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(54) Title: SOLID-STATE LIGHT DETECTION AND RANGING SYSTEM BASED ON AN OPTICAL PHASED ARRAY WITH AN OPTICAL POWER DISTRIBUTION NETWORK

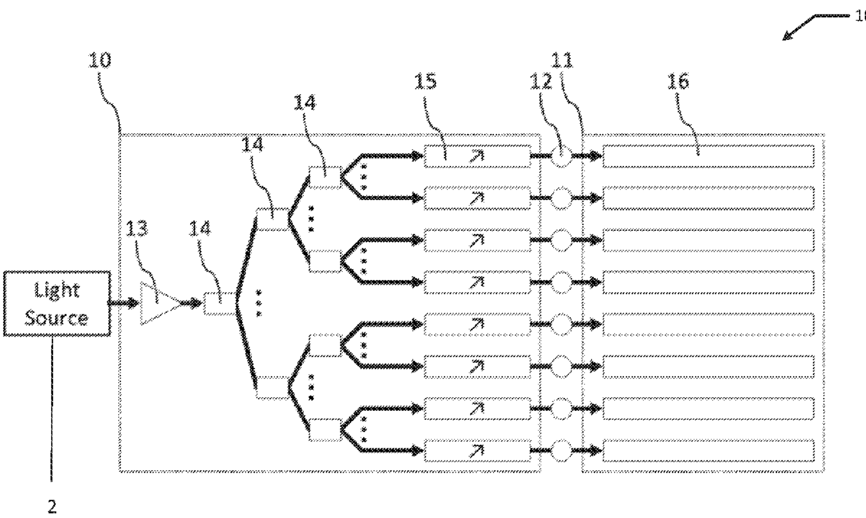

Fig. 1

(57) Abstract: An example solid-state light detection and ranging system based on an optical phased array with an optical power distribution network that includes a distribution network having an input coupler and a network splitter. The input coupler receives power from a power source, and the network splitter receives power from the input coupler. The system further includes an optical array that receives power from the distribution network. The distribution network is made of a first material, and the optical array is made of a second material.

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[Continued on next page]

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TITLE

SOLID-STATE LIGHT DETECTION AND RANGING SYSTEM BASED ON AN OPTICAL PHASED ARRAY WITH AN OPTICAL POWER DISTRIBUTION NETWORK

PRIORITY

[0001] This application claims priority to and the benefit of U.S. Provisional Application Serial No. 62/532,814, titled SOLID-STATE LIGHT DETECTION AND RANGING SYSTEM BASED ON AN OPTICAL PHASED ARRAY WITH AN OPTICAL POWER DISTRIBUTION NETWORK, filed July 14, 2017, the entire contents of which are incorporated herein by reference and relied upon.

BACKGROUND

[0002] The present disclosure is in the technical field of solid-state LIDAR.

[0003] Generally, LIDAR, which stands for Light Detection and Ranging, is a remote sensing method that uses a laser to measure ranges or distances to a target object. Generally, a laser generates an intense beam of coherent monochromatic light, or other electromagnetic radiation, by stimulating the emission of photons from excited atoms or molecules. LIDAR typically measures distance to a target by illuminating the target with the laser and measuring the reflected signals with a sensor. Differences in laser return time and frequency may be gathered to generate precise, three-dimensional representations regarding the shape and surface characteristics of the target.

[0004] Typically, LIDAR uses ultraviolet, visible, or near infrared light to image objects. It may target a wide range of materials, including metal or non-metal objects, rocks, rain, chemical compounds, aerosols, clouds, etc. Further, a laser beam may be capable of mapping physical features with very high resolutions.

SUMMARY

[0005] The present disclosure provides new and innovative methods and systems for a solid-state light detection and ranging based on an optical phased array with an optical power distribution network. An example method includes an input coupler receiving light from a high-power light source, and a network splitter receiving light from the input coupler. The input coupler and the network splitter are part of a distribution network. The network splitter divides the light, creating divided light energy. An optical array receives the divided

light energy. The optical array here may refer to any optical waveguide system that may consist of more than three optical phase shifters. The distribution network is fabricated on a first material, and the optical array is fabricated on a second material.

[0006] An example system includes a distribution network that includes an input coupler and a network splitter. The input coupler receives power from a power source, and the network splitter receives power from the input coupler. The system further includes an optical array that receives power from the distribution network. The distribution network is made of a first material, and the optical array is made of a second material.

[0007] Additional features and advantages of the disclosed methods and system are described in, and will be apparent from, the following Detailed Description and the Figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Fig. 1 is a block diagram of a solid-state LIDAR system based on an optical phased array with an optical power distribution network according to an example of the present disclosure.

[0009] Fig. 2 is a block diagram of an OPA subarray in a solid-state LIDAR system based on an optical phased array with an optical power distribution network according to an example of the present disclosure.

