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**Hesham Taha**, Jerusalem (IL)(52) **U.S. Cl.**CPC ..... **G02B 6/4214** (2013.01); **G02B 6/423**  
(2013.01); **G02B 6/4249** (2013.01); **G02B**  
**6/3885** (2013.01)(21) Appl. No.: **18/964,911**(22) Filed: **Dec. 2, 2024****Related U.S. Application Data**

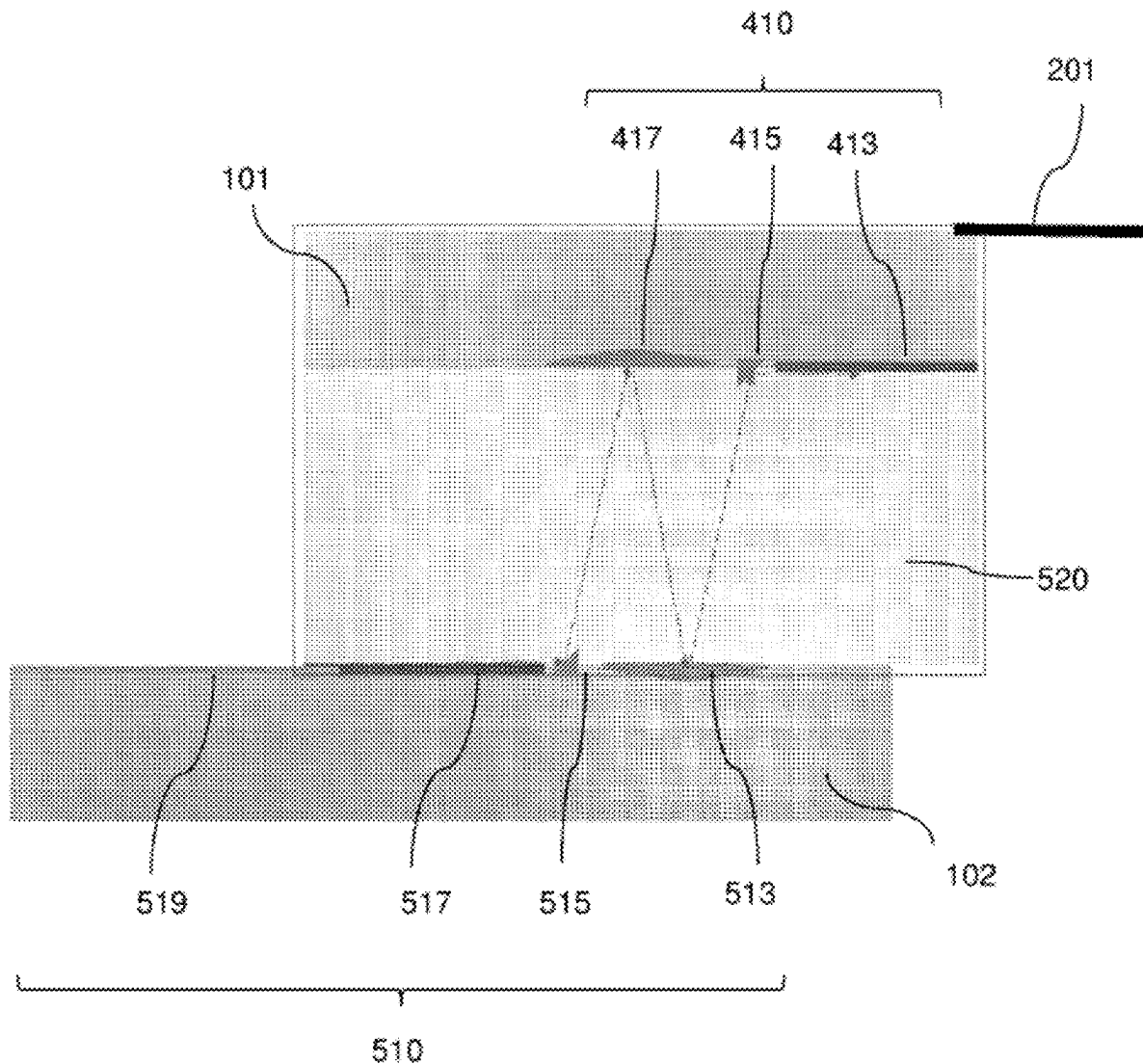
(63) Continuation of application No. 18/153,167, filed on Jan. 11, 2023, now Pat. No. 12,197,019, which is a continuation of application No. 16/801,682, filed on Feb. 26, 2020, now Pat. No. 11,585,991.

(60) Provisional application No. 62/811,840, filed on Feb. 28, 2019.

(57)

**ABSTRACT**

Electro-optical systems and methods are described including a photonic substrate optically coupled to a photonic integrated circuit (PIC). The photonic substrate and the PIC may comprise one or more optical elements. A mechanical aligner may be coupled to the photonic substrate. The mechanical aligner may be configured to align an optical element (e.g., optical fiber) to optically couple the optical element to the PIC via the one or more optical elements.



