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(54) **SPATIALLY-DISTRIBUTED GAIN ELEMENT  
SELF-PHASE-LOCKED, LASER APPARATUS  
AND METHOD**

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**G02B 5/1857** (2013.01); **H01S 3/0675**  
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27/123; G02B 27/14  
See application file for complete search history.

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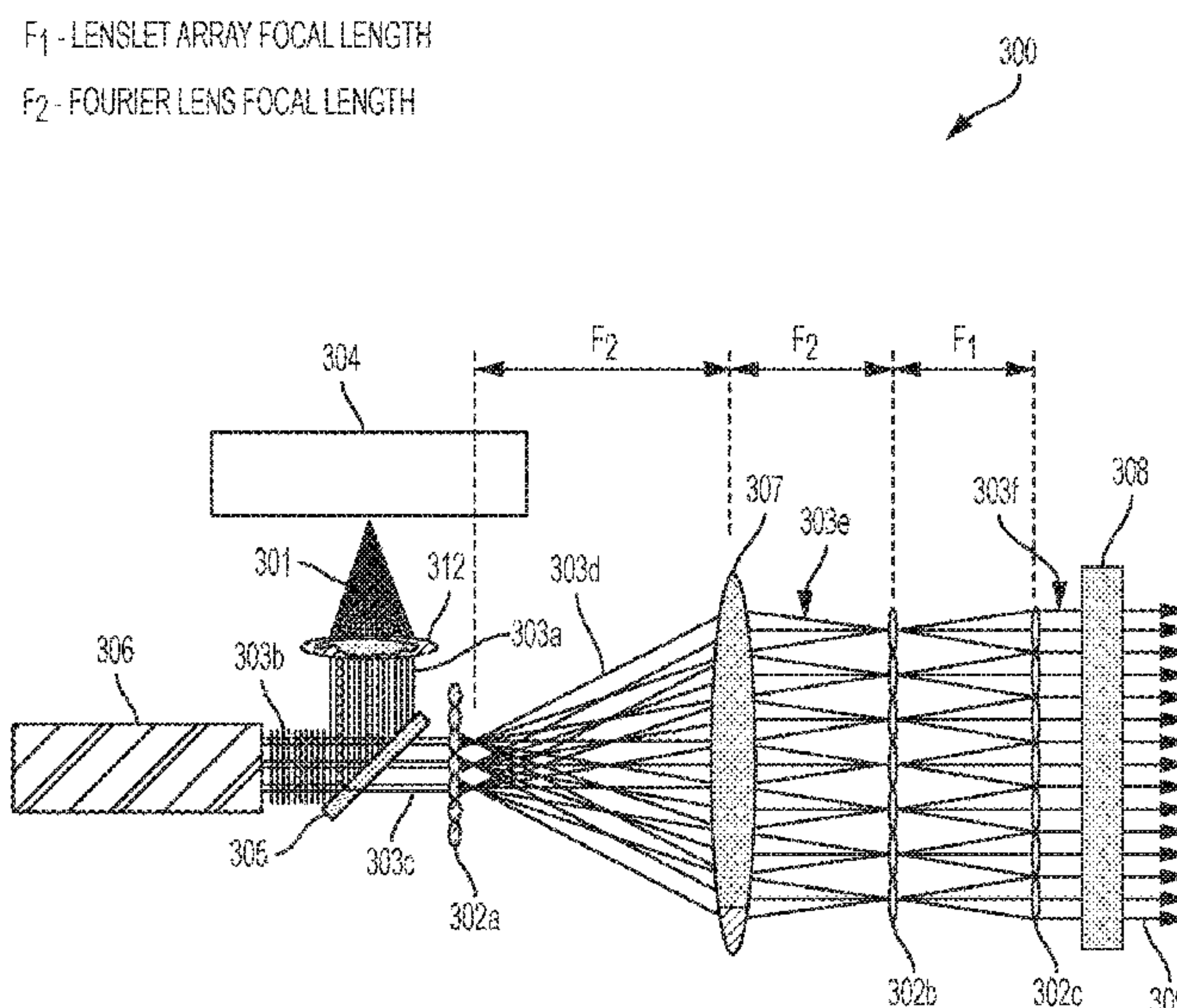
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Bryan A. Geurts

(57) **ABSTRACT**

The present invention is related to laser technology which enables efficient, passive, coherent beam combination from distributed gain sources. The present invention includes a novel architecture which coherently combines the power from multiple sources, and which adds considerable flexibility to laser gain materials for many applications. The novel architecture of the present invention combines two techniques: 1) beam splitting and combination; and 2) phase-locking (i.e., maintaining a common phase relationship between multiple beams), using reflective gratings. Thus, the present invention addresses important limitations in laser technology: efficiency, power scaling and wavelength selectivity.