[0010] Fig. 3 is a block diagram of an OPA subarray in a solid-state LIDAR system based on an optical phased array with an optical power distribution network according to an example of the present disclosure.

[0011] Fig. 4 is a block diagram of an OPA subarray in a solid-state LIDAR system based on an optical phased array with an optical power distribution network according to an example of the present disclosure.

[0012] Fig. 5 is a flowchart illustrating an example method for using a solid-state LIDAR system based on an optical phased array with an optical power distribution network.

DETAILED DESCRIPTION

[0013] Generally, conventional LIDAR systems employ mechanical moving parts to steer a laser beam. They are generally considered bulky, incredibly costly and unreliable for many applications. These mechanical moving parts typically are the largest and most expensive part of a laser-scanning system. Generally, solid-state LIDAR systems can overcome these issues by eliminating moving and mechanical parts. For example, by using the same manufacturing technology as silicon microchips, LIDAR systems can be incredibly small and inexpensive, without sacrificing loss in performance.

[0014] An optical phased array (OPA) is typically used to realize low-cost solid-state LIDARs. Generally, a phased array is an array of unmoving antennas creating light beams which can be steered to point in different directions. In an example, an OPA steers the laser beam by sweeping the optical phase of a phase shifter for each array element. Typically, high power light beams may be used to improve the signal-to-noise ratio (SNR) constraints of LIDAR detection systems. However, conventional solid-state materials often exhibit undesirable non-linear effects at high power intensities (*e.g.*, C-band wavelengths of between 1530-1565nm). These undesirable non-linear effects may include two-photon absorption (TPA).

[0015] Generally, TPA is the absorption of two photons of identical or different frequencies in order to excite a molecule from one state (usually the ground state) to a higher energy electronic state. TPA may dominate over linear absorption at high intensities causing loss of power in waveguides and power saturation problems. These example non-linear effects may cause signal degradation, generate crosstalk, and trigger catastrophic failure of elements in an OPA system. Therefore, an optical power distribution network with high power handling capabilities may enhance the performance of a solid-state OPA LIDAR system.

[0016] In an example, the present disclosure remedies the above noted deficiencies by utilizing a solid-state LIDAR system having a high power optical distribution network made of a first material system. The distribution network on the first material system may supply divided power to an OPA that is comprised of a second material system. The second material system may be utilized to provide phase control of light energy in order to steer beams emitted by the OPA. In the example, by utilizing two different materials for the distribution network and the OPA, the system may be able to use a high power light source while deterring high power signal degradation.

[0017] Fig. 1 depicts an example block diagram of a solid-state LIDAR system 100 according to an example of the present disclosure. The LIDAR system 100 may include an optical power distribution network 10 and an OPA 11. The distribution network 10 may receive optical power from a light source 2 via an input coupler 13. The distribution network 10 may be made from material system X, which may route optical power to OPA 11. OPA 11 may be made from material system Y. In the example system 100, materials X and Y may be any solid state materials. In a further example, material X of the distribution network 10 may be silicon nitride (Si_3N_4), and material Y of the OPA may be silicon (Si).

[0018] In the example, a vertical coupler 12 is employed (*e.g.* direct butt-joint, tapered evanescent wave) to bridge the distribution network 10 and the OPA 11. The vertical coupler 12 may include waveguides made of both materials X and Y in order to allow a path for the light to travel between the distribution network 10 and the OPA 11. Generally, a waveguide structure may guide waves, such as optical waves, and may enable a signal to propagate with minimal loss of energy by restricting expansion to one or two dimensions. The vertical coupler 12 may include a portion made of material X that becomes progressively more tapered or narrow, so that as light travels through it the light wave becomes stronger. On top of this narrowed portion of material X may be a narrowed portion of material Y, which may begin narrow but expand in a direction away form material X, becoming progressively wider and/or larger. Therefore, the two tapered portions of materials X and Y may overlap. This overlap in tapered materials X and Y may produce an evanescent wave coupling. The smallest portions of material Y may receive the light traveling through material X.

[0019] In the example system 100, the distribution network 10 consists of the input coupler 13, network splitters 14, and optionally network phase adjusters 15. The OPA 11 consists of subarrays 16. In the example, the input coupler 13 may be a typical fiber-to-chip coupler, such as a grating coupler or an edge coupler. The input coupler 13 couples a laser or light source 2 to the distribution network 10. The distribution network 10 and OPA 11 may be located on a chip. A chip as used herein refers to a circuit such as, for example, an electronic circuit, an integrated circuit, a microchip, a semiconductor fabricated device, etc.

[0020] The network splitters 14 divide or split the optical power from the light source 2 into a plurality of branches. For example, the splitting ratio of power between each branch may be the same between all branches. In an alternative example, power may be split unequally between the branches. In the example, each network splitter 14 may be identical.

