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(54) OFFLOADING PHOTONIC INTEGRATED CIRCUIT FUNCTIONALITY INTO OPTICAL INTERCONNECTS

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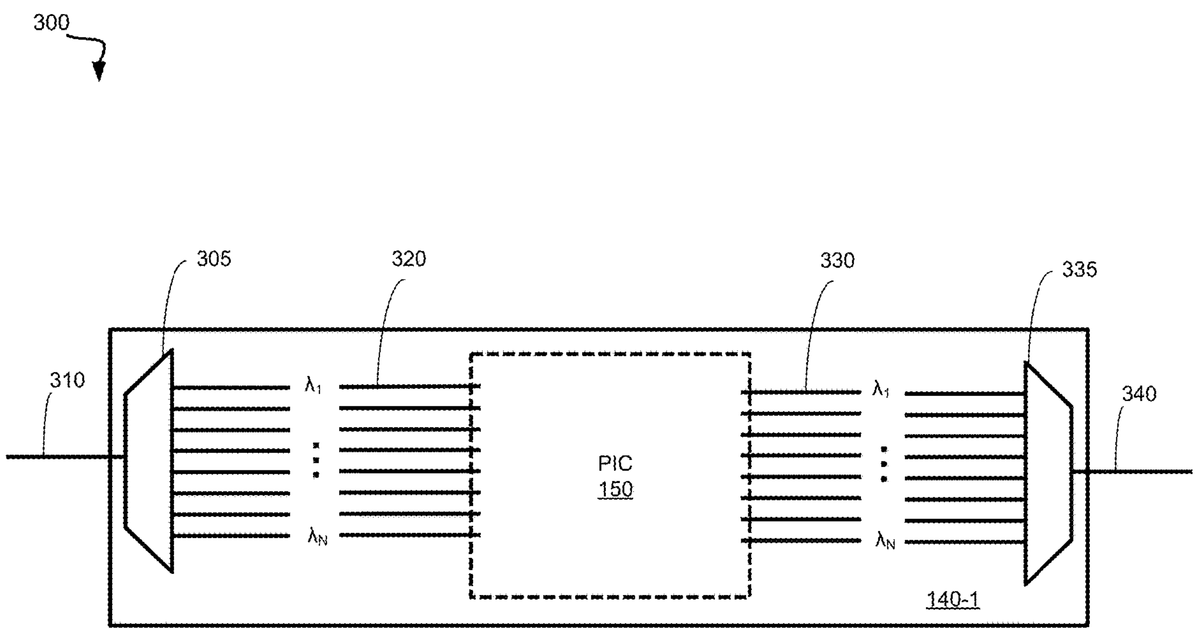
(57) **ABSTRACT**

A system includes an interconnect including at least one power splitter; and a photonic integrated circuit (PIC) disposed on the interconnect, the PIC including at least one set of modulators.