**16 Claims, 6 Drawing Sheets**



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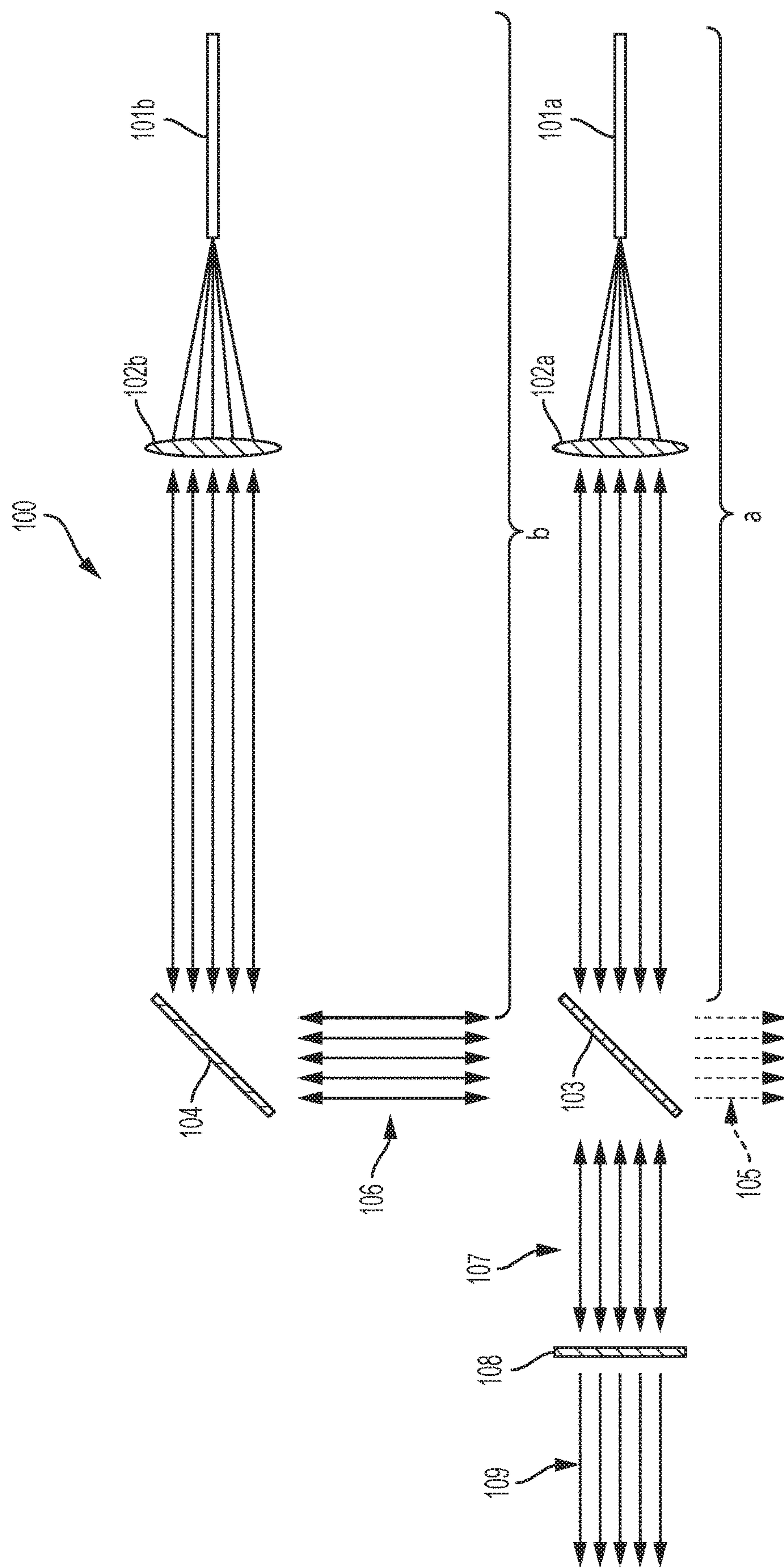


