method of claim **1**, further comprising:

allowing the composite beam to pass through a path selector.

10. The method of claim **9**, wherein an output coupler reflects at least a portion of the composite beam back through the path selector.

11. The method of claim **10**, wherein the output coupler comprises a three-dimensional optical element having a Bragg grating recorded holographically therein.

12. The method of claim **11**, wherein the Bragg grating is a reflective Bragg grating.

13. The method of claim **11**, wherein the Bragg grating is a transmissive Bragg grating.

14. The method of claim **10**, wherein the output coupler comprises a phase-conjugate mirror.

15. The method of claim **10**, wherein the output coupler comprises a diffraction grating.

16. The method of claim **10**, wherein the output coupler is a tunable output coupler that provides for wavelength tuning of the reflected portion of the composite beam.

17. The method of claim **16**, wherein the tunable output coupler provides for the wavelength tuning via angular adjustment of the output coupler.

18. The method of claim **1**, wherein the respective contributions from each of the emitters are received by a three-dimensional optical element.

19. The method of claim **18**, wherein the composite beam is created via an optical method that includes the three-dimensional optical element.

20. The method of claim **19**, wherein the composite beam is created via an optical method that includes the three-dimensional optical element receiving the beams from the emitters and forming the composite beam containing the respective contributions from each of the emitters.

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