[0021] In an alternate example, the network splitters 14 may have a different number of outputs or ports at each cascaded layer. In the alternate example, the first layer may include one network splitter 14 that may have two output ports, and the second layer may have two network splitters that may each have four output ports to further subdivide power. In the example system 100, depicted are three cascading layers of network splitters 14. However, the number of cascading layers should not be limited thereto, as there may be any number of cascading layers in the system 100. Further, as depicted in Fig. 1, the outputs of some network splitters 14 may be connected to other network splitters 14 or to network phase adjusters 15. In an alternate example, some outputs of network splitters 14 may be connected directly to vertical couplers 12.

[0022] In the example system 100, the subarrays 16 may include a plurality of antennas. In the OPA 11, the number of subarrays 16 may be more or less than those depicted in Fig. 1. In an example, there may be only one subarray 16. In an alternate example, there may be many subarrays 16. The number of subarrays 16 may depend upon the application or use of the system 100. Further, the OPA 11 and/or subarrays 16 may include a nested power distribution network in material system Y.

[0023] In the example, the network phase adjusters 15 may be thermally tunable phase adjusters or electrically tunable phase adjusters. Typically, thermally tunable phase adjusters are more commonly utilized due to a lower loss of optical power, but may operate at a slower rate. Generally, electrically tunable phase adjusters may operate more quickly, but may cause extra optical loss. Both types of phase adjusters may be utilized for the example disclosure of Fig. 1.

[0024] Material X, typically silicon nitride, may typically be used for the distribution network 10 as it is generally very effective at handling high power laser energy. However, generally silicon nitride may be less efficient for phase adjusters/shifters. Typically, silicon may be used for phase adjusters and antennas, however silicon may not efficiently handle high power laser energy. Therefore, it may be ideal, in the example, to provide a configuration of network splitters, such as shown in system 100 of network splitters 14, which will divide the laser power energy before reaching material Y of the OPA 11.

[0025] As depicted in system 100, the network splitters 14 may be arranged in a tree configuration to divide the power or energy produced by light source 2. By using input coupler 13 and network splitters 14 made of material X, the high power laser energy produced by light source 2 may be provided directly to components capable of properly handling the high power laser energy. This high power energy may be divided up by these components (*e.g.*, network splitters 14) in order to be provided to the OPA 11 comprised of material Y at a power level material Y is capable of handling. In the example, power may be split in a hierarchical tree structure with Y splitters or MMI splitters. As indicated by the ellipses between network splitters 14, there may be more or less network splitters 14 and outputs from network splitters 14 in various alternate embodiments. In an alternate example, the network splitters 14 may be configured in further nested configurations.

[0026] For the optical power distribution system 100, the cascaded network splitters 14 rapidly reduce the optical power available at the OPA for beam steering. By choosing material system X with desired optical properties (e.g., high power tolerance, etc.), the ceiling of optical power delivered to the OPA subarrays can be raised, thus improving the performance of the LIDAR system.

[0027] Fig. 2 depicts an example block diagram of an OPA subarray configuration 200 in a solid-state LIDAR system according to an example of the present disclosure. The subarray 16 may be fabricated in solid-state material Y. Each subarray 16 in the OPA 11 may include an optical phase adjuster 20 and optical antennas 21. The optical phase adjuster 20 may adjust the phase of the light prior to the light reaching optical antennas 21. In an alternate example, there may be more than one optical phase adjuster in one subarray 16. The optical phase adjuster 20 may be identical to the network phase adjuster 15 other than being composed of a different material, as network phase adjuster 15 is made from material X and optical phase adjuster 20 is made from material Y. In an alternate example, the optical phase adjuster 20 is not identical to network phase adjuster 15.

[0028] Although approximately fifteen optical antennas 21 are depicted in Fig. 2, the subarray 16 may include any number of optical antennas 21. In an alternate example, the OPA subarray configuration 200 in Fig. 2 may optionally include its own nested optical power distribution network with nested couplers, splitters, optical phase adjusters, and optical antennas in material system Y.

[0029] Fig. 3 depicts an example block diagram of an alternate OPA subarray configuration 300 according to an example of the present disclosure. Fig. 3 depicts the subarray 16 including a plurality of optical phase adjusters 20 arranged in a serial fashion to accumulate phase along the optical path. The optical phase adjusters 20 are connected to horizontal couplers 22. Horizontal couplers 22 may also be referred to as directional couplers. Horizontal couplers 22 may be used to transfer light from the optical phase adjusters 20 to the optical antennas 21. The horizontal coupler 22 may be similar in nature to vertical coupler 12. However, unlike vertical coupler 12, horizontal coupler 22 may be made from only one material (*e.g.*, material Y). Additionally, horizontal coupler 22 may differ from vertical coupler 12 in that horizontal coupler 22 may not include a tapered or narrowed section. Rather, horizontal coupler 22 may include two waveguides positioned side by side and/or close together in order to transfer light. In the example, horizontal coupler 22 may provide a much weaker coupling than vertical coupler 12, and therefore may couple only a small portion of the power between optical phase adjusters 20 and antennas 21.