FIG. 1



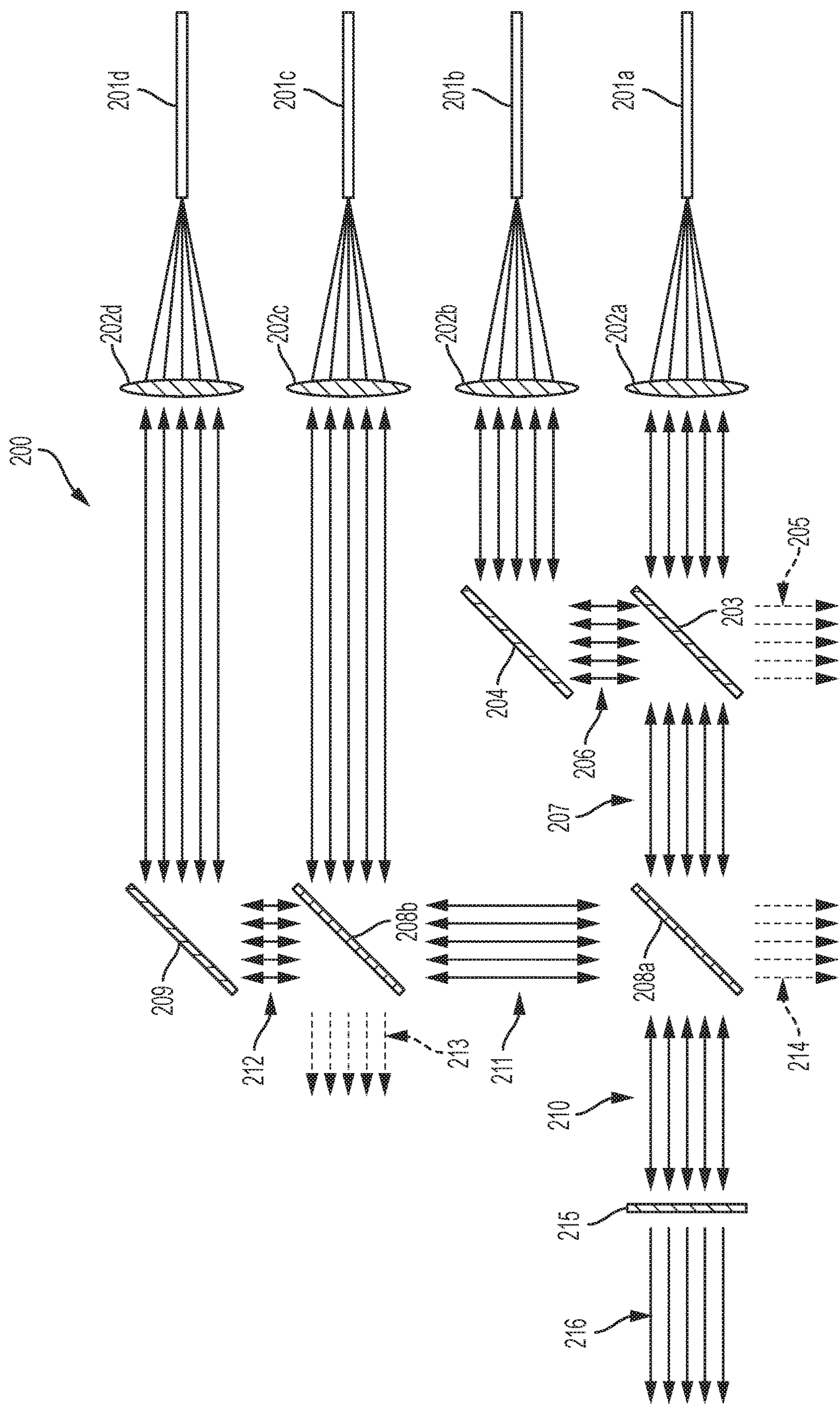
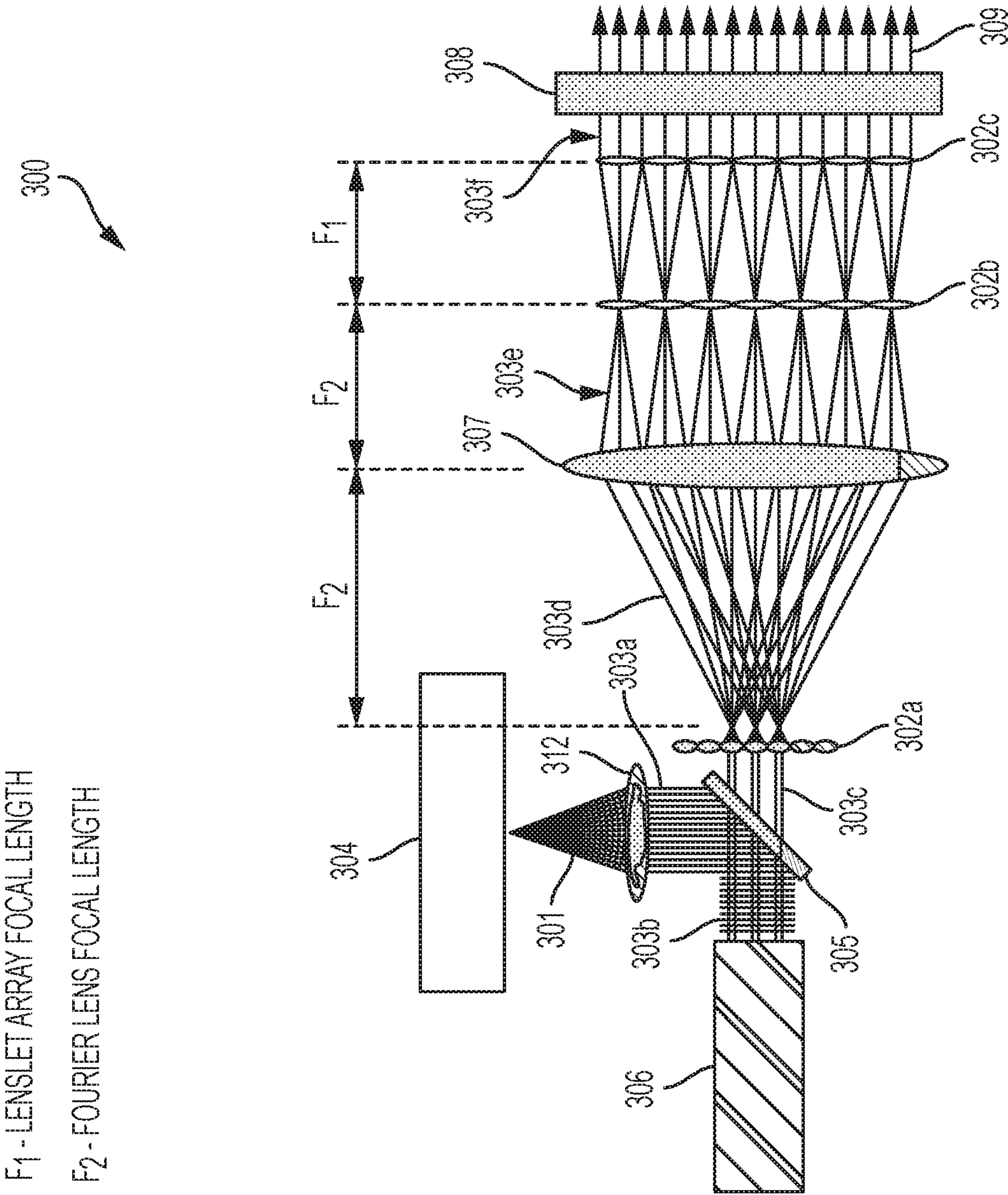