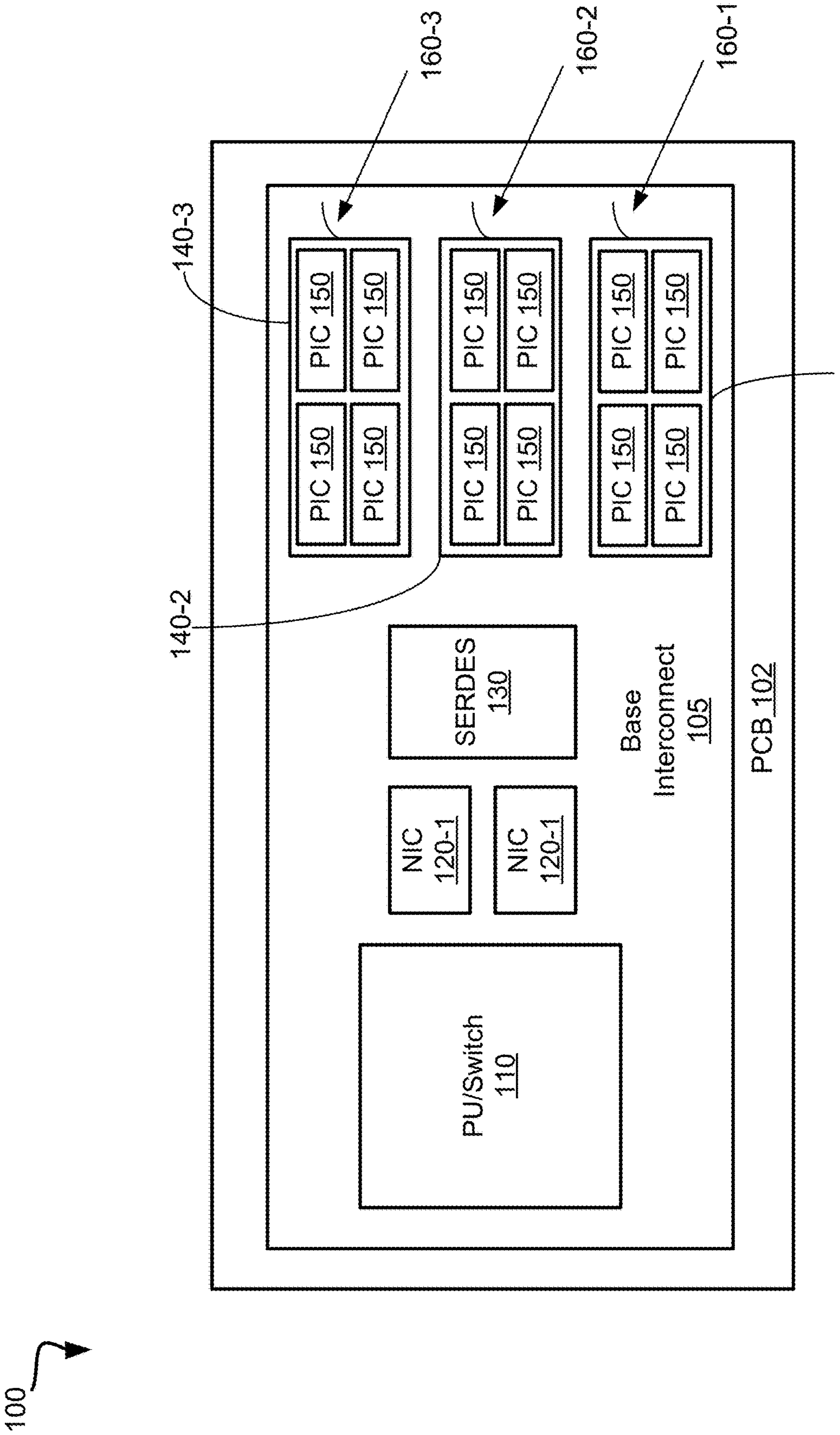
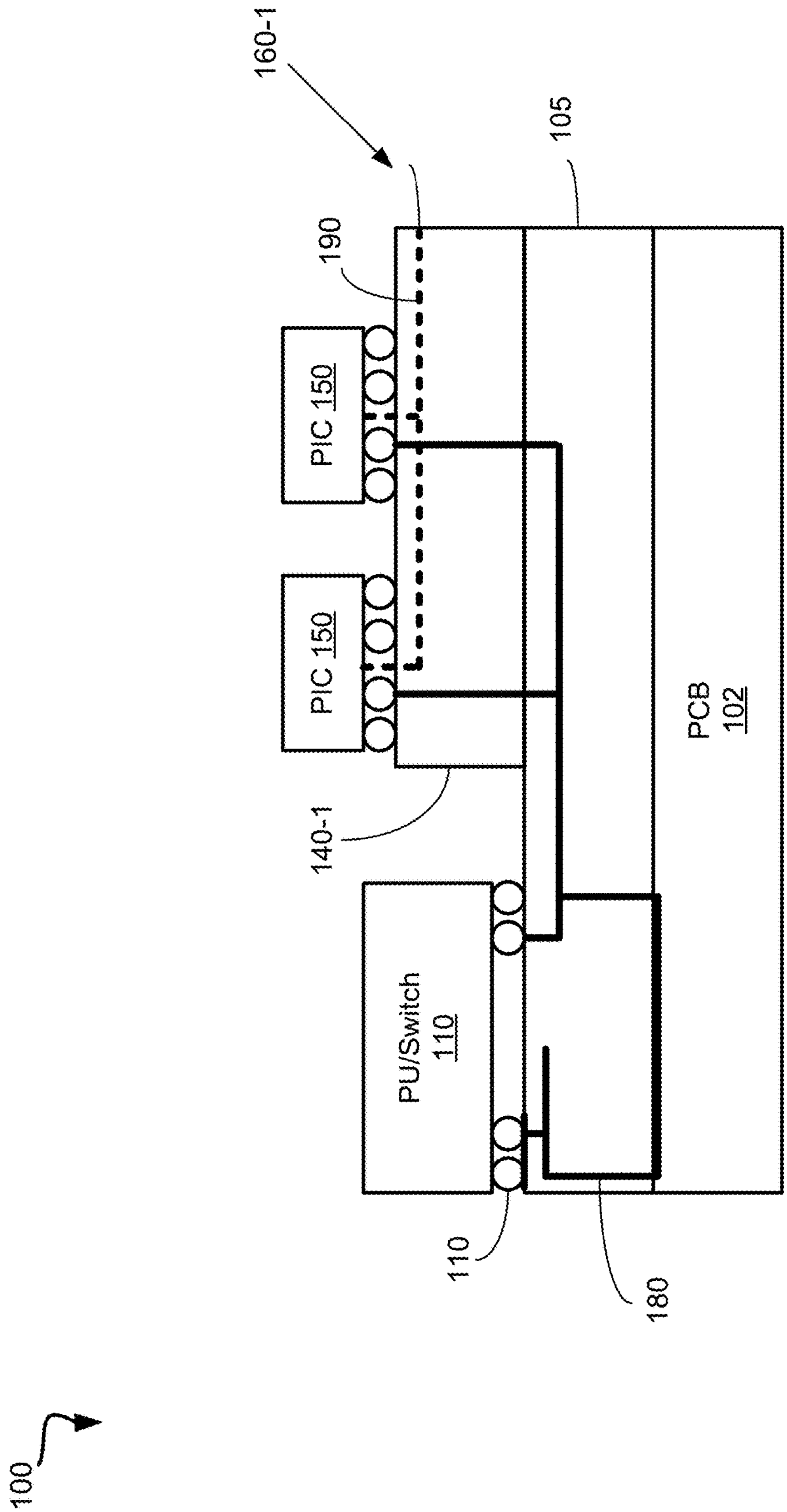