[0030] In the example serial configuration 300 of the optical phase adjusters 20, the accumulated phase after the second optical phase adjuster 20 may be the sum of two phase shifts. This may be because the light that enters the second optical phase adjuster 20 may already be phase shifted once by the first optical phase adjuster 20. Therefore, in the example, the already once phase shifted light will be phase shifted again by the second optical phase adjuster 20. Therefore, the total adjusted phase after the second phase adjuster 20 will be the sum of the two phase shifts. Similarly, as the light continues to travel through the remaining serially related optical phase adjusters 20, the phase will continue to accumulate. In an alternate example, a nested power distribution network may also be included in this arrangement.

[0031] Fig. 4 depicts an example block diagram of an alternate OPA subarray configuration 400 according to an example of the present disclosure. In this example, the subarray 16 includes its own optical power distribution network with splitters 23, optical phase adjusters 20, and optical antennas 21. Splitters 23 may be similar to network splitters 14, but composed of a different material. As indicated by the ellipses between the splitters 23, there may be more or less splitters 23 and outputs of the splitters 23 in various alternate embodiments. In Fig. 4, the splitters 23 may be arranged in a tree configuration in order to further subdivide power from light source 2. In an alternate example, the splitters 23 may be configured in further nested configurations.

[0032] All of the example OPA subarray configurations 200, 300, and 400 in Figs. 2, 3, and 4 may include further nested levels of splitters.

[0033] Fig. 5 is a flowchart illustrating an example method for using a solid-state LIDAR system based on an optical phased array with an optical power distribution network. Although the example method 500 is described with reference to the flowchart illustrated in Fig. 5, it will be appreciated that many other methods of performing the acts associated with the method may be used. For example, the order of some of the blocks may be changed, certain blocks may be combined with other blocks, and some of the blocks described are optional.

[0034] The method 500 begins when an input coupler receives light from a high-power light source (block 502). For example, input coupler 13 of Fig. 1 on distribution network 10 may receive light from light source 2. Light source 2 may supply high power laser energy.

[0035] Next, a network splitter receives the light from the input coupler (block 504). For example, one of the many disclosed network splitters 14 of Fig. 1 may receive the high power laser energy from input coupler 13. In the example, the first network splitter 14 will receive the light from input coupler 13.

[0036] Next, the network splitter divides the light, creating divided light energy (block 506). For example, the first network splitter 14 may divide the high power laser energy. Additionally, in the example, the other network splitters 14 connected to each output of the first network splitter 14 may further divide the energy. This energy may be called divided light energy. This divided light energy may be provided to a network phase adjuster 15 to have phase adjusted before entering into the vertical coupler 12. In an alternate example, the network phase adjusters 15 are not present in distribution network 10 of Fig. 1, and thus the divided light energy is provided directly to the vertical coupler 12.

[0037] Next, an OPA receives the divided light energy (block 508). For example, the divided laser energy is put into vertical coupler 12 and supplied to OPA 11, and particularly to subarrays 16 in the OPA 11. This light energy may be used by the phase adjusters and antennas in the OPA 11 to produce beams that can be steered. In an example, the divided light energy may be provided directly to a phase adjuster 20 as in Figs. 2 and 3. Once the phase has been adjusted, the light energy will be provided to antennas 21. In an alternate example, once the subarrays 16 receive the divided light energy, the light energy may be further subdivided, as in Fig. 4, using splitters 23 prior to being supplied to the phase adjusters 20.

[0038] It should be understood that various changes and modifications to the examples described herein will be apparent to those skilled in the art. Such changes and modifications can be made without departing from the spirit and scope of the present subject matter and without diminishing its intended advantages. It is therefore intended that such changes and modifications be covered by the appended claims.

CLAIMS

What is claimed is:

1. An optical power distribution system, comprising:

a distribution network, wherein the distribution network includes:

an input coupler, wherein the input coupler receives power from a power source, and

a network splitter, wherein the network splitter receives power from the input coupler; and

an optical array that receives power from the distribution network, wherein the distribution network is made of a first material and the optical array is made of a second material.

2. The optical power distribution system of claim 1, further comprising:

the distribution network includes network phase adjusters connected to outputs of the network splitter.

3. The optical power distribution system of claim 1, further comprising:

a vertical coupler coupling the distribution network and the optical array, wherein the vertical coupler includes a first tapered edge made of the first material and a second tapered edge made of the second material.

4. The optical power distribution system of claim 3, wherein the first tapered edge and the second tapered edge overlap.

5. The optical power distribution system of claim 4, wherein a tapered evanescent wave is produced.

6. The optical power distribution system of claim 1, wherein the first material and the second material are different solid state materials.

7. The optical power distribution system of claim 6, wherein the first material is silicon nitride and the second material is silicon.