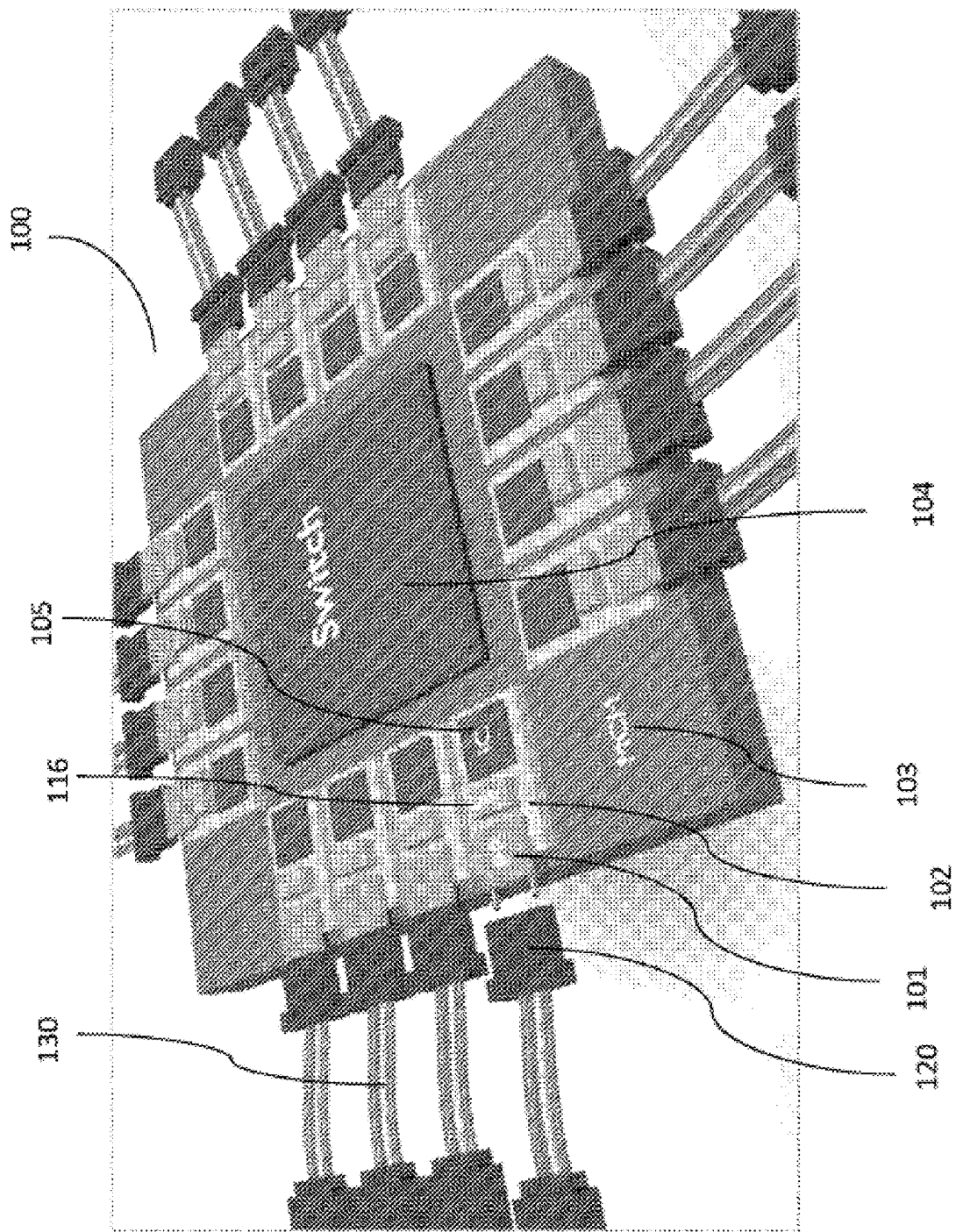
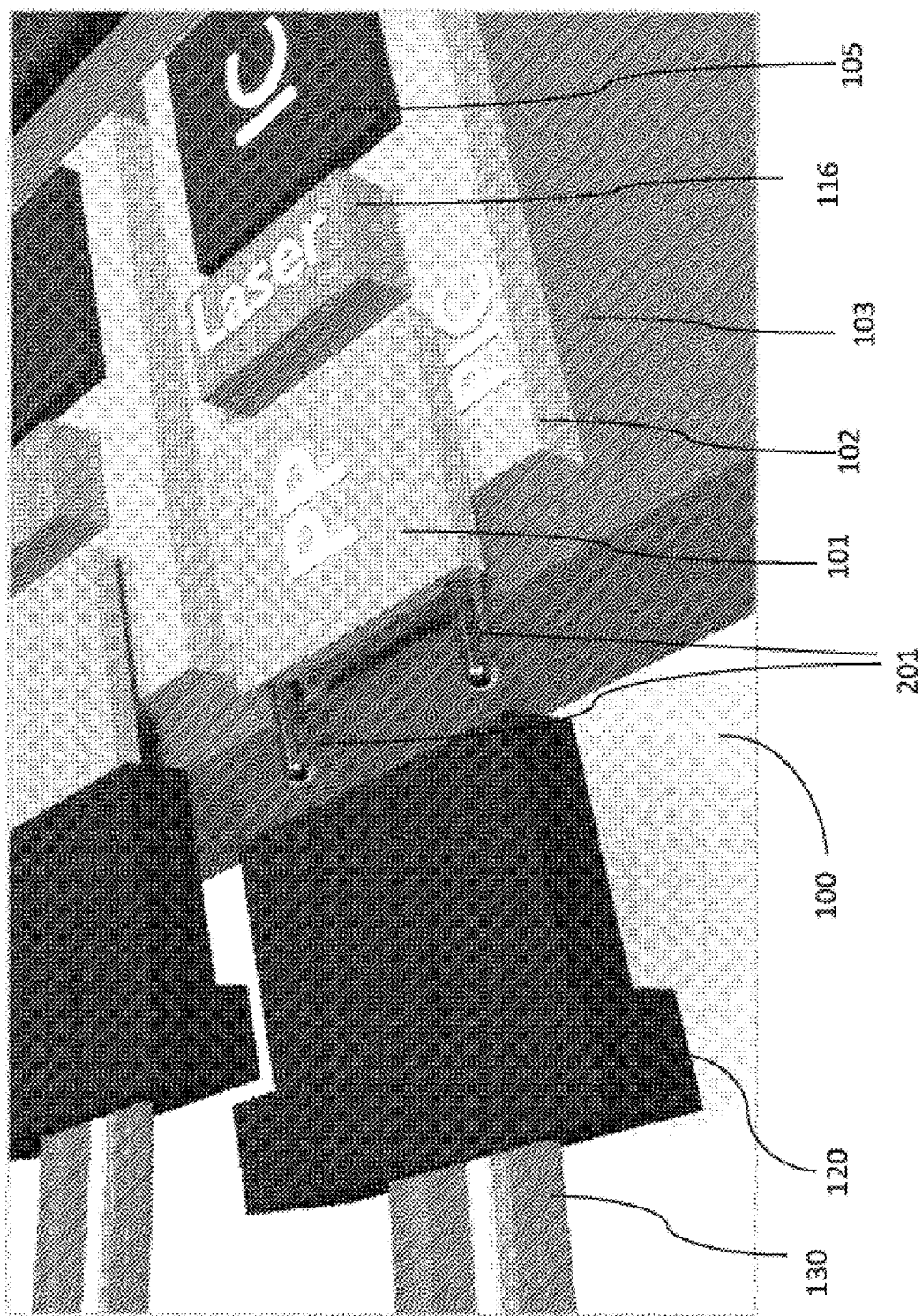