160-3
160-2
160-1
140-3
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
PIC 150
140-1
140-2
SERDES 130
Base Interconnect 105
PCB 102
NIC 120-1
NIC 120-1
PU/Switch 110
100

FIG. 1A



160-1
105
190
PIC 150
PIC 150
PCB 102
140-1
PU/Switch 110
110
180
100

FIG. 1B

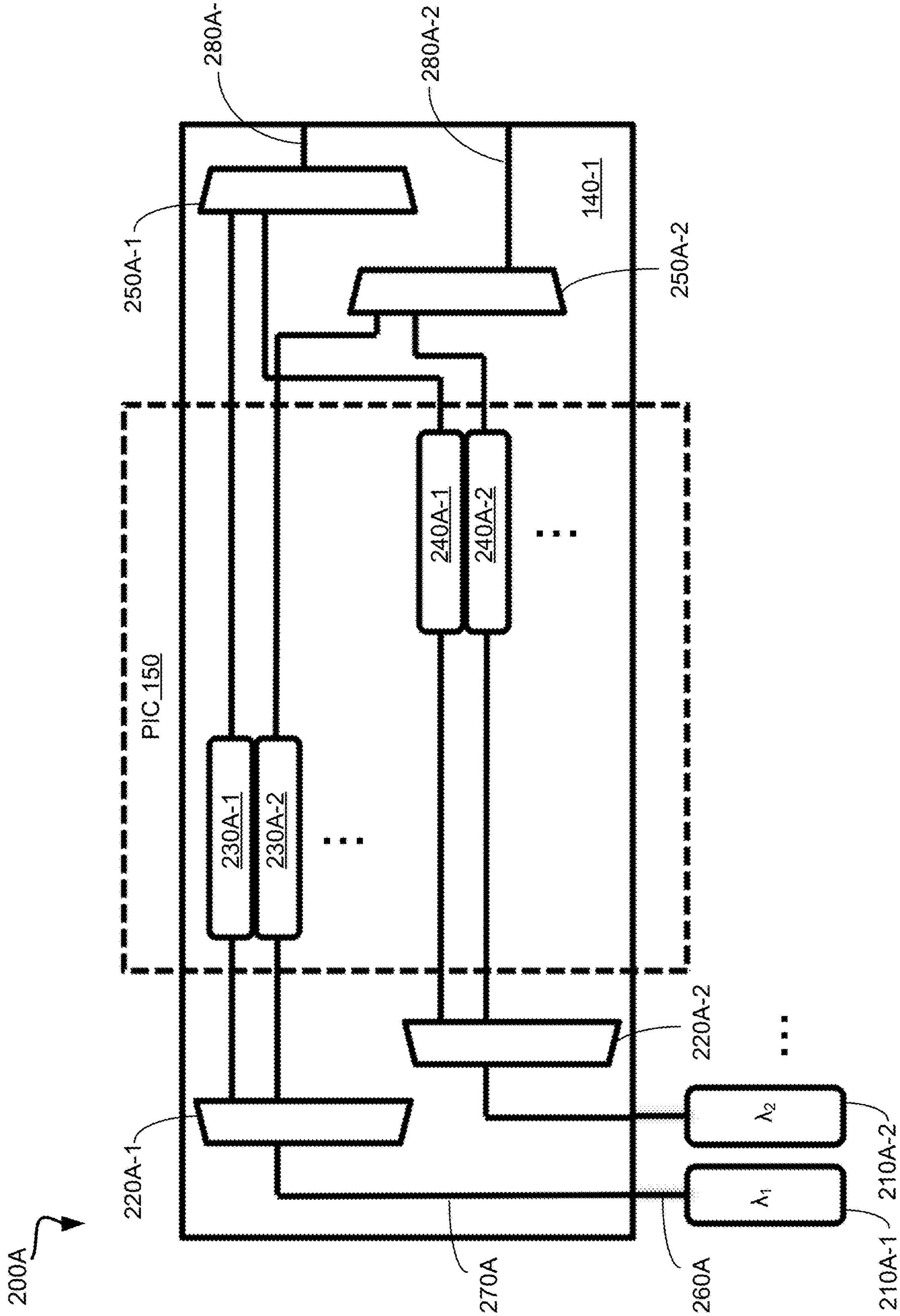

200A
280A-1
280A-2
140-1
250A-1
250A-2
PIC 150
230A-1
230A-2
240A-1
240A-2
220A-1
220A-2
λ_1
λ_2
210A-1
210A-2
270A
260A

FIG. 2A

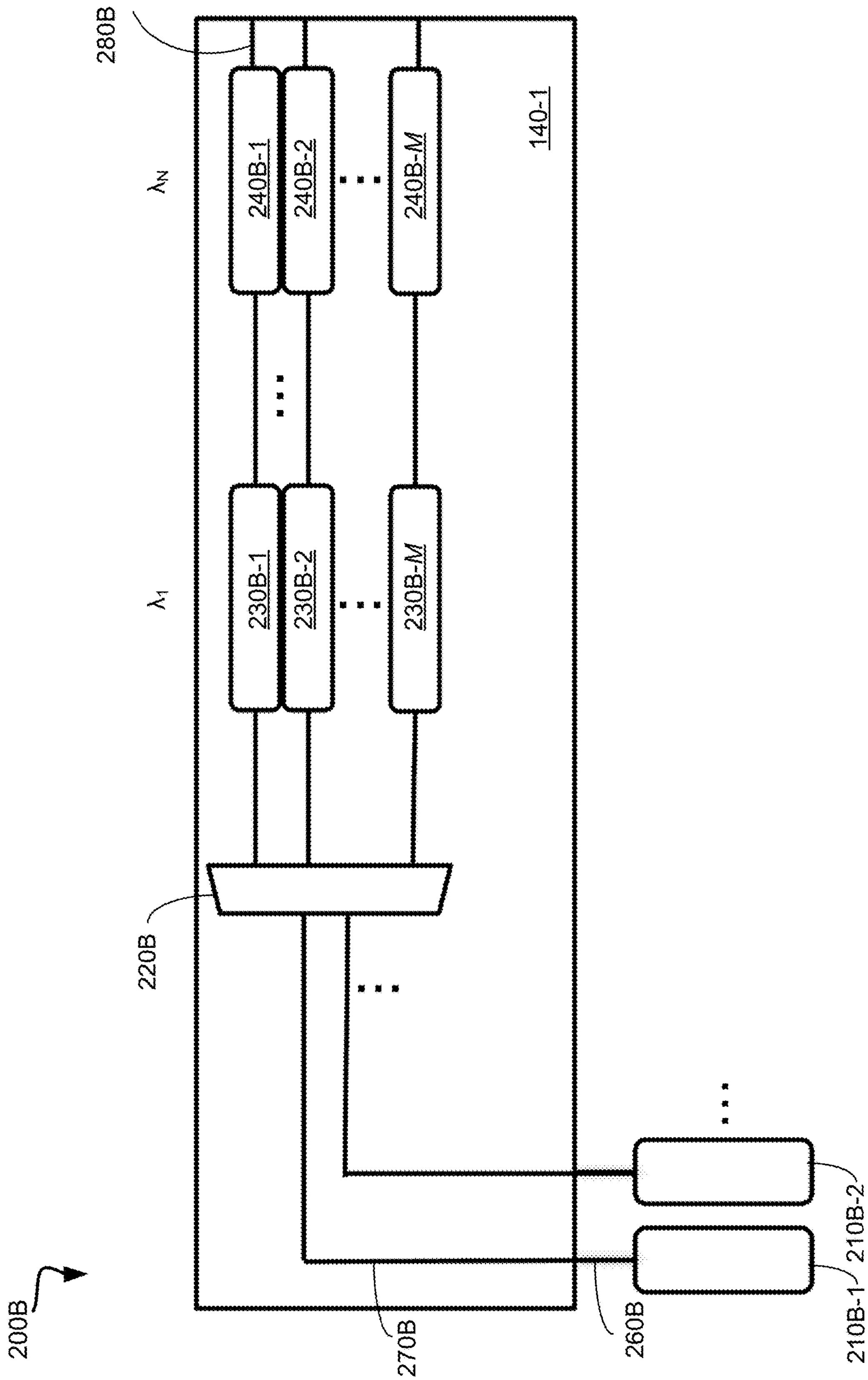

200B
280B
λ_N
λ_1
240B-1
240B-2
240B-M
230B-1
230B-2
230B-M
140-1