8. The optical power distribution system of claim 1, further comprising:
the optical array includes subarrays.

9. The optical power distribution system of claim 8, further comprising:
the subarrays include at least one optical phase adjuster and a plurality of antennas, wherein the at least one optical phase adjuster adjusts a phase of light before the light reaches the plurality of antennas.

10. The optical power distribution system of claim 9, further comprising:
the subarrays include a horizontal coupler, wherein the horizontal coupler is used to direct light from the at least one optical phase adjuster to the plurality of antennas.

11. The optical power distribution system of claim 10, wherein the at least one optical phase adjuster includes a first optical phase adjuster and a second optical phase adjuster, and the first optical phase adjuster and the second optical phase adjuster are connected in series to accumulate phase.

12. The optical power distribution system of claim 9, further comprising:
the subarrays include at least one nested distribution network, wherein the nested distribution network includes at least one of a nested coupler, a nested splitter, a nested optical phase adjuster, and a nested optical antenna.

13. The optical power distribution system of claim 9, further comprising:
the subarrays include at least one optical array splitter.

14. The optical power distribution system of claim 13, further comprising:
the at least one optical array splitter includes a plurality of optical array splitters.

15. The optical power distribution system of claim 12, wherein the plurality of optical array splitters are arranged in a tree network structure.

16. The optical power distribution system of claim 1, wherein the network splitter includes a plurality of network splitters.

17. The optical power distribution system of claim 1, wherein the plurality of network splitters are arranged in a tree network structure.

18. The optical power distribution system of claim 1, wherein the power source is a high-power laser.

19. A method of optical power distribution, comprising:

receiving, at an input coupler, light from a high-power light source;

receiving, at a network splitter, the light from the input coupler;

dividing, by the network splitter, the light, creating divided light energy; and

receiving, by an optical array, the divided light energy, wherein the input coupler and the network splitter are part of a distribution network,

the distribution network is fabricated on a first material, and

the optical array is fabricated on a second material.

20. The method of optical power distribution of claim 19, further comprising:

receiving, at a vertical coupler, the divided light energy, wherein the vertical coupler couples the distribution network to the optical array,

wherein the vertical coupler includes a first tapered edge made of the first material and a second tapered edge made of the second material.