FIG. 2





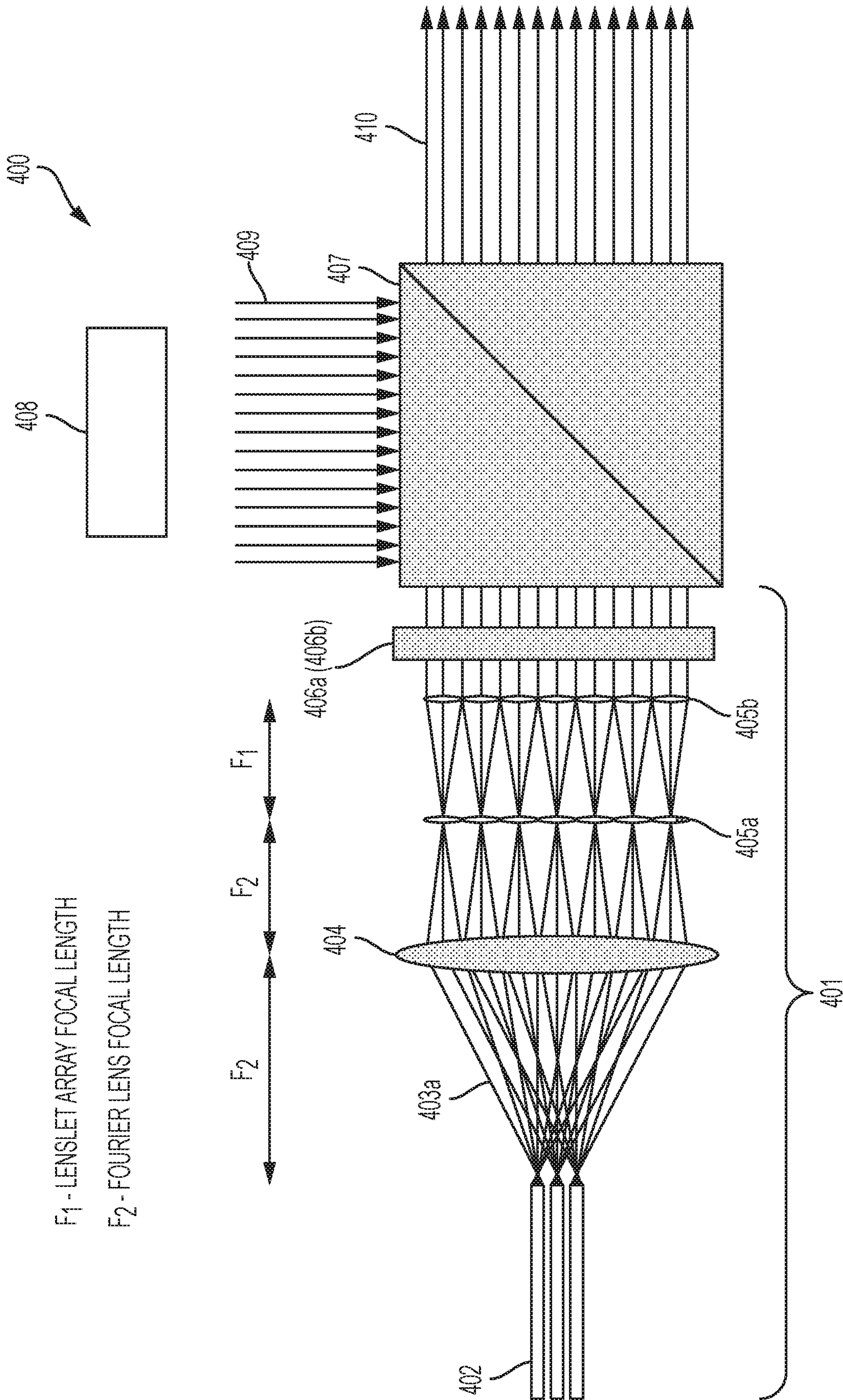
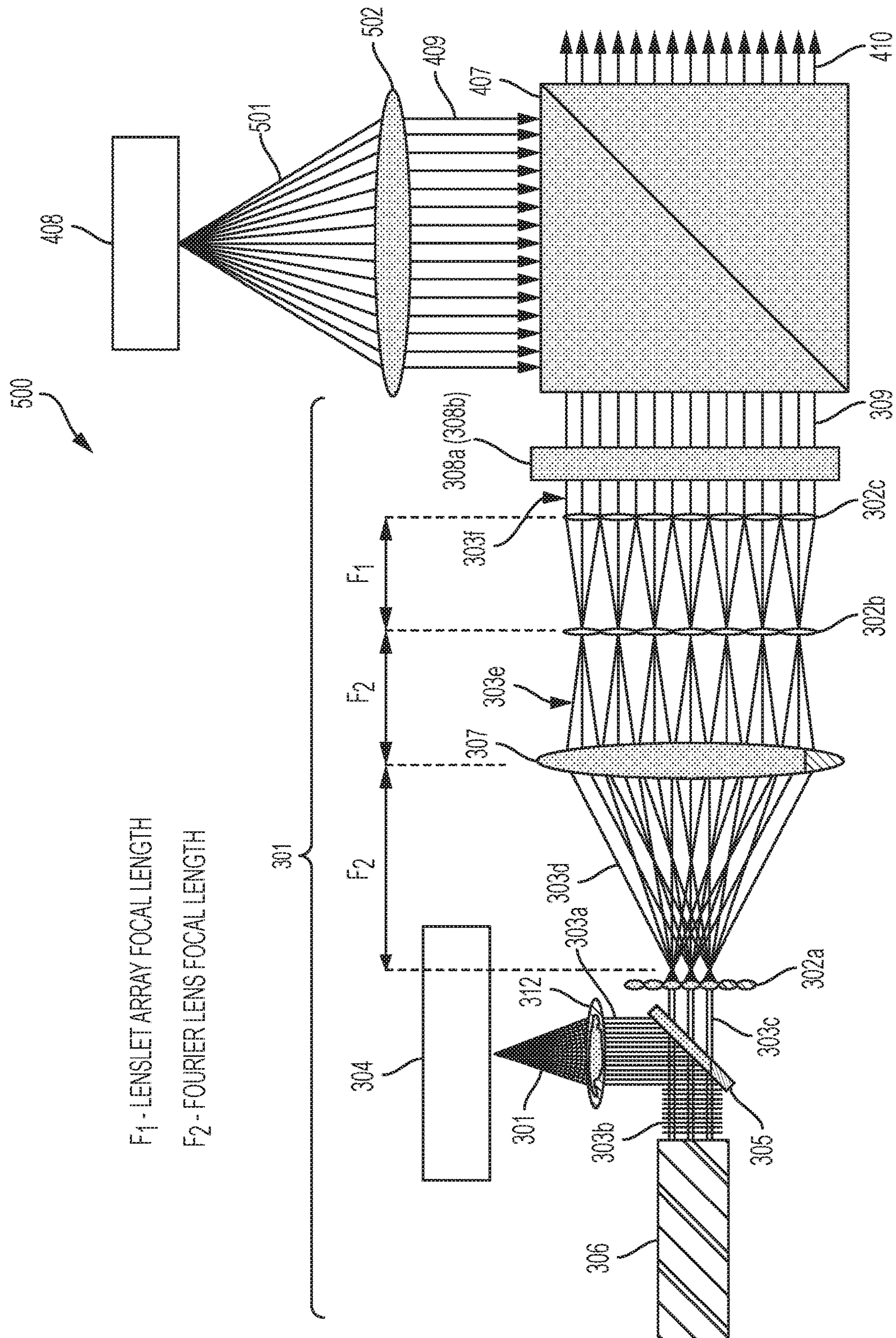