220B
270B
260B
210B-1
210B-2

FIG. 2B

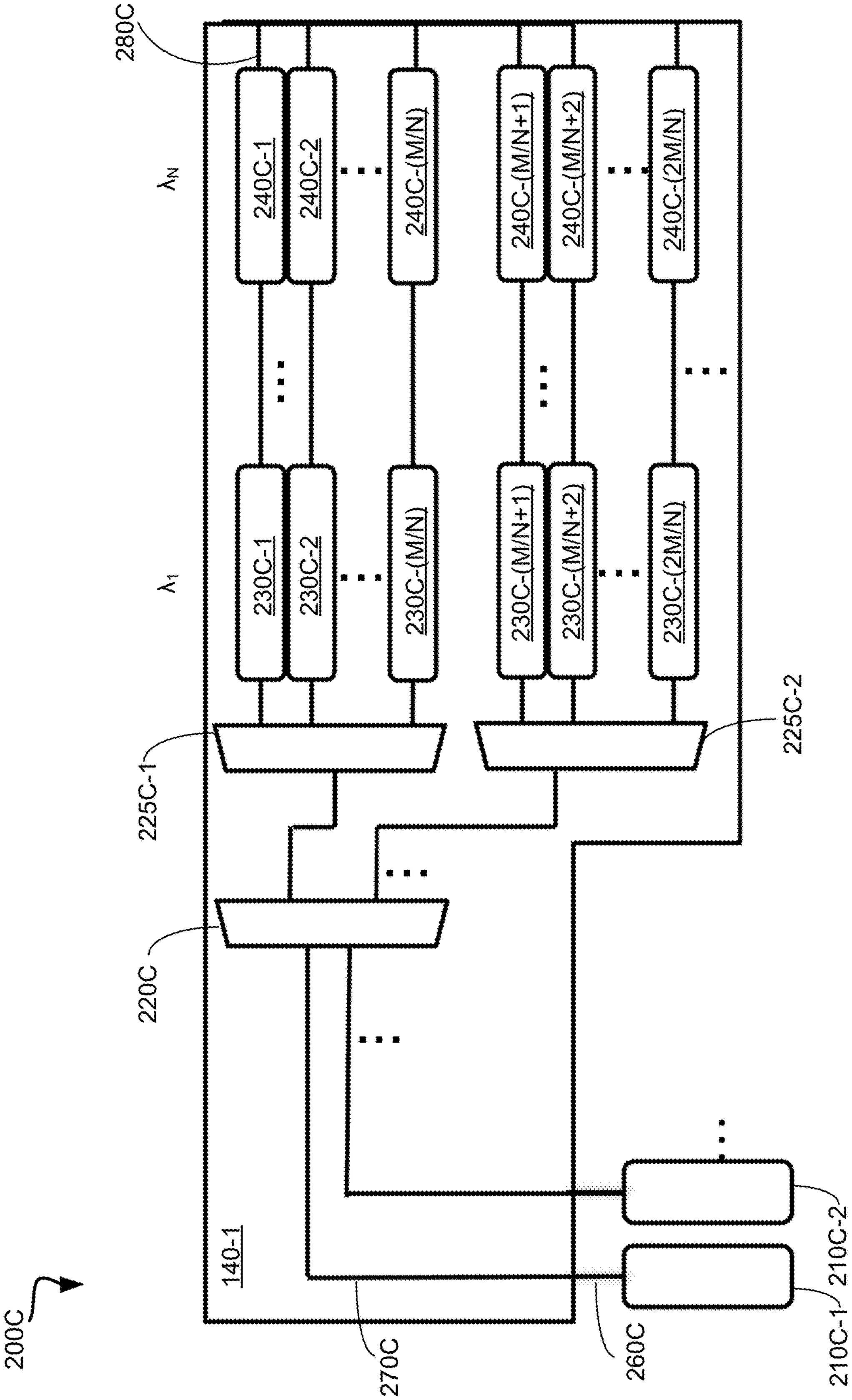

200C
140-1
280C
λ_N
λ_1
240C-1
240C-2
240C-(M/N)
240C-(M/N+1)
240C-(M/N+2)
240C-(2M/N)
230C-1
230C-2
230C-(M/N)
230C-(M/N+1)
230C-(M/N+2)
230C-(2M/N)
225C-1
225C-2
220C
210C-1
210C-2
260C
270C