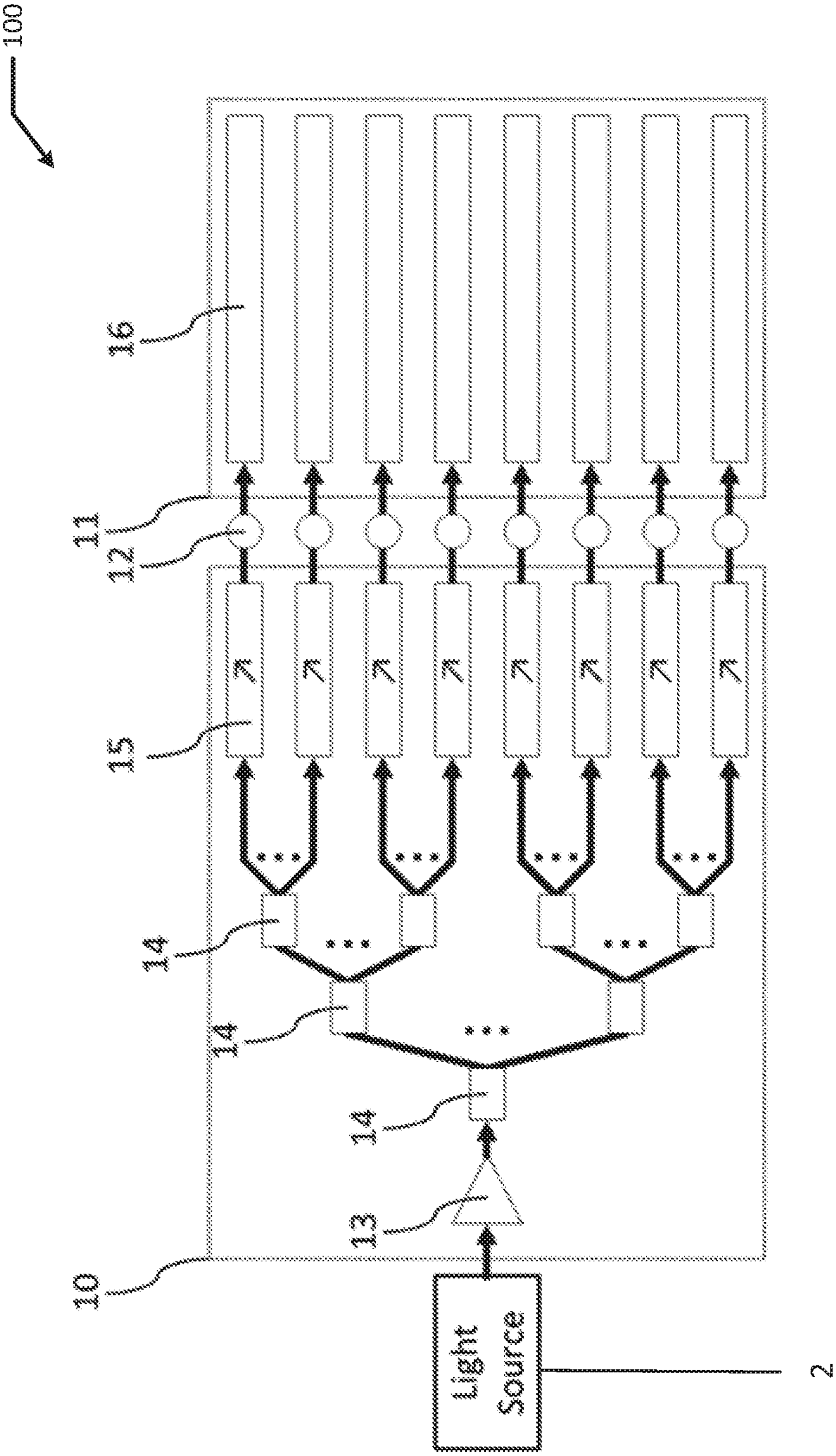

Fig. 1

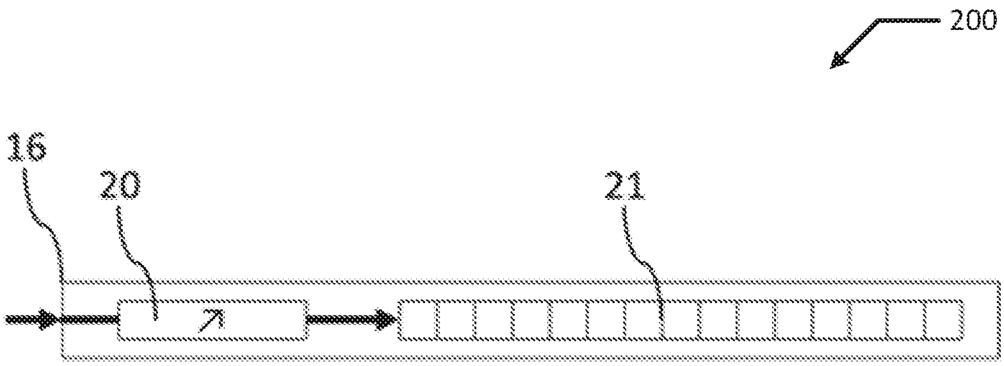

Fig. 2

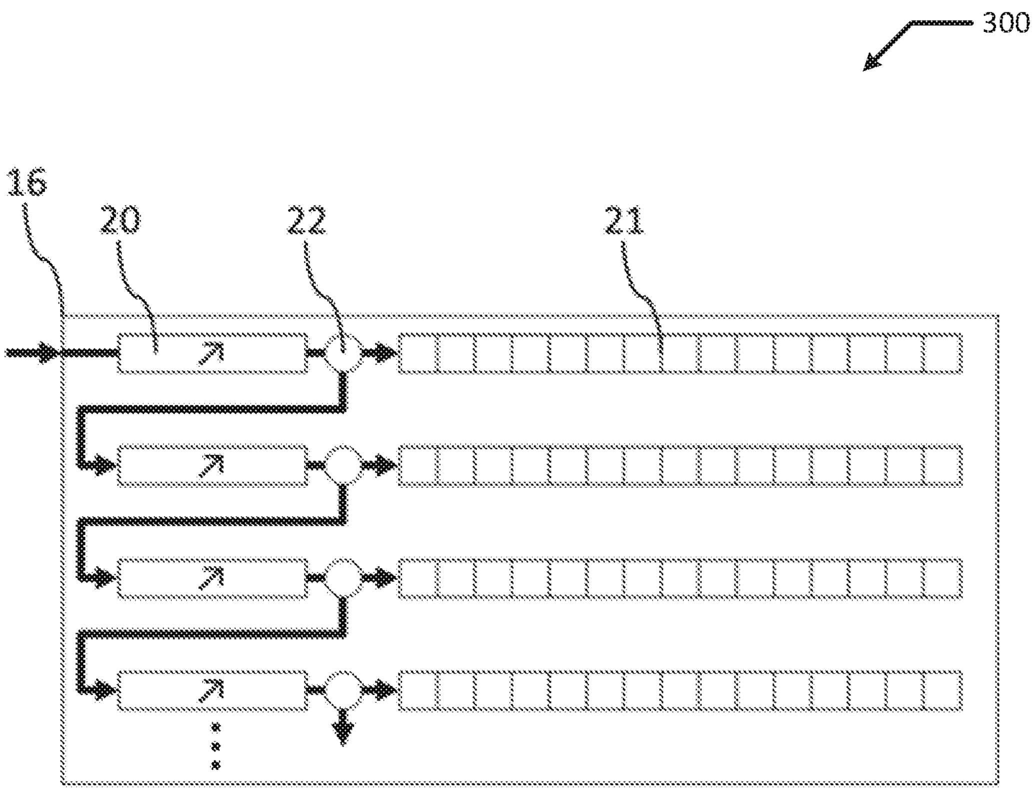

Fig. 3

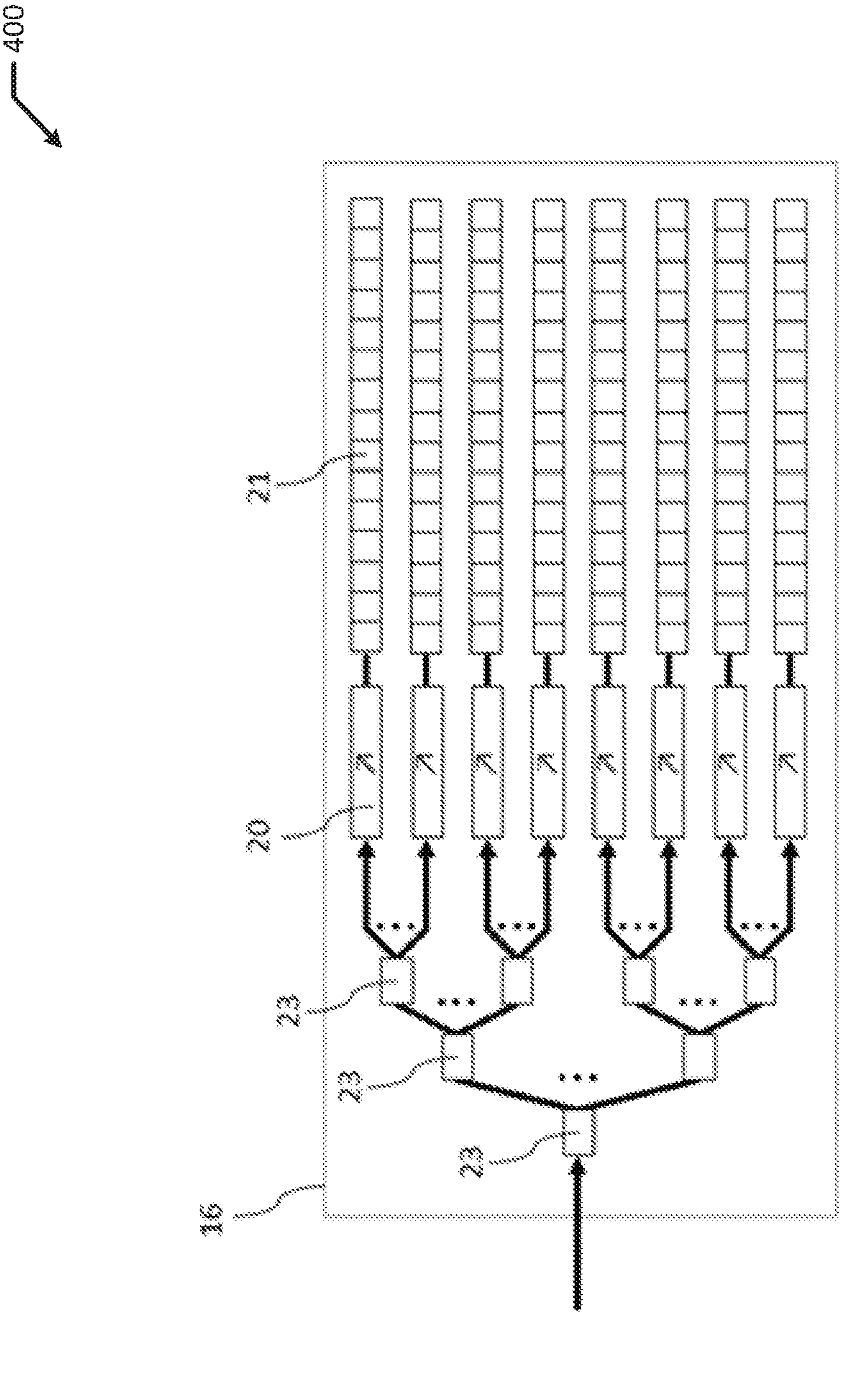

Fig. 4

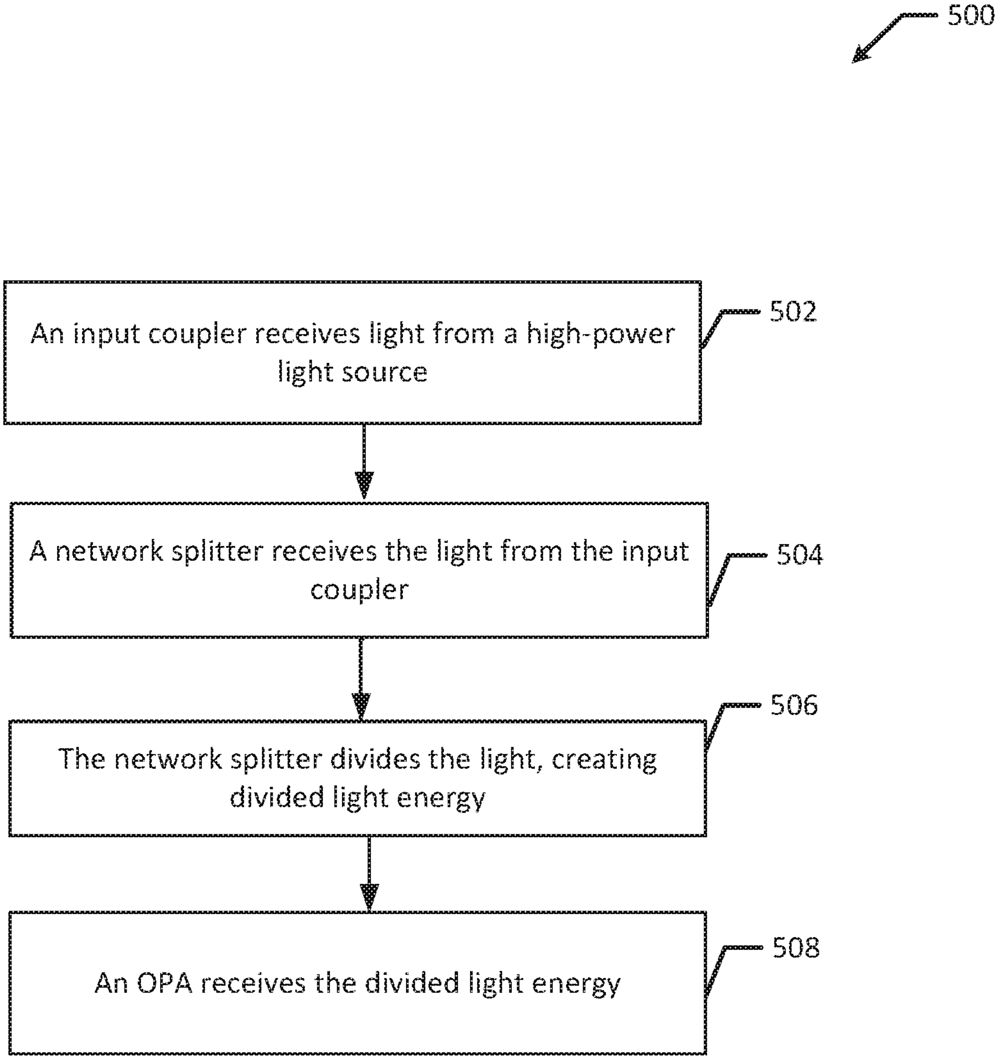
500
An input coupler receives light from a high-power light source
502
A network splitter receives the light from the input coupler
504
The network splitter divides the light, creating divided light energy
506
An OPA receives the divided light energy
508

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/042093

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01S 7/481; G01S 17/42 (2018.01)