FIG. 4





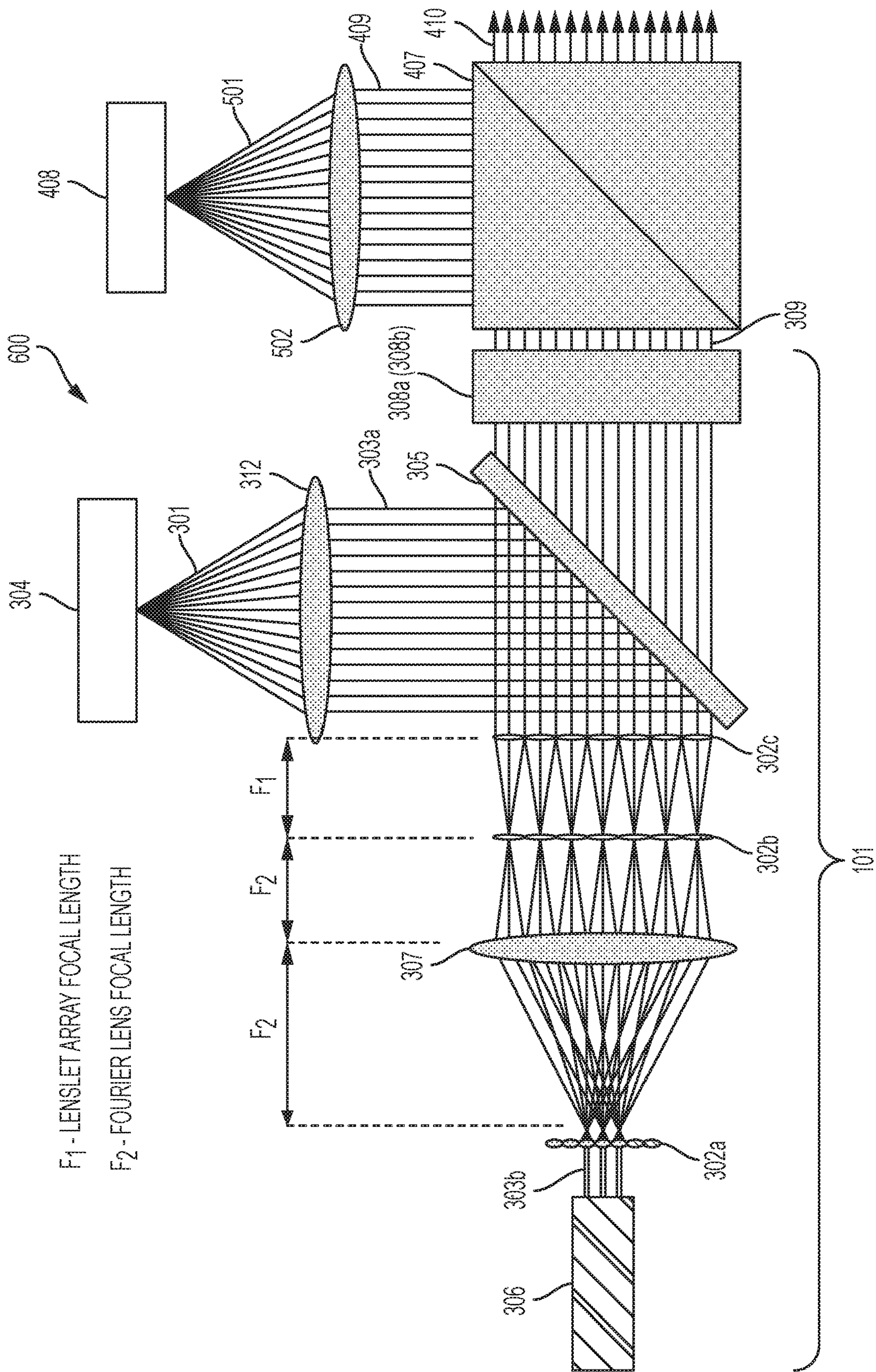


FIG. 6



# SPATIALLY-DISTRIBUTED GAIN ELEMENT SELF-PHASE-LOCKED, LASER APPARATUS AND METHOD

## ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government, and may be manufactured or used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

The present invention relates to laser technology which enables efficient, passive, coherent beam combination from distributed gain sources. The present invention includes a novel architecture which coherently combines the power from multiple sources, and which adds considerable flexibility to laser gain materials for many applications. The novel architecture of the present invention combines two techniques: 1) beam splitting and combination; and 2) phase-locking (i.e., maintaining a common phase relationship between multiple beams), using reflective gratings. Thus, the present invention addresses important engineering factors in laser technology: efficiency, power scaling and wavelength selectivity.

### 2. Description of the Related Art

High power, high efficiency, flexible laser sources are desired for many applications. The main limitation for many current gain material sources, including semiconductors and fibers, is power scaling the output due to excessive optical intensity, due to the confinement from the 2-dimensional (2-D) waveguide. Although the power can be increased by having multiple gain elements, combining the power efficiently into a single optical stream has not been effective to date. Phase-locking multiple sources to each other is one possibility, but doing so at optical frequencies is complex and relatively unstable, and the degree of difficulty increases nonlinearly with the number of sources.

Thus, a laser technology that will enable power-scaling using multiple distributed gain sources, and which includes an architecture which is widely applicable to almost any laser technology, but will have particular benefits for fiber and semiconductor gain media where power scaling is difficult, is desired.

## SUMMARY OF THE INVENTION

The present invention relates to laser technology which enables efficient, passive, coherent beam combination from distributed gain sources. The present invention includes a novel architecture which coherently combines the power from multiple sources, and which adds considerable flexibility to laser gain materials for many applications.

In one embodiment, the present invention coherently combines the energy from spatially distributed gain sources, meaning a 1-dimensional (1-D) or 2-D array of optical gain elements, into a single spatial mode, narrow frequency laser beam. In one exemplary embodiment, the novel architecture of the present invention combines two techniques: 1) beam splitting and recombination; and 2) phase-locking (i.e.,

tion addresses the most important limitations in laser technology: efficiency, power scaling and wavelength selectivity.

In one embodiment, an optical apparatus includes: at least one energy source which emits a plurality of beams of light; at least one gain source and a reflective grating, the reflective grating which maintains a fixed phase relationship between the plurality of beams of light; and a plurality of optical elements which split the plurality of beams of light from the at least one reflective grating and recombine the plurality of beams of light, into a single spatial mode output laser beam; wherein the at least one reflective grating reflects the plurality of beams of light with the fixed phase relationship to the plurality of beams of light input from the at least one energy source, independent of a distance of the at least one reflective grating from the at least one energy source.

In one embodiment, the at least one reflective grating includes one of a volume Bragg grating recorded in a photo-thermo-refractive (PTR) glass, or a plurality of ytterbium (Yb)-doped gain fibers with integrated fiber Bragg gratings (FBGs), or at least one semiconductor diode with reflective grating.

In one embodiment, at least one array of lenslets allows the plurality of beams of light from the reflective grating to be split and phase-locked.

In one embodiment, the array of lenslets are one dimensional or two dimensional in configuration.

In one embodiment, the apparatus is a laser apparatus and the plurality of optical elements includes an output coupler.

In one embodiment, the apparatus is an amplifier apparatus and the plurality of optical elements includes a Faraday rotator and a polarizer.

In one embodiment, the energy source is a pump laser.

In one embodiment, the optical apparatus further includes a seed laser which provides energy to the polarizer.

In one embodiment, a method of increasing an output of a laser beam, includes: emitting a plurality of laser beams of light from at least one energy source; maintaining a fixed phase relationship between the plurality of beams of light using at least one gain source and a reflective grating; and splitting the plurality of beams of light from the at least one reflective grating and recombining the plurality of beams of light using a plurality of optical elements, into a single spatial mode output laser beam; wherein the at least one reflective grating reflects the plurality of beams of light with the fixed phase relationship to the plurality of beams of light input from the at least one energy source, independent of a distance of the at least one reflective grating from the at least one energy source.