FIG. 1



**FIG. 2**

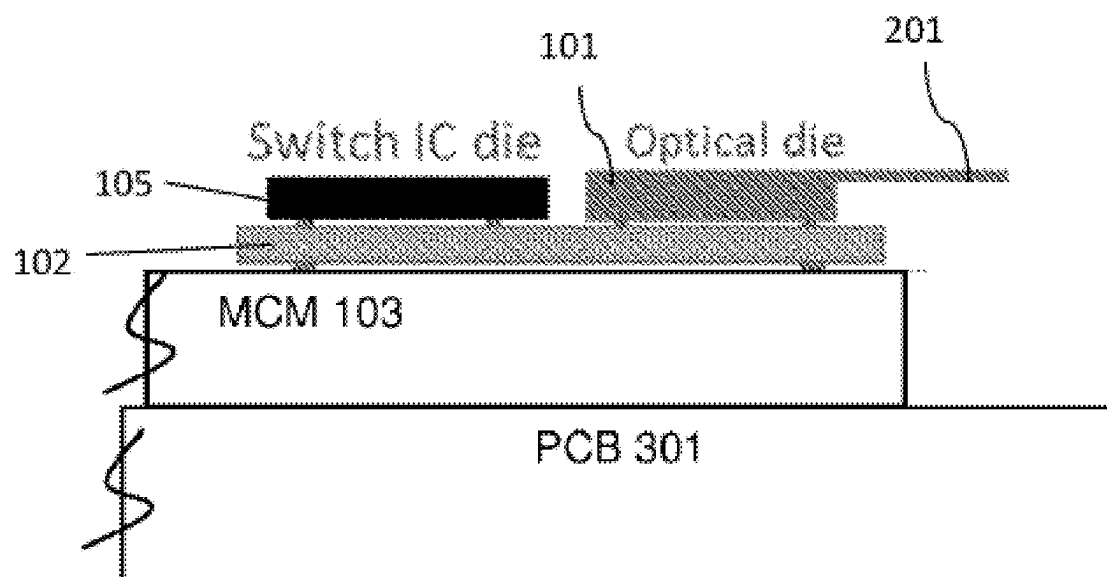


FIG. 3

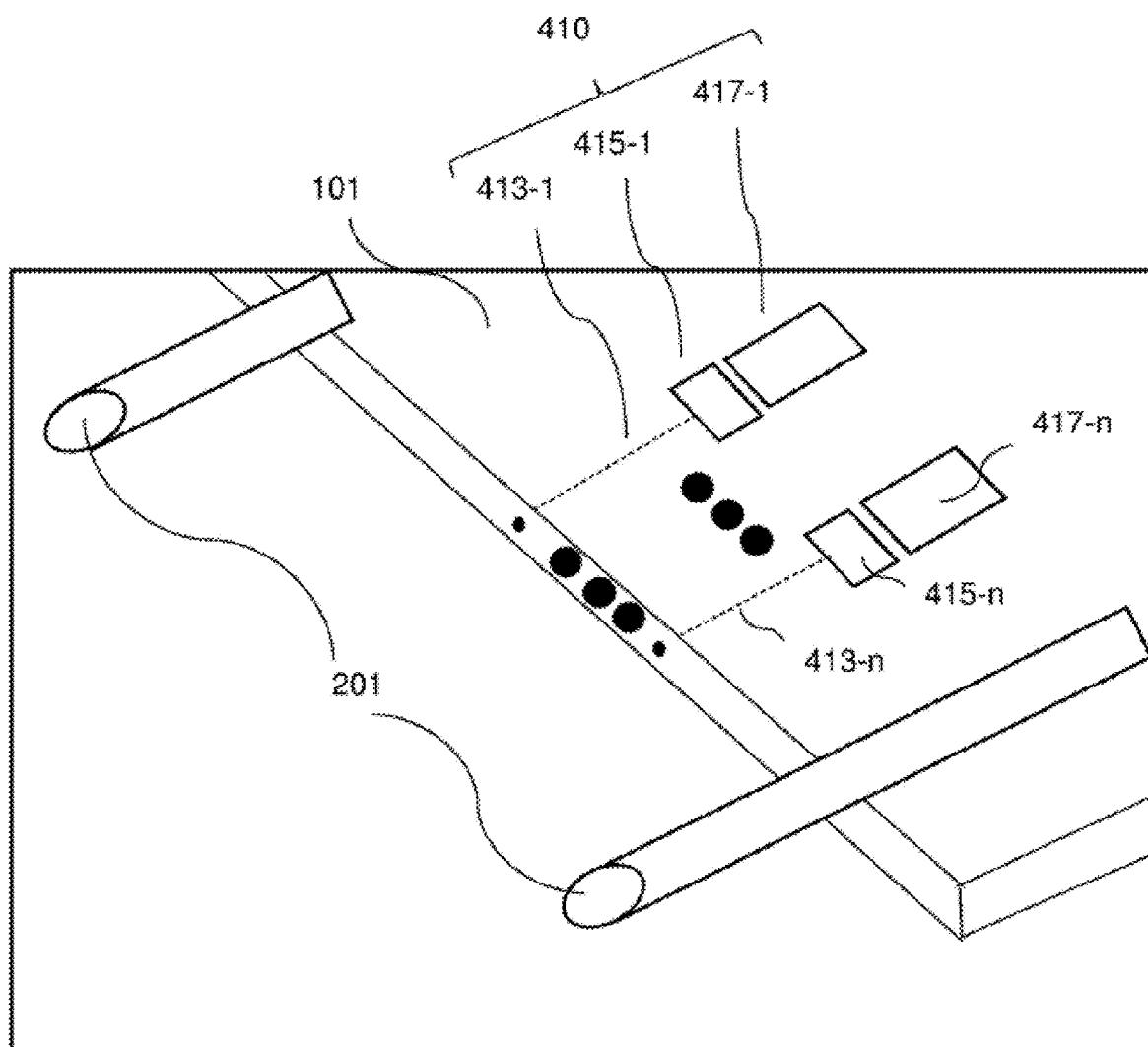
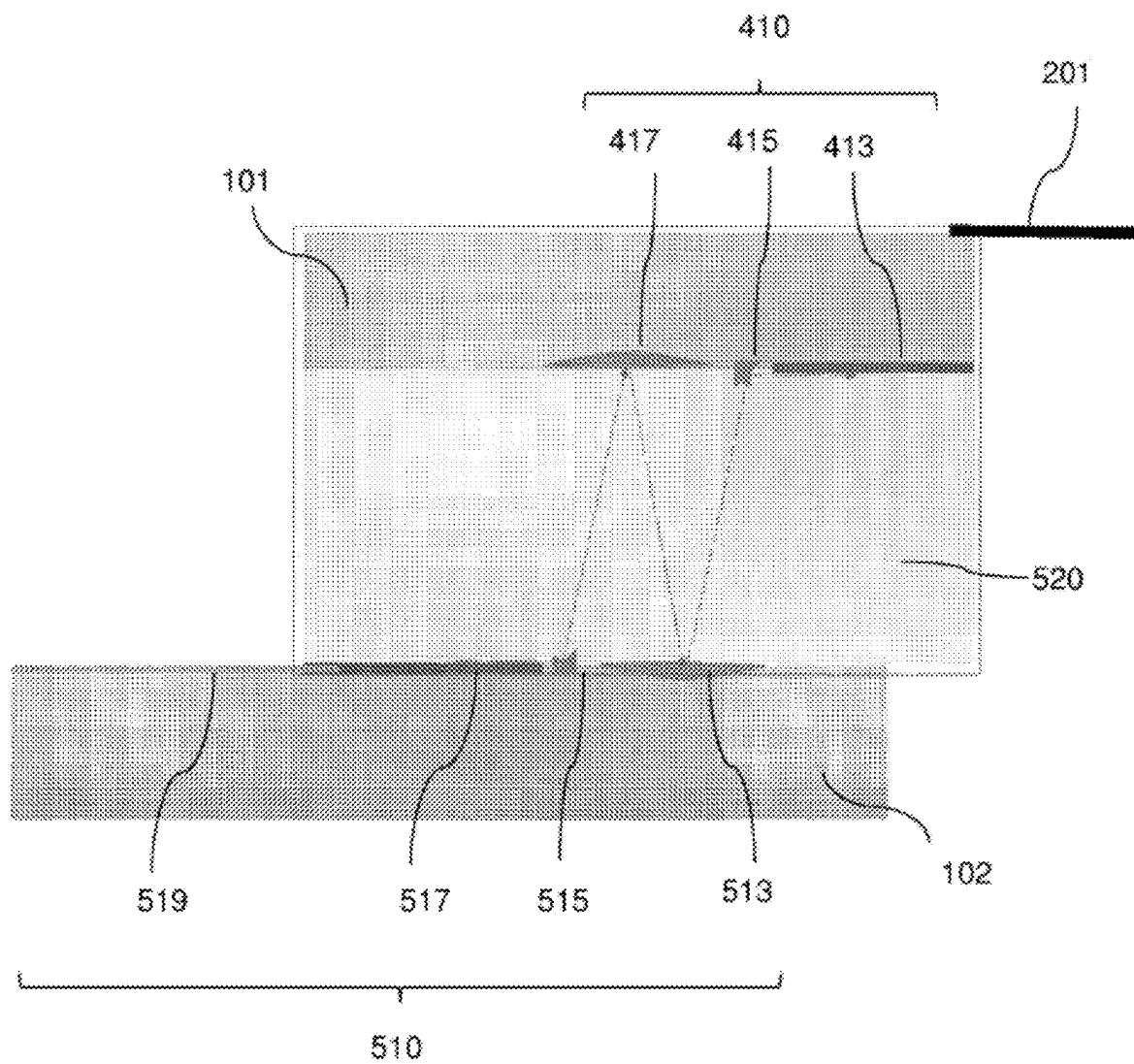