CPC - G01S 7/481; G01S 17/08 (2018.08)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 356/326; 356/327; 356/478; 356/479; 385/14; 385/15 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2014/0376001 A1 (SWANSON) 25 December 2014 (25.12.2014) entire document	1, 2, 6-8, 16, 17 --- 3-5, 9-15, 18-20
Y	US 2010/0187442 A1 (HOCHBERG et al) 29 July 2010 (29.07.2010) entire document	3-5, 20
Y	US 2016/0356960 A1 (CORIANT ADVANCED TECHNOLOGY, LLC) 08 December 2016 (08.12.2016) entire document	5
Y	US 2014/0192394 A1 (SUN et al) 10 July 2014 (10.07.2014) entire document	9-15
Y	US 2015/0214122 A1 (ACACIA COMMUNICATIONS INC.) 30 July 2015 (30.07.2015) entire document	10, 11
Y	US 2010/0303469 A1 (BARTON et al) 02 December 2010 (02.12.2010) entire document	12-15
Y	US 2006/0231771 A1 (LEE et al) 19 October 2006 (19.10.2006) entire document	18-20
A	US 2013/0121354 A1 (FURUKAWA ELECTRIC CO., LTD.) 16 May 2013 (16.05.2013) entire document	1-20
A	US 2017/0155225 A1 (LUMINAR TECHNOLOGIES, INC.) 01 June 2017 (01.06.2017) entire document	1-20
A	US 2014/0085634 A1 (PRESTON et al) 27 March 2014 (27.03.2014) entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance
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Date of the actual completion of the international search	Date of mailing of the international search report
12 September 2018	25 SEP 2018

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774