In one embodiment, the method of increasing an output of a laser beam further includes: splitting and phase-locking the plurality of beams of light from the at least one reflective grating, using at least one array of lenslets.

In one embodiment, the plurality of optical elements includes an output coupler of a laser apparatus.

In one embodiment, the plurality of optical elements includes a Faraday rotator and a polarizer of an amplifier apparatus.

In one embodiment, the method of increasing an output of a laser beam further includes: providing energy to the polarizer using a seed laser.

Thus, has been outlined, some features consistent with the present invention in order that the detailed description thereof that follows may be better understood, and in order that the present contribution to the art may be better appreciated. There are, of course, additional features consistent



with the present invention that will be described below and which will form the subject matter of the claims appended hereto.

In this respect, before explaining at least one embodiment consistent with the present invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. Methods and apparatuses consistent with the present invention are capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein, as well as the abstract included below, are for the purpose of description and should not be regarded as limiting.

As such, those skilled in the art will appreciate that the conception upon which this disclosure is based may readily be utilized as a basis for the designing of other structures, methods and systems for carrying out the several purposes of the present invention. It is important, therefore, that the claims be regarded as including such equivalent constructions insofar as they do not depart from the spirit and scope of the methods and apparatuses consistent with the present invention.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic drawing of an interferometer configuration, according to one embodiment consistent with the present invention.

FIG. 2 shows a schematic drawing of a more complex interferometer configuration, according to one embodiment consistent with the present invention.

FIG. 3 shows a schematic drawing of a laser configuration, according to one embodiment consistent with the present invention.

FIG. 4 shows a schematic drawing of an amplifier configuration, according to one embodiment consistent with the present invention.

FIG. 5 shows a schematic drawing of yet another amplifier configuration, according to one embodiment consistent with the present invention.

FIG. 6 shows a schematic drawing of yet another amplifier configuration, according to one embodiment consistent with the present invention.

#### DESCRIPTION OF THE INVENTION

The present invention relates to laser technology which enables efficient, passive, coherent beam combination from distributed gain sources. The present invention includes a novel architecture which coherently combines the power from multiple sources, and which adds considerable flexibility to laser gain materials for many applications.

In one embodiment, the present invention coherently combines the energy from spatially distributed gain sources, meaning a 1-dimensional (1-D) or 2-D array of optical gain elements, into a single spatial mode, narrow frequency laser beam. In one exemplary embodiment, the novel architecture of the present invention combines two techniques: 1) beam splitting and recombination; and 2) phase-locking (i.e., maintaining a common phase relationship between multiple beams), using reflective gratings. Thus, the present invention addresses the most important limitations in laser technology: efficiency, power scaling and wavelength selectivity.

One of ordinary skill in the art would recognize that the first technique, regarding actual beam splitting and recom-

bination, can be performed in various different ways to achieve the claimed features of the present invention.

As an exemplary embodiment, an interferometer **100** (see FIG. 1) is shown, having a gain source (i.e., doped fibers, laser crystal, semiconductor diodes, etc.), such as multiple ytterbium (Yb)-doped gain fibers with integrated fiber Bragg gratings (FBGs) **101a**, **101b**. In one exemplary embodiment, an anti-reflection coating is applied to the front facets of the fibers **101a**, **101b**, which are mounted in an array configuration.

In the exemplary embodiment of FIG. 1, light beams from the FBGs **101a**, **101b** proceed through lenses **102a**, **102b**, respectively. The light beams from lens **102a** impact a 50% beam splitter **103**, where light beams are transmitted through the beam splitter **103** as beams **107**, and reflected out of the apparatus as beams **105**. Due to destructive interference with the beams from **102b**, no net optical power is contained in beams **105**.

Light beams from lens **102b** are reflected at mirror **104**, and impact beam splitter **103**, before being reflected from the beam splitter **103** and joining the transmitted beams from lens **102a** as high output beams **107**. The reflected beams **106** from mirror **104** that are transmitted through **103** destructively interfere with the beams from lens **102a**, which are reflected at beam splitter **103**, and which exit the apparatus as beams **105**. No losses are created at beam splitter **103** in the output beams **105**.

The high output beams **107** are directed to output coupler **108**. Some light exits the array as a single spatial mode beam **109** with high power, while some light is reflected from **108** to circulate in the optical cavity. Accordingly, the present configuration provides a novel distributed-gain laser cavity that can make dramatic improvements in laser performance and flexibility.

In the exemplary embodiment of FIG. 1, the FBGs **101a**, **101b** are operated at the short wavelength band edge ( $\sigma = +K$ ) of the filter, where light **107** at this wavelength reflected from interferometer arm "b" and transmitted from interferometer arm "a" will interfere constructively, regardless of the relative optical path lengths to the FBGs **101a**, **101b**. The FBGs should have the same short wavelength band edge to accomplish the above results. Thus, as shown in FIG. 1, the present configuration is exploited for coherent beam combination (recombination).

In the exemplary embodiment of FIG. 1, the relative phase of the two arms "a", "b" of the laser beams does not change even if the optical path length to the FBGs **101a**, **101b** is changed. This means that thermal variations or small changes in one arm (i.e., arm "b", or arm "a") will not affect the phase of the beam (i.e., beam **106** or beam **107**) it returns to the larger system. Operating at the short wavelength band edge of the FBG **101a**, **101b** is important to this phase property.

One of ordinary skill in the art would know that the embodiment shown in FIG. 1, could be made more complex with additional FBGs, mirrors, etc., without deviating from the principles described herein regarding the present invention.

Thus, as shown in FIG. 2, a more complex embodiment includes, for example, an interferometer **200** having four FBGs, **201a-201d**, where light beams therefrom pass through lenses **202a-202d**. Light from lens **202a**, which impacts 50% beam splitter **203**, is transmitted as light beams **207**.

The beams from lens **201b** impact mirror **204**, and are reflected towards beam splitter **203** as beams **206**. The beams **206** are reflected at beam splitter **203** to join the



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beams from lens **202a**, as a high output beam **207**, and are not transmitted through beam splitter **203**, due to destructive interference with the reflected beams from lens **202a**. Thus, no net optical power is contained in beams **205**.