FIG. 4



**FIG. 5**

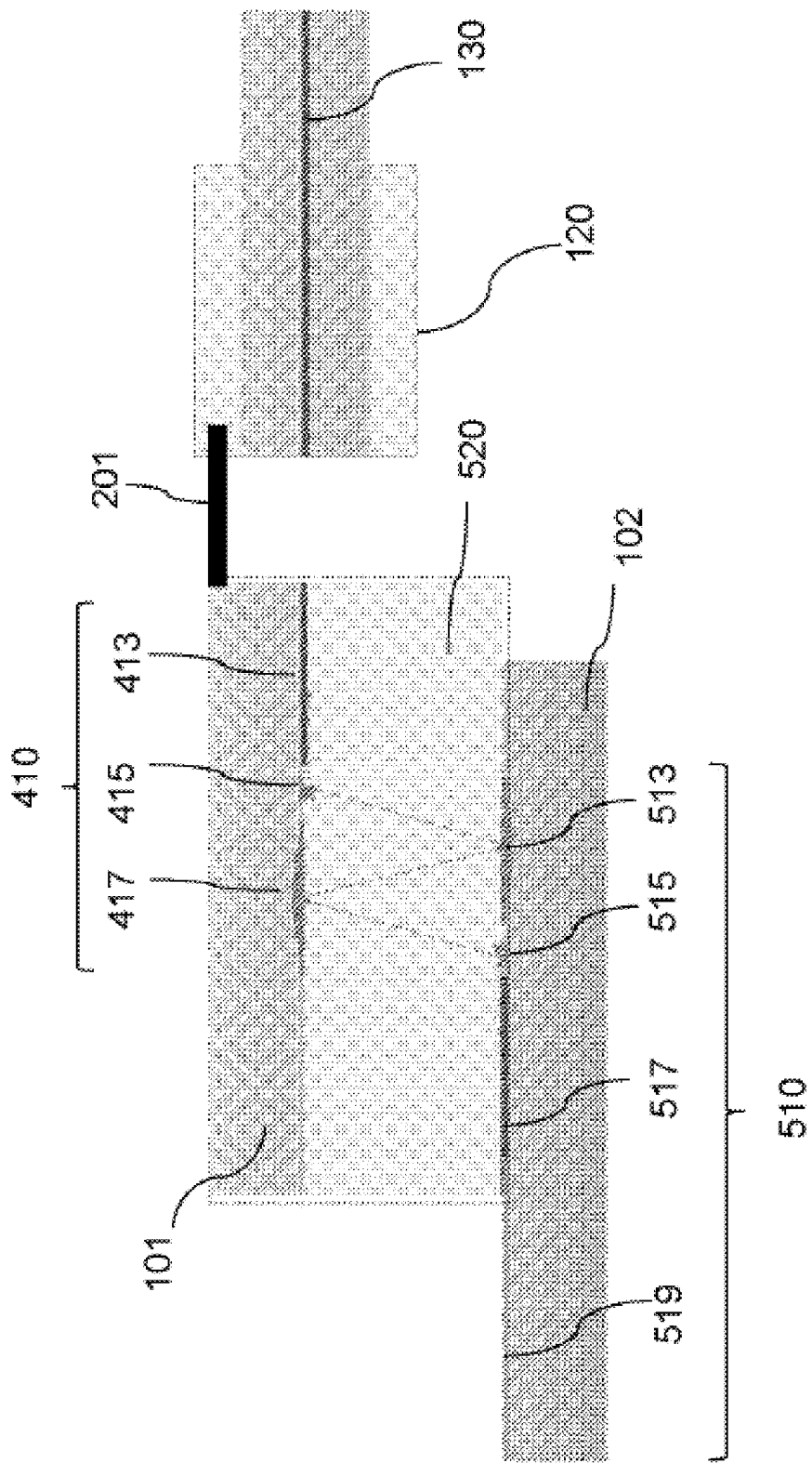
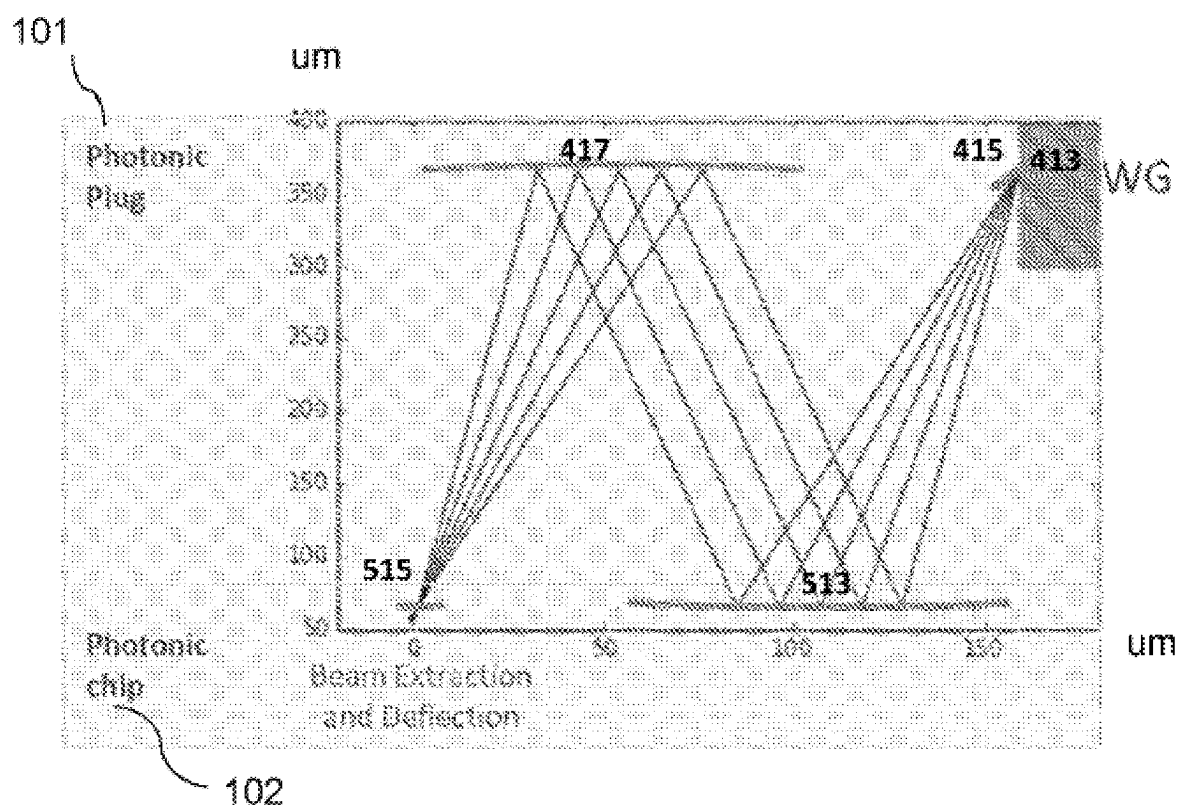


FIG. 6



**FIG. 7**



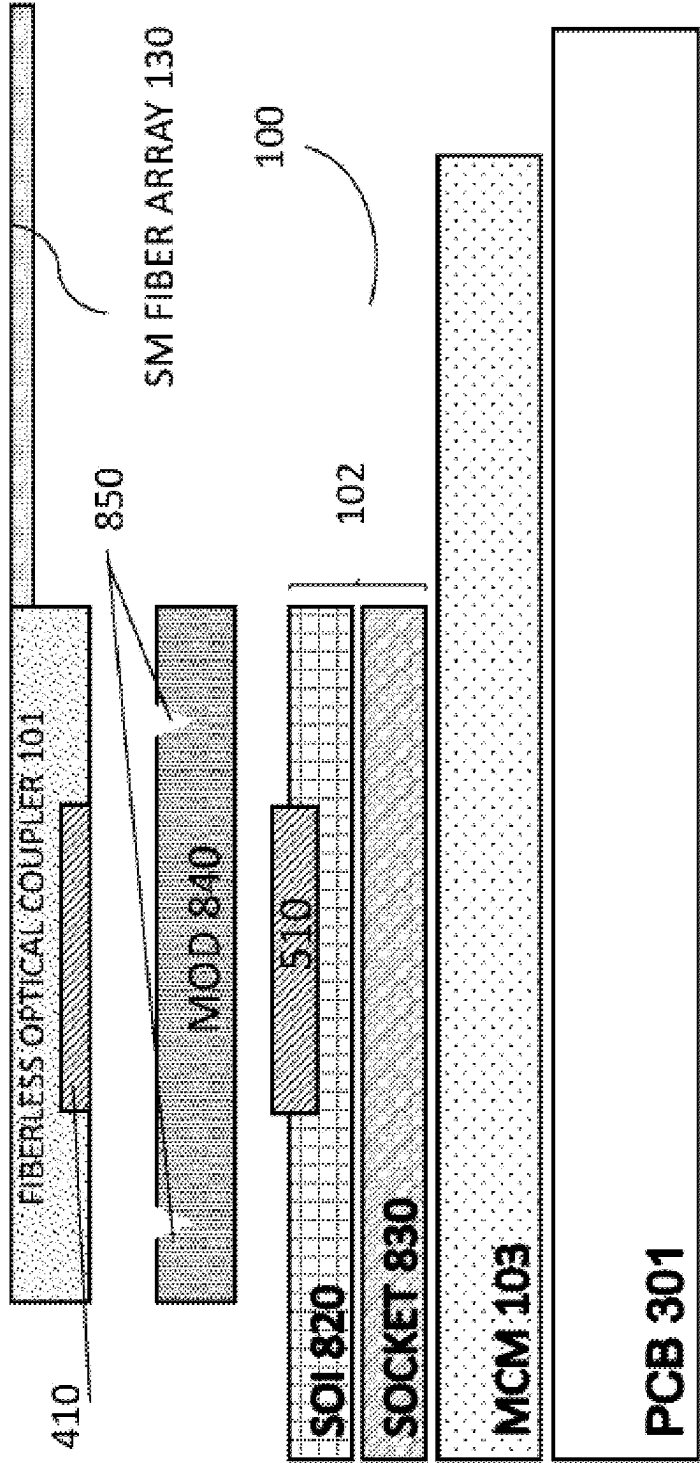
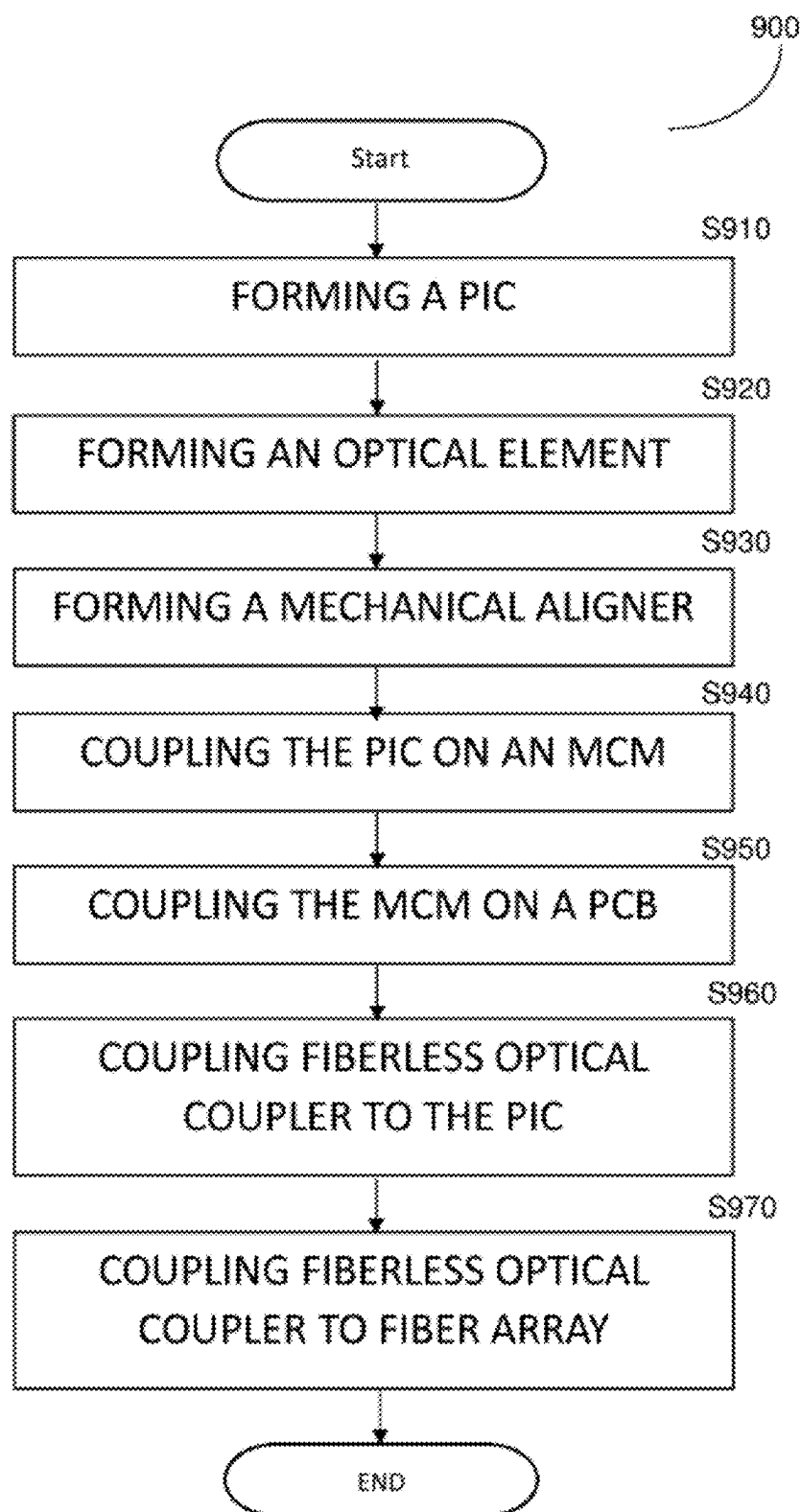