FIG. 2C

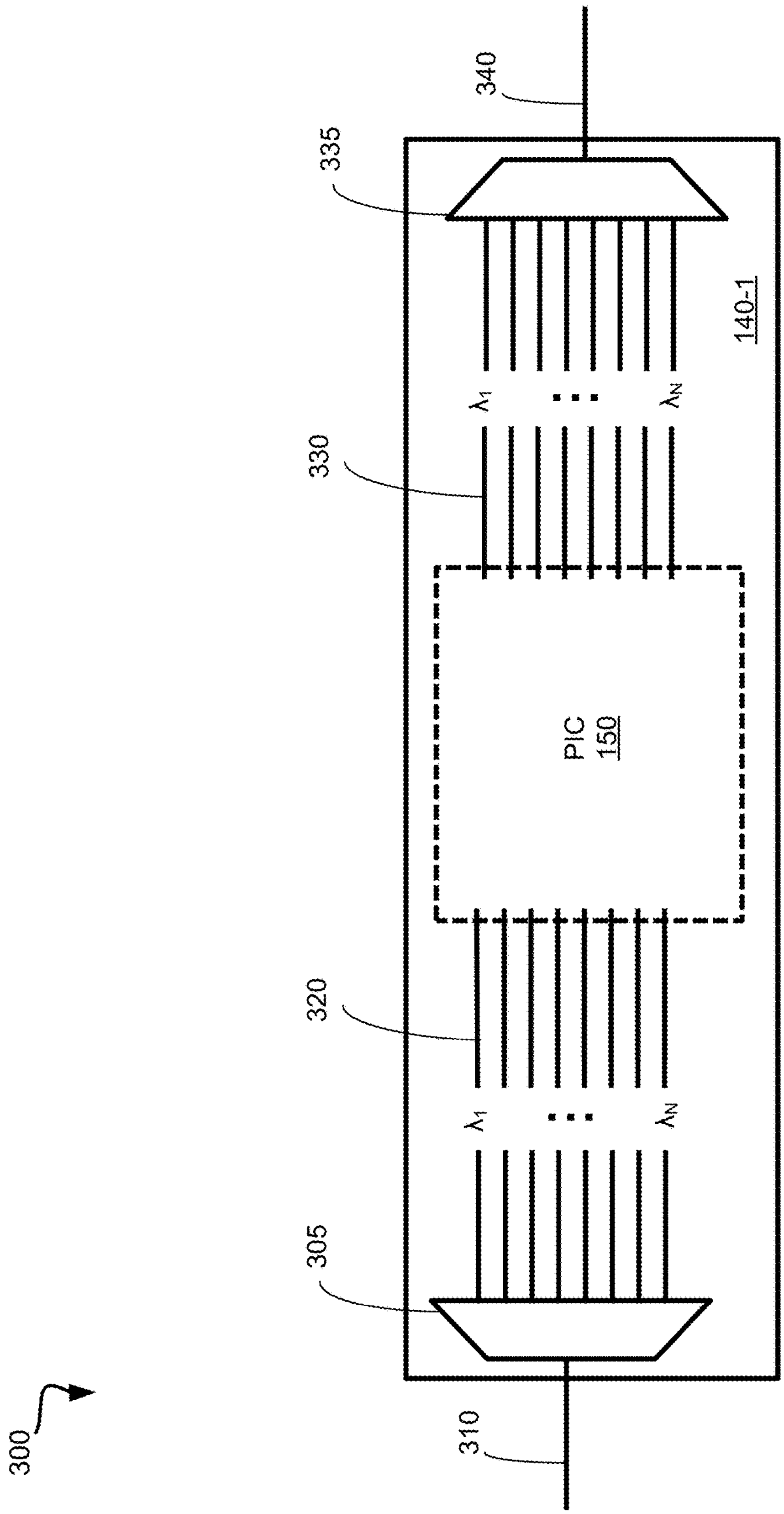


FIG. 3

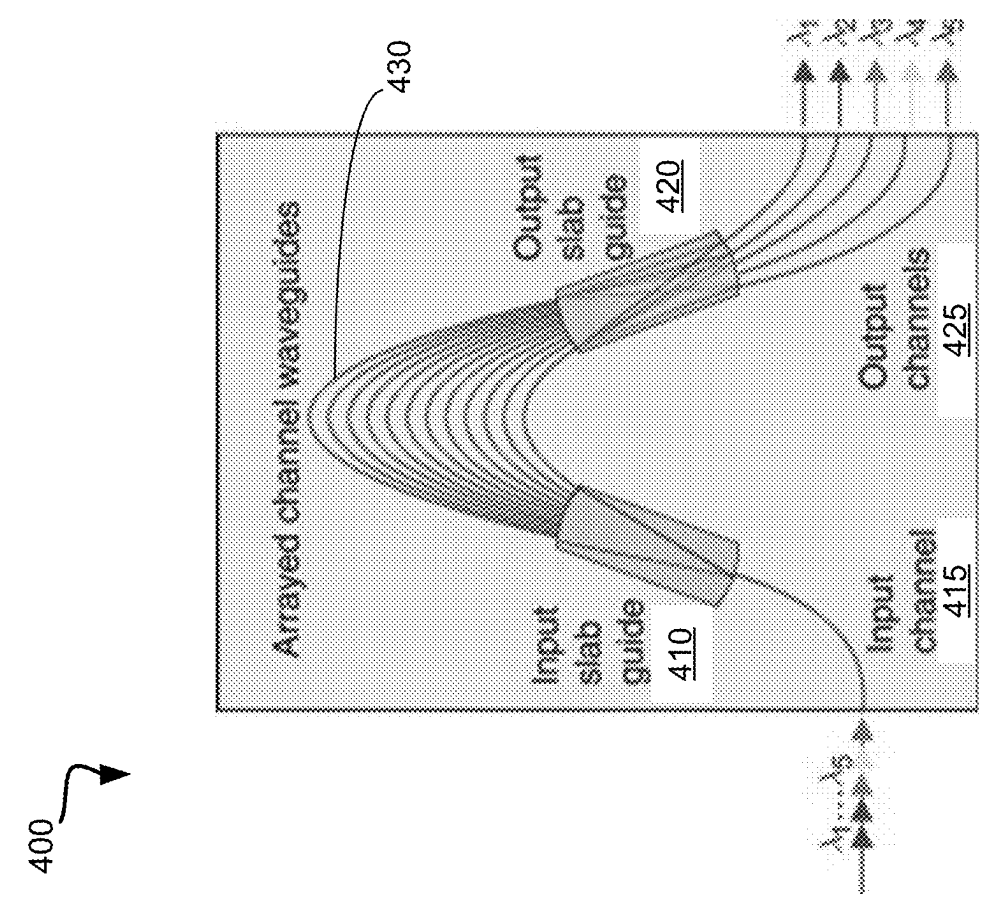

400
Arrayed channel waveguides