This arrangement is similar to the configuration discussed above with respect to FIG. 1. However, instead of beams **207** impacting an output coupler, beams **207** impact another 50% beam splitter **208a**, and a configuration of FBGs **201c-201d**, which utilize 50% beam splitter **208b** and mirror **209**, respectively, to create additional power for beams **210**, and after proceeding through output coupler **215**, increased output power for beams **216**.

As shown in the exemplary embodiment of FIG. 2, beams **212** from lens **202d** are reflected by mirror **209** to beam splitter **208b**, and are transmitted as beams **211** to impact beam splitter **208a**. Reflected beams at beam splitter **208b**, destructively interfere with transmitted beams from lens **202c**, to not exit the array. Thus, there is no net optical power contained in beams **213**.

Reflected beams from mirror **209** pass through beam splitter **208b**, and join with reflected beams from lens **202c**, to be reflected at beam splitter **208a**, and join together with the beams from beam splitter **203**, to form high output beam **210**. Transmitted beams from beam splitter **208b** pass through the beam splitter **208a**, where destructive interference with reflected beams from beam splitter **203** results in no beams **214** exiting the array. Some of beams **210** pass through output coupler **215** and exit the array **200** as a single spatial mode beam of higher power **216**, while some light is reflected from **215** and is circulated back into the interferometer.

Thus, as one of ordinary skill in the art would appreciate, the present invention can be used to split and combine/recombine beams in other laser, amplifier and passive configurations. Note that one of ordinary skill in the art would know that in the descriptions of these exemplary embodiments, substitute or additional gain sources (i.e., doped fibers, laser crystals, semiconductor diodes, etc.), or optical elements (i.e., mirrors, beam splitters, etc.), other than those described, may be added to achieve the desired purposes. Further, one of ordinary skill in the art would include the focal lengths, pitch dimensions, fiber numerical apertures and beam size, that are well-known to one of ordinary skill in the art.

In another exemplary embodiment of the present invention, as shown in FIG. 3, the present invention may include a laser configuration **300**, which exhibits yet another way to arrange the beam splitting and recombination, and phase locking techniques. In this exemplary embodiment, the laser apparatus **300** includes a laser gain source **306**, such as Ytterbium-doped glass with a volume Bragg grating (e.g., a photo-thermo-refractive (PTR) glass (i.e., optical quality silicate glass co-doped with Ytterbium)).

As shown in FIG. 3, the laser configuration **300** includes a pump diode laser **304** (e.g., pump wavelength of 975 nm), which transfers energy in the form of emitting beams of light **303a** via lens **312**, the beams **303a** which impact a dichroic mirror **305**, and where the beams **303a** are reflected to the laser gain source **306**. As shown in FIG. 3, the overall lasing cavity is between the high-reflecting volume Bragg grating in **306** and the output coupler **308**.

In the exemplary embodiment as shown in FIG. 3, the lenslet array **302a** (spacing between spots, about 1 mm) focuses the light beams **303c**, and emits light beams **303d** to a Fourier lens **307**, which Fourier transforms the beams **303d** and transmits them through the microlens arrays **302b**, **302c**. The light beams **303f** exit the lenslet arrays **302b**, **302c** to

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output coupler **308**. The beams **303e** are formed into a single-mode output beam, as long as all the individual gain sources (i.e., laser gain material **306**.) are in phase with one another. In one embodiment, the lenslet arrays **302c**, **302b** split the light from a single beam **303e** into multiple beams **303e** and to recombine the multiple beams back into a single beam **303f**. This same function (of the lenslet array pair) could be accomplished with a diffractive optical element (DOE) in a different embodiment. The beams exiting the output coupler **308** form a single spatial mode, narrow frequency laser beam **309**.

In yet another exemplary embodiment, as shown in FIG. 4, an amplifier configuration **400** is shown, which operates generally the same as the configuration in FIG. 3. In this exemplary embodiment, the laser apparatus **401** includes a gain source **402**, such as a single mode, multiple ytterbium (Yb)-doped gain fibers with integrated fiber Bragg gratings (FBGs). In one exemplary embodiment, an anti-reflection coating is applied to the front facets of the fibers **402**, which are mounted in an array configuration.

As shown in FIG. 4, the light beams **403a** from FBG **402** pass through Fourier lens **404**, and through lenslet arrays **405a**, **405b**, to output coupler **406a**. Output coupler **406a** can be a partially reflecting mirror, or in another embodiment, could be a volume Bragg grating in which the peak reflection matches the short wavelength band edge of the FBGs **402** so the preferred wavelength for phase-locking is reinforced by the output coupler **406a** reflection.

In an amplifier arrangement, the output coupler **406a** is replaced by Faraday rotator **406b**, and the beams **409** from laser source **408** are reflected by polarizer **407**, pass through the optical elements (lenslet arrays **405a**, **405b** etc.) into fibers **202**, are reflected by the FBGs **402**, and form a single spatial mode, narrow frequency laser beam **410**.

Thus, in one exemplary embodiment, the Bragg reflector (i.e., FBGs **402**) enables passive phase-locking of multiple sources, instead of current techniques which require very complicated, active control of the optical phase. Rather, in current technology, phase-locking multiple sources to each other at optical frequencies is complex and relatively unstable, and the degree of difficulty increases nonlinearly with the number of sources. However, the present invention, utilizing a reflection from Bragg grating reflectors **402** at the short wavelength band edge, reflect light with a fixed phase relationship to the input light **409** independent of the optical path length of the reflector **402** from the light source **408**. This unique property of the present invention means that multiple sources can be passively self-phase-locked to each other, removing the most challenging part of the beam combination.

Further, since, in general, very small perturbations in temperature or alignment would be enough to alter the optical phase characteristics of alternate designs, locking all the phases together needs active control. The unique property of using the FBG reflections at the short wavelength band edge is that it returns a phase relative to the incident phase irrespective of the optical path length. This means that as the laser power is building up, all the phases from the various fibers (gain sources) will lock to each other as they mix from the feedback of a common output coupler. This architecture of the present invention provides a novel distributed-gain laser cavity that can make dramatic improvements in laser performance and flexibility.

In yet another exemplary embodiment, FIG. 5 shows an amplifier configuration **500** which embodies elements of FIG. 3 and FIG. 4. Like reference numerals represent like elements.