FIG. 8

**FIG. 9**

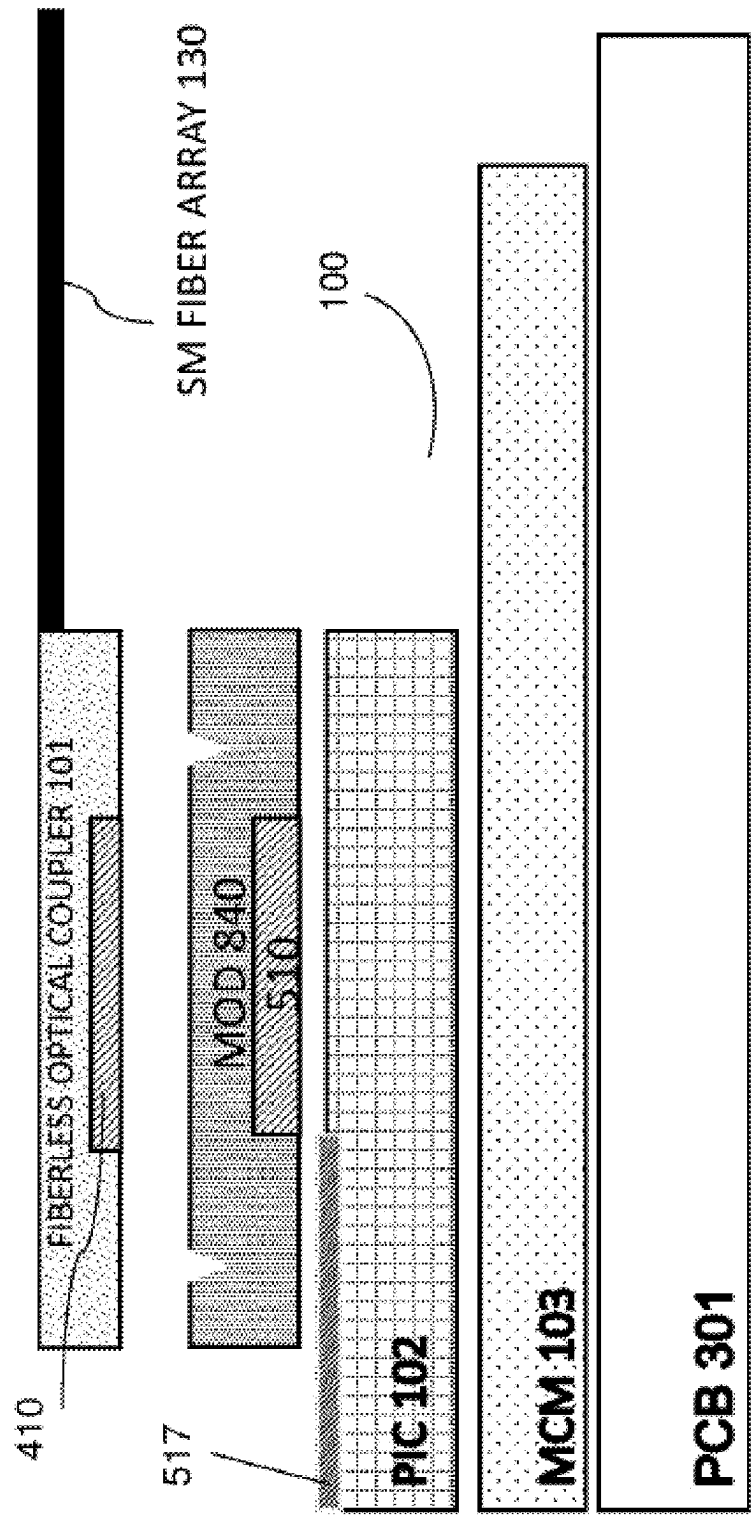


FIG. 10

## CO-PACKAGED OPTICS

### CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. application Ser. No. 18/153,167, filed on Jan. 11, 2023, which is a continuation of U.S. application Ser. No. 16/801,682, filed on Feb. 26, 2020 (now U.S. Pat. No. 11,585,991), and claims the benefit of U.S. Provisional Application No. 62/811,840 filed on Feb. 28, 2019. The contents of each of the above-referenced applications are incorporated herein by reference in their entirety for all purposes.

### TECHNICAL FIELD

[0002] The present disclosure relates generally to coupling an optical fiber to a substrate, and more particularly to coupling the optical components to an optoelectronic Integrated Circuit (IC).

### BACKGROUND

[0003] Communications systems and data centers are required to handle massive data at ever increasing speeds and ever decreasing costs. To meet these demands, optical fibers and optical ICs (such as, a Photonic Integrated Circuit (PIC) or integrated optical circuit) are used together with high speed electronic ICs. A PIC is a device that integrates multiple photonic functions (similar to an electronic IC or RF IC). PICs are typically fabricated using indium phosphide or silicon oxide (SiO<sub>2</sub>), which allows for the integration of various optically active and passive functions on the same circuit.

[0004] The coupling of PICs to optical fibers is not as well advanced as the integration and/or coupling of electronic ICs. Specifically, the challenges facing optical connections are different and much more complex than connecting electronic ICs to, for example, a Printed Circuit Board (PCB). Some difficulties are inherent in wavelength, signal losses, assembly tolerance, and polarization characteristics of optical packaging.

[0005] Existing solutions utilize various techniques for connecting optical fibers to PICs. One technique suggests using various types of butt connections to the edge and surface fiber connections a PIC. The butt of a fiber can be connected to a planar waveguide at the edge of a PIC. This technique is efficient only if the cross sectional of the propagating mode of the fiber and the waveguide areas of the fiber core and the waveguide are of similar size. In most cases, this technique suffers from poor assembly tolerance and is not suitable for high fiber-port count.