430
Input slab guide 410
Input channel 415
Output slab guide 420
Output channels 425

FIG. 4A

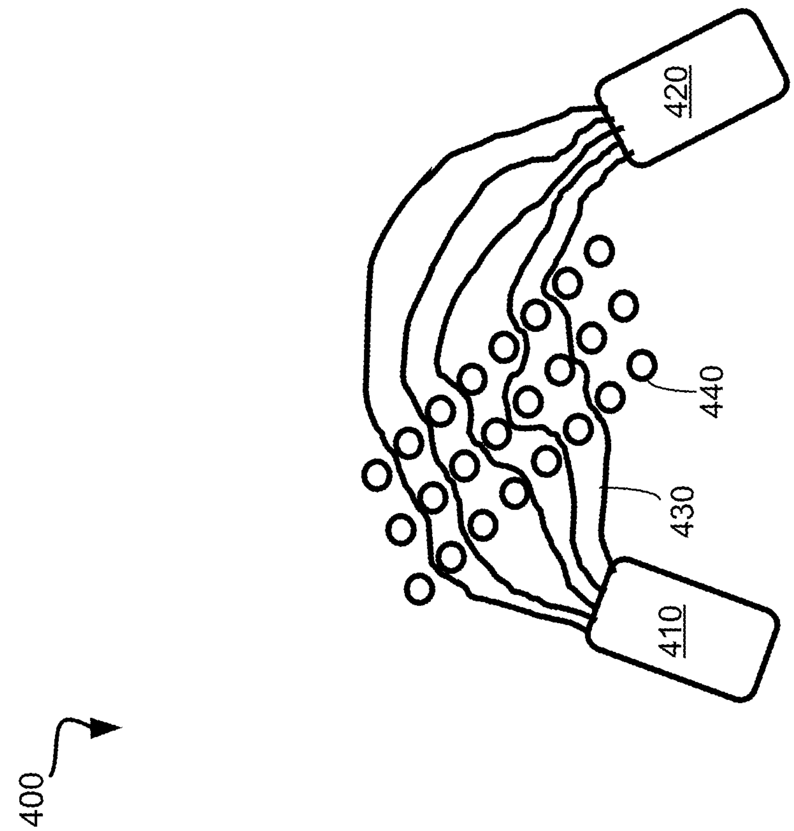