In this embodiment, there are pump laser **304** and seed laser **408**, and the beams from seed laser **408** emits beams **501** through lens **502**, to polarizer **407**, where it joins with beams **309** reflected from gain source **306**, to emit a high output laser beam **410**. In the amplifier configuration, the output coupler **308a** is replaced by a Faraday rotator **308b**, which transmits light **309** towards the polarizer **407**. (The combination of the Faraday rotator **308b** and polarizer **407** functions as an optical circulator and separates the amplified return signal **410** (i.e., signal wavelength 1030 nm) from the seed input signal **409**).

Thus, the exemplary embodiment of FIG. **5** shows that spatially distributed gain sources, meaning a 1-dimensional (1-D) or 2-D array of optical gain elements, can be combined into a single spatial mode, narrow frequency laser beam **410**.

In yet another exemplary embodiment showing that the beam splitting and recombination elements can be arranged in various ways, FIG. **6** depicts another amplifier configuration **600**, where like reference numerals indicate like elements of FIG. **5**.

In the exemplary embodiment of FIG. **6**, in contrast to the configuration of FIG. **5**, the pump laser **304**, emits beams **301** through lens **312**, which beams **303a** impact dichroic mirror **305** which is disposed between lenslet array **302c** and Faraday rotator **308b**. The other elements are the same, and the same high-power output, of a single spatial mode, narrow frequency laser beam **410**, can be achieved.

Thus, one of ordinary skill in the art would recognize that there are various arrangements and configurations where one can achieve the claimed features of the present invention by combining the techniques of beam splitting and recombination, and phase-locking (i.e., maintaining a common phase relationship between multiple beams), using reflective gratings.

In other embodiments, because of the unique beam combination of the present invention that allows many beams of light to be combined into one, single spatial mode beam, traditional laser components, like Q-switches, that enable specialized performance, can be used. For example, these components would be used in the section of the laser cavity between the output coupler and the second lens array (see FIG. **3**, for example), where the beams have already been combined. The beams of light from each fiber of the FBGs, is distributed across all lenses in the array (i.e., Fourier lens, lenslet arrays), so that the feedback from the output coupler mixes light beams between all the fibers (FBGs). The light beams must be mutually coherent (i.e., phase-locked) so that the beams of light do not create destructive interference patterns.

The present invention can be used with high power, high efficiency, flexible laser sources. With the demonstration of an effective energy combination from multiple fibers, this technique can be generalized to both solid-state and diode sources. The ability to combine semiconductor lasers is particularly important because they have the highest efficiency and very nearly continuous wavelength coverage from the visible to the mid-infrared (IR).

The present invention can be used to power scale the output for semiconductor lasers, which can directly combine the energies from arrays of semiconductors, to provide a significant advantage in applications where existing laser technologies have been unable to achieve the required power or efficiency at the desired wavelength.

The present invention could, therefore, include semiconductor laser arrays with reflective gratings grown in the semiconductor material, which could be fabricated all on the

same wafer, and the cost and manufacturability of the same would be a vast improvement over currently-available systems. This type of multi-element manufacturing is already produced for laser diode arrays used for solid-state pumping, but the output with the present invention could now be single spatial mode through phase-locking, which would significantly improve performance.

It should be emphasized that the above-described embodiments of the invention are merely possible examples of implementations set forth for a clear understanding of the principles of the invention. Variations and modifications may be made to the above-described embodiments of the invention without departing from the spirit and principles of the invention. All such modifications and variations are intended to be included herein within the scope of the invention and protected by the following claims.

What is claimed is:

1. An optical apparatus comprising:

at least one energy source which emits a plurality of beams of light;

at least one gain source and a reflective grating, said reflective grating which maintains a fixed phase relationship between said plurality of beams of light; and a plurality of optical elements which split said plurality of beams of light from said at least one reflective grating and recombine said plurality of beams of light, into a single spatial mode output laser beam;

wherein said at least one reflective grating reflects said plurality of beams of light with said fixed phase relationship to said plurality of beams of light input from said at least one energy source, independent of a distance of said at least one reflective grating from said at least one energy source.

2. The optical apparatus of claim 1, wherein said at least one reflective grating comprises one of a volume Bragg grating recorded in a photo-thermo-refractive (PTR) glass, or a plurality of ytterbium (Yb)-doped gain fibers with integrated fiber Bragg gratings (FBGs), or at least one semiconductor diode with said reflective grating.

3. The optical apparatus of claim 2, further comprising: at least one array of lenslets which allows said plurality of beams of light from said reflective grating to be split and phase-locked.

4. The optical apparatus of claim 3, wherein said at least one array of lenslets are one dimensional or two dimensional in configuration.

5. The optical apparatus of claim 1, wherein said apparatus is a laser apparatus and said plurality of optical elements includes an output coupler.

6. The optical apparatus of claim 1, wherein said apparatus is an amplifier apparatus and said plurality of optical elements includes a Faraday rotator and a polarizer.

7. The optical apparatus of claim 5, wherein said energy source is a pump laser.

8. The optical apparatus of claim 7, further comprising a seed laser which provides energy to said polarizer.

9. A method of increasing an output of a laser beam, comprising:

emitting a plurality of laser beams of light from at least one energy source;

maintaining a fixed phase relationship between said plurality of beams of light using at least one gain source and a reflective grating; and

splitting said plurality of beams of light from said at least one reflective grating and recombining said plurality of beams of light using a plurality of optical elements, into a single spatial mode output laser beam;



wherein said at least one reflective grating reflects said plurality of beams of light with said fixed phase relationship to said plurality of beams of light input from said at least one energy source, independent of a distance of said at least one reflective grating from said at least one energy source. 5

**10.** The method of claim **9**, wherein said at least one reflective grating comprises one of a volume Bragg grating recorded in a photo-thermo-refractive (PTR) glass, or a plurality of ytterbium (Yb)-doped gain fibers with integrated fiber Bragg gratings (FBGs) or at least one semiconductor diode with said reflective grating. 10

**11.** The method of claim **10**, further comprising: splitting and phase-locking said plurality of beams of light from said at least one reflective grating, using at least one array of lenslets. 15

**12.** The method of claim **11**, wherein said at least one array of lenslets are one dimensional or two dimensional in configuration.

**13.** The method of claim **9**, wherein said plurality of optical elements includes an output coupler of a laser apparatus. 20

**14.** The method of claim **9**, wherein said plurality of optical elements includes a Faraday rotator and a polarizer of an amplifier apparatus. 25

**15.** The method of claim **13**, wherein said energy source is a pump laser.

**16.** The method of claim **15**, further comprising: providing energy to said polarizer using a seed laser. 30

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