[0006] An existing technique suggests laying a section of fiber on top of the surface of the PIC where the end of the fiber has been cut at an angle to form an angled tip. The angled tip has a flat surface, which reflects a light beam down to a waveguide grating coupler disposed on the integrated circuit. The light beam is reflected off the reflective surface of the angled tip by total internal reflection. The waveguide grating coupler is designed to accept the slightly diverging light beam from the reflective surface of the angled tip of the fiber. The light beam can also propagate through the fiber to a chip coupler in the opposite direction, up from the substrate through the waveguide grating and into an optical fiber after bouncing off the reflective surface

of the angled tip. This technique further requires coating on the exterior of the reflective surface with epoxy.

[0007] Among others, all of the above-noted techniques require precise alignment and active positioning of the optical fiber to the PIC. As such, current techniques suffer from poor and very tight alignment tolerance to gain an efficient connectivity. For example, a misalignment between an optical fiber and a PIC of 1-2 microns would result in a signal loss of about 3 db. Furthermore, the alignment is now performed with expensive equipment or labor-intensive assembly solutions. As a result, mass production of PICs and/or optical couplers is not feasible. Furthermore, most current Single Mode (SM) fiber-chip connection uses non-scalable assembly technologies due to active-alignment protocols. Such protocols support low volume production and cannot be scaled to application with large port count. For example, data-center switches with high density and chip-to-chip connectivity applications are not supported by the active-alignment protocol.

[0008] Furthermore, current wide-band optical fiber to chip connectivity uses complicated edge coupling geometry and sub-micron tight tolerance, which mostly requires active alignment of specialized tools.

[0009] It would therefore be advantageous to provide a solution that would overcome the challenges noted above.

### SUMMARY

[0010] A summary of several example embodiments of the disclosure follows. This summary is provided for the convenience of the reader to provide a basic understanding of such embodiments and does not wholly define the breadth of the disclosure. This summary is not an extensive overview of all contemplated embodiments, and is intended to neither identify key or critical elements of all embodiments nor to delineate the scope of any or all aspects. Its sole purpose is to present some concepts of one or more embodiments in a simplified form as a prelude to the more detailed description that is presented later. For convenience, the term “some embodiments” or “certain embodiments” may be used herein to refer to a single embodiment or multiple embodiments of the disclosure.

[0011] Certain embodiments disclosed herein include an electro-optical system. The electro-optical system includes a Photonic Integrated Circuit (PIC) having a laser source located on the PIC, a fiberless optical coupler located on the PIC. The fiberless optical coupler is configured to be coupled to a fiber array. The electro-optical system also includes an optical element, and a mechanical aligner. The optical element is aligned with the fiber array, via the mechanical aligner, for a light from the laser source to transmit in between the fiber array and the PIC through the optical element, when the fiberless optical coupler is coupled to the fiber array.

[0012] Certain embodiments disclosed herein also include a method of manufacturing the electro-optical system. The method includes forming a Photonic Integrated Circuit (PIC), the PIC having a laser source formed on the PIC, forming an optical element, forming a mechanical aligner, coupling the PIC on a Multi-Chip Module (MCM), coupling the MCM on a Printed Circuit Board (PCB), and coupling a fiberless optical coupler to the PIC, the fiberless optical coupler configured to be coupled to a fiber array. The optical element is aligned with the fiber array via the mechanical aligner, for a light from the laser source to transmit in

between the fiber array and the PIC through the optical element, when the fiberless optical coupler is coupled to the optical connector via the mechanical aligner.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The subject matter disclosed herein is particularly pointed out and distinctly claimed

[0014] in the claims at the conclusion of the specification. The foregoing and other objects, features, and advantages of the disclosed embodiments will be apparent from the following detailed description taken in conjunction with the accompanying drawings.

[0015] FIG. 1 is a top view of the electro-optical interconnection platform for co-packaging a high-speed switch to high-density optical engine showing the position of the fiberless optical coupler according to some embodiments.

[0016] FIG. 2 is a magnified view of the electro-optical interconnection platform according to some embodiments.

[0017] FIG. 3 is a side schematic view of the electro-optical interconnection platform according to some embodiments.

[0018] FIG. 4 is a magnified schematic view of the fiberless optical coupler according to some embodiments.

[0019] FIG. 5 is a schematic side view of the fiberless optical coupler on the Photonic

[0020] Integrated Circuit (PIC) according to some embodiments.

[0021] FIG. 6 is a schematic side view of a PIC mounted with a fiberless optical coupler that is attached to a fiber array according to some embodiments.

[0022] FIG. 7 is a magnified schematic side view of the self-aligning optics according to some embodiments.

[0023] FIG. 8 is a schematic side view of the electro-optical interconnection platform according to some embodiments.

[0024] FIG. 9 is a flowchart of a method of manufacturing an electro-optical interconnection platform according to some embodiments.

[0025] FIG. 10 is a schematic side view of the electro-optical interconnection platform according to some embodiments.

#### DETAILED DESCRIPTION

[0026] It is important to note that the embodiments disclosed herein are only examples of the many advantageous uses of the innovative teachings herein. In general, statements made in the specification of the present application do not necessarily limit any of the various claimed embodiments. Moreover, some statements may apply to some inventive features but not to others. In general, unless otherwise indicated, singular elements may be in plural and vice versa with no loss of generality. In the drawings, like numerals refer to like parts through several views.

[0027] Based on the problems stated above, a scalable single-mode fiber to chip assembling methodology is needed in applications where fiber high density or large port count is used, for example, co-packaged optical Switch connectivity. Co-packaged optical connectivity brings multiple fibers closer to Switch die which is packaged on an expensive packaging platform such as a Multi-Chip Module (MCM). Therefore, co-packaged optical connectivity should be compatible with standard chip packaging methodologies and equipment. Separating the fiber from the MCM pack-

aging steps, and keeping the fiber and MCM packaging to the last stage in a pluggable way is not only unique, but also makes the process a scalable technology.

[0028] Furthermore, fiberless detachable connections are suitable not only in switches, but also in transceivers and other applications such as connections between memory and processors and chip-to-chip connectivity in general.

[0029] According to some embodiments, an electro-optical interconnection platform for co-packaging a high-speed switch to high-density optical engine is disclosed. In an embodiment, the platform includes a fiberless optical coupler that may cover various geometries. The coupler includes a plurality of mirrors, one or more mechanical aligners for fiber mount connector, that are rods located in V-grooves, which are accurately placed relative to the optics, and a waveguide (e.g., a polymeric waveguide or other types of mirror with different optical arrangements). In an example embodiment, the chip includes a plurality of mirrors, and a positive tapered wave guide, an interface medium, (e.g., MCM), and a high-speed switch's die. In an example embodiment, a laser can be part of the platform.

[0030] In yet another embodiment, a fiberless optical coupler for interfacing with an optical fiber connector and a Photon Integrated Circuit (PIC) is disclosed. The coupler includes a plurality of mirrors, one or more mechanical alignment rods, and a waveguide, (e.g., a polymeric or Si waveguide).

[0031] FIG. 1 is a top view of an electro-optical interconnection platform 100 according to an embodiment. The platform 100 includes a fiberless optical coupler 101 (also known as fiberless Photonic Plug (PP) coupler), an Integrated Circuit (IC) 105, and a laser source 116 packaged on a PIC 102 (also known as a photonic chip or high-density optical engine), and a high-speed switch's die 104 co-packaged with the PIC 102 as a set of electronic components on an MCM 103.

[0032] The fiberless optical coupler 101 is designed with an optical arrangement that provides high tolerance alignment and a passive positioning of the fiberless optical coupler, thus aligning the optical fiber with respect to the PIC. An example optical arrangement of the coupler 101 can be found in U.S. Pat. No. 9,840,334 and U.S. patent application Ser. No. 14/878,591, each of which are herein incorporated by reference in their entirety and assigned to the common assignee. The fiberless optical coupler 101 can be mass-produced and its design further allows for compact and secured packaging of PICs.

[0033] In an embodiment, multiple sets of the fiberless optical coupler 101, the PIC 102, the IC 105 and the laser source 116 are assembled surrounding the high-speed switch die 104 on the MCM 103.