400
420
410
430
440

FIG. 4B

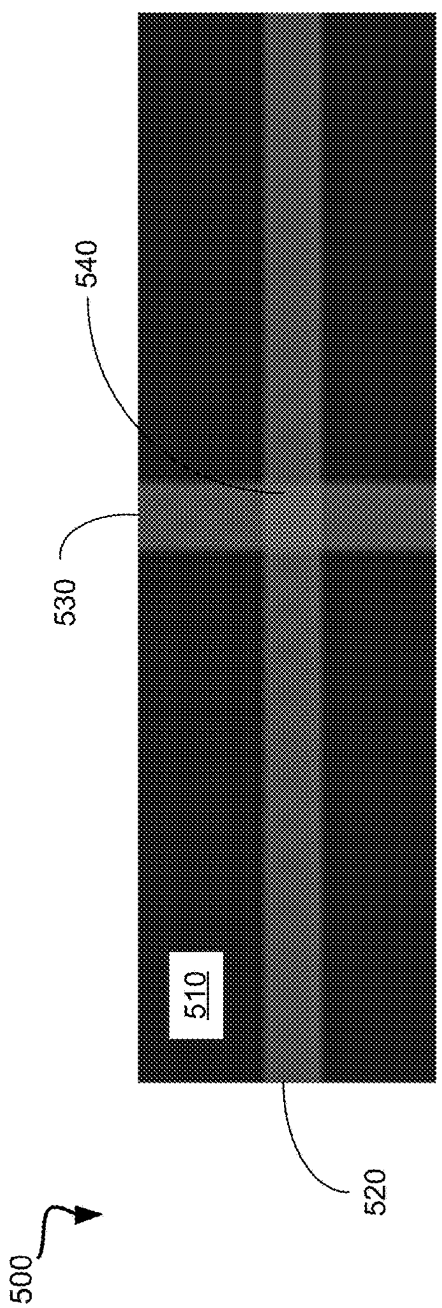


FIG. 5

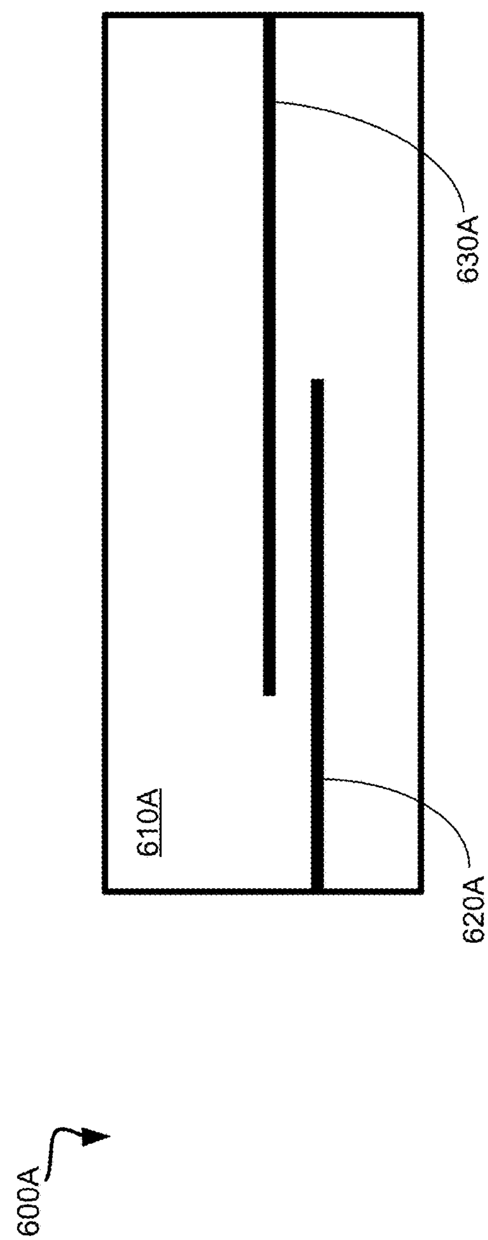


FIG. 6A