[0034] Each of the fiberless optical coupler 101 may be connected to electrical-optical connectors 120 and the fiber array 130 to transmit power or data to the components mounted on the MCM 103, the details of which will be further discussed below. Also, the fiberless optical coupler 101 is assembled on the PIC 102 through a flip-chip machine (not shown) with passive alignment and large tolerances using "self-aligning optics". Such alignment does not require additional adjustments or alignment of the optical components are necessary, and accurate placement of mechanical aligners with reference to optics at wafer level sizes are enabled. The details of the "self-aligning optics" are explained below with reference to FIGS. 4 through 7.

[0035] It should be appreciated that by using the flip-chip machine using self-aligning optics, surface coupling may be achieved, and issues with complicated edge geometry may be removed.

[0036] FIG. 2 is an example magnified view of the electro-optical interconnection platform 100 according to an embodiment. In one embodiment, the fiberless optical coupler 101 includes a mechanical aligner 201 that is compatible with various types of electrical optical connectors 120 that ensure mechanical alignment of fiber ribbon relative to the optics on the fiberless optical coupler 101.

[0037] In another embodiment, the mechanical aligner 201 may be a pair of cylindrical rods arranged on opposite sides of the fiberless optical coupler 101 at a distal end, both of which are connectible to the electrical optical connectors 120. The pair of cylindrical rods may be parallel to each other and be of the same length. The assembly of the electro-optical interconnection platform 100 can be performed by connecting the fiberless optical coupler 101 on the MCM module 103 to a switch board (not shown).

[0038] FIG. 3 is an example schematic side view of the electro-optical interconnection platform 100 according to an embodiment. The fiberless optical coupler 101, which is also known as an optical die and includes the mechanical aligner 201, is mounted on the PIC 102 adjacent to the IC 105, which is also known as the switch IC die. The PIC 102 is in turn mounted on the MCM module 103, and the entire assembly including the fiberless optical coupler 101, the mechanical aligner 201, IC 105, PIC 102, and the MCM module 103 is mounted on a printed circuit board (PCB) 301.

[0039] As shown in the example FIG. 3, the co-packaged components reduce power consumption, as this arrangement brings the components closer to the IC 105, thereby reducing the electrical port's length to about 2-3 millimeters, compared to the 10-15 centimeters electrical link seen in typical pluggable transceiver optics connectivity.

[0040] FIG. 4 is an example diagram of a high magnification of the fiberless optical coupler 101 according to an embodiment. The mechanical aligner 201, embodied as a pair of mechanical alignment rods are included on the fiberless optical coupler 101. The fiberless optical coupler 101 also includes wafer-level optical elements 410. Based on the description below, these optical elements 410 may be "self-aligning."

[0041] In an embodiment, the optical elements 410 may include a plurality of waveguides 413-1 through 413-*n* (collectively referred to as a waveguide 413 or waveguides), deflectors 415-1 through 415-*n* (collectively referred to as a deflector 415 or deflectors 415) and curved mirrors 417-1 through 417-*n* (collectively referred to as a curved mirror 417 or curved mirrors 417). The optical elements 410 may be arranged between the mechanical alignment rods within the fiberless optical coupler 101, and are arranged to guide light waves to and from the fiber array (not shown) and elements, the details of which will be further described in FIG. 5.

[0042] It is noted that other types of mechanisms besides mechanical alignment rods may be used to ensure alignment. An example of such an alternative embodiment will be discussed with respect to FIG. 8.

[0043] FIG. 5 is a schematic side view of the fiberless optical coupler 101 on the PIC 102 according to an embodiment. The fiberless optical coupler 101 includes the optical

elements 410, which may include the waveguide 413, the deflector 415, and the curved mirror 417.

[0044] The waveguide 413 may be a polymeric or a silicon (Si) waveguide. When polymer is used for the waveguide 413, the polymer may be designed to match the single-mode fiber optics in terms of mode diameter. Also, the deflector 415 may be a reflective surface, preferably a tilted reflective surface.

[0045] The PIC 102 includes a second plurality of optical elements 510 for coupling with the wafer-level optics elements 410 of the fiberless optical coupler 101. The second plurality of optical elements 510 includes a curved mirror 513, a deflector 515, and a tapered polymer waveguide 517. In an embodiment, a silicon waveguide 517 may be used. The PIC 102 can also include an additional polymeric or a silicon waveguide 519. In some embodiments, the waveguide 519 may be coupled to the tapered polymer waveguide 517.

[0046] Optical elements 410, 510 may be "self-aligning," in the sense that the components of the optical elements 410, 510 are adjustable so that the beams of light are properly guided by the components from waveguide 201 to waveguide 519, and vice-versa. That is, the corresponding deflectors 415, 515, and curved mirrors 417, 513 within the respective fiberless optical coupler 101 and PIC 102 may be individually movable to adjust the path of the light beam from either the waveguide 201 or 519, to account for slight misalignment of the components during the manufacturing process. Therefore, adjustment of the optical elements 410, 510 allows for slight tolerance for misalignment during manufacturing.

[0047] Additionally, a spacer 520 may be included in between the fiberless optical coupler 101 and the PIC 102, for light from the waveguides 201, 517 to travel through after being reflected by the corresponding deflectors 415, 515 and curved mirrors 417, 513. The spacer 520 may be made of a transparent and non-conductive material, such as glass, polydimethylsiloxane, air, or any other index matching materials. The height of the spacer 520 determines, in part, the efficiency of the light beam (optical signal) that propagates through the spacer 520. In an exemplary and non-limiting embodiment, the height of the spacer 520 may be about 300 microns.

[0048] FIG. 6 is a schematic side view of the fiberless optical coupler 101 on the PIC that is attached to the fiber array 130, according to an embodiment. Here, the various components of the fiberless optical coupler 101, PIC, 102, and the spacer and the spacer 520 are substantially the same as that shown in FIG. 5, with the spacer 520. The fiberless optical coupler 101 is coupled to the optical connector 120 via the mechanical aligner 201, which houses the end tips of the fiber array 130.

[0049] The mechanical aligner 201 is arranged so that when the aligner 201 is inserted into the optical connector 120, the fiber array 130 is accurately aligned to the polymeric waveguide 413 with the same beam mode size within the fiberless optical coupler 101, with a space defined by the length of the mechanical aligner 201 in between the fiberless optical coupler 101 and the optical connector 120.

[0050] In an embodiment, the positioning of the mirrors 417, 513, and the deflectors, 415, 515 can be performed using a wafer level process such as, but not limited to, grayscale lithography. The mirrors 417 and 513, are placed and created during fabrication, which ensures high accuracy

positioning and accurate reflective mirrors. For example, the curved mirror **417**, deflector **415**, and waveguide **413** are all placed by wafer level process with high accuracy. On the PIC **102** side, waveguide **517**, deflector **515**, and curved mirror **513** are accurately placed by wafer level process.

[0051] As a non-limiting example, the fabrication process utilized to create the mirrors may include wafer level imprint lithography, and may include the use of a Silicon-On-Insulator (SOI), and Complementary Metal-Oxide Semiconductor (CMOS).

[0052] FIG. 7 is an example magnified schematic side view of the self-aligning optics, according to an embodiment. Here, the waveguide **413**, the deflector **415**, and the curved mirror **417** within the fiberless optical coupler **101**, which is herein described as a Photonic Plug (PP), and the curved mirror **513** and the deflector **515** within the PIC **102**, which is herein described as the photonic chip, are arranged in substantially the same way as that described in FIG. 5 and FIG. 6.

[0053] In an embodiment, as light beam is received at the waveguide **413** within the fiberless optical coupler **101** side, it is expanded and redirected by the deflector **415** at an angle to the curved mirror **513** at the PIC **102** side through a medium (not shown). The curved mirror **513** receives the expanded light beam and reflects the expanded light beam to the curved mirror **417** on back on the fiberless optical coupler **101** side. The curved mirror **417** then further reflects the expanded light beam to the deflector **515** back on the PIC **102** side, where the expanded light beam is collimated and further processed by the PIC **102**.

[0054] The arrangement described above allows for the separation of the fiber array **130** from the PIC **102**, thereby gaining high and relaxed alignment tolerances between the fiberless optical coupler **101** and PIC **102** (in three-dimensions). Also, the scalability of the disclosed fiberless optical coupler **101** is achieved due to its optical arrangement that provides high tolerance alignment and a passive positioning of the fiberless optical coupler **101**, thus aligning the optical fiber with respect to the PIC. Therefore, the disclosed fiberless optical coupler **101** can be mass-produced. In certain embodiments, the disclosed fiberless optical coupler **101** further allows for compact and secured packaging of PICs.

[0055] FIG. 8 is a schematic side view of the electro-optical interconnection platform **100**

[0056] According to an embodiment. An MCM **103** is shown along with the PIC **102** including an SOI wafer **820** mounted on a socket **830**, the socket **310** being coupled to the MCM **103**. The fiberless optical coupler **101** is located on the PIC **102**, with the fiberless optical coupler **101** coupled to the fiber array **130**. The fiberless optical coupler **101** includes a first set of optical elements **410**, and the SOI wafer **820** includes a second set of optical elements **510**. Each of the first and second sets of the optical elements **410**, **450** have similar components as described in FIGS. 4 and 5.

[0057] In an embodiment, the mechanical aligner **201** previously described in FIG. 1 is configured as a Mechanical Optical Device (MOD) **840** located between the fiberless optical coupler **101** and the PIC **102**. The first set of optical elements **410** and the second set of optical elements **510** are aligned with the fiber array **130**, via the MOD **840**, in order for light to transmit in between the fiber array **130** and the PIC **102** through the sets of the optical elements **410, 510**.

[0058] In the embodiment, the MOD **840** allows light to pass through between the sets of the optical elements **410, 510** within the fiberless optical coupler **101** and the PIC **102**. Also, the MOD **840** further includes V-shaped grooves **850** that receive the fiberless optical coupler **101**, so that the optical elements **410**, **510** are in alignment with the fiber array **130** when receiving light transmitted to and from the fiber array **130**. That is, the V-shaped grooves **850** ensures a later aligned placement of additional optical elements **410** included in the fiberless optical coupler **101**.

[0059] Also, the optical elements **510** may be formed on the SOI wafer **820** as a bump via a wafer level process, and may include various expansion and collimating optics, including the mirror **513**, deflector **515**, and waveguide **517** described in FIG. 5.

[0060] FIG. 9 is an example flowchart **900** of a method of manufacturing an electro-optical interconnection platform **100**, according to an embodiment. At S910, the PIC **102** is formed, in which the laser source **116** is also formed on the PIC **102**. Next, at S920, the second optical elements **510** are formed on the PIC **102**, while the optical elements **410** are separately formed on the fiberless optical coupler **101**. Further, at S940, a mechanical aligner **201** is formed.

[0061] Additionally, at S940, the PIC **102** is coupled on the MCM **103**, and at S950, the MCM **103** is coupled on the PCB **301**. Next, at S960, the fiberless optical coupler **101** is coupled to the PIC **102**, and at S970, the fiberless optical coupler **101** is coupled to the fiber array **130**.

[0062] With the method **900** above, a flip-chip assembly process may be used to employed to couple components of the PIC **102** together (e.g., coupling SOI wafer with the socket) and with other elements, and coupling the mechanical aligner **201** to the PIC **102** or the fiberless optical coupler **101**. This ensures accurate placement of the optics on the PIC **102**. Also, when the MOD **840** is used, additional accuracy in aligning optical elements **410, 510**, along with added optical functionality of the MOD **840** may be achieved.

[0063] FIG. 10 is a schematic side view of the electro-optical interconnection platform **100** according to an embodiment. Here, the components of the platform **100** are arranged in substantially the same way as depicted in FIG. 8. However, the optical elements **510** that were previously located within the PIC **102** are instead formed within the MOD **840**. By having the optical elements **510** formed in the MOD **840**, further alignment of the optical components may be assured, and the MOD **840** may be given additional optical functionality besides being just a medium or spacer that provides merely mechanical alignment between the various optical elements **410**, **510** and the fiber array **130**.

[0064] All examples and conditional language recited herein are intended for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

[0065] It should be understood that any reference to an element herein using a designation such as “first,” “second,” and so forth does not generally limit the quantity or order of those elements. Rather, these designations are generally used herein as a convenient method of distinguishing between two or more elements or instances of an element. Thus, a reference to first and second elements does not mean that only two elements may be employed there or that the first element must precede the second element in some manner. Also, unless stated otherwise, a set of elements comprises one or more elements.

[0066] As used herein, the phrase “at least one of” followed by a listing of items means that any of the listed items can be utilized individually, or any combination of two or more of the listed items can be utilized. For example, if a system is described as including “at least one of A, B, and C,” the system can include A alone; B alone; C alone; 2A; 2B; 2C; 3A; A and B in combination; B and C in combination; A and C in combination; A, B, and C in combination; 2A and C in combination; A, 3B, and 2C in combination; and the like.

1. An apparatus, comprising:
  - a first photonic substrate comprising one or more first optical elements comprising:
    - a waveguide, and
    - a first curved mirror;
  - a second photonic substrate optically coupled to the first photonic substrate, the second photonic substrate comprising one or more second optical elements comprising:
    - a second curved mirror; and
  - a mechanical aligner of the first photonic substrate configured to receive an optical fiber connector and configured to align an optical fiber with the first optical elements to transmit light between the optical fiber and the second photonic substrate via the first and second optical elements.
2. The apparatus of claim 1, wherein the one or more first optical elements further comprise a deflector configured to redirect the light to the second curved mirror of the second photonic substrate.
3. The apparatus of claim 2, wherein the deflector is further configured to expand the light.
4. The apparatus of claim 1, wherein the one or more second optical elements further comprise a deflector of the second photonic substrate configured to redirect the light received from the first curved mirror.
5. The apparatus of claim 4, wherein the one or more second optical elements further comprise a tapered waveguide configured to receive the light from the deflector of the second photonic substrate.
6. The apparatus of claim 1, wherein the mechanical aligner extends from the first photonic substrate to engage and align the received optical fiber connector.
7. The apparatus of claim 1, wherein the optical fiber connector comprises an electrical-optical connector, and wherein the first photonic substrate is configured to electrically and optically interface with the optical fiber connector.
8. The apparatus of claim 1, wherein the first curved mirror is horizontally and vertically offset from the second curved mirror.

9. An apparatus, comprising:
  - a first photonic substrate comprising one or more first optical elements comprising:
    - a waveguide, and
    - a first curved mirror,
  - wherein, the one or more first optical elements are configured to optically connect to one or more second optical elements, comprising a second curved mirror, of a second photonic substrate; and
  - a mechanical aligner of the first photonic substrate configured to receive an optical fiber connector and configured to align an optical fiber with the waveguide to transmit light between the optical fiber and the first optical elements.
10. The apparatus of claim 9, wherein the one or more first optical elements further comprise a deflector configured to redirect the light to the second curved mirror of the second photonic substrate.
11. The apparatus of claim 10, wherein the deflector is further configured to expand the light.
12. The apparatus of claim 9, wherein the mechanical aligner extends from the first photonic substrate to engage and align the received optical fiber connector.
13. The apparatus of claim 9, wherein the optical fiber connector comprises an electrical-optical connector, and wherein the first photonic substrate is configured to electrically and optically interface with the optical fiber connector.
14. The apparatus of claim 9, wherein the first curved mirror is configured to be vertically and horizontally offset from the second curved mirror.
15. An apparatus, comprising:
  - a first photonic substrate comprising one or more first optical elements comprising one or more first reflective elements,
  - wherein, the one or more first optical elements are configured to optically connect to one or more second optical elements, comprising one or more second reflective elements, of a second photonic substrate; and
  - a mechanical aligner of the first photonic substrate configured to receive an optical fiber connector and configured to align an optical fiber with the one or more first optical elements to transmit light between the optical fiber and the one or more first optical elements.
16. The apparatus of claim 15, wherein the one or more first reflective elements comprise a curved mirror of the first photonic substrate and a deflector of the first photonic substrate, each of the curved mirror of the first photonic substrate and the deflector of the first photonic substrate configured to interface the light with the one or more second optical elements.
17. The apparatus of claim 15, wherein the one or more second optical elements comprise a curved mirror of the second photonic substrate and a deflector of the second photonic substrate.
18. The apparatus of claim 15, wherein the mechanical aligner extends from the first photonic substrate to engage and align the received optical fiber connector.
19. The apparatus of claim 15, wherein the optical fiber connector comprises an electrical-optical connector, and wherein the first photonic substrate is configured to electrically and optically interface with the optical fiber connector.
20. The apparatus of claim 15, wherein the one or more first reflective elements comprise a first curved mirror and wherein the one or more second reflective elements com-



prise a second curved mirror, and wherein the first curved mirror is configured to be vertically and horizontally offset from the second curved mirror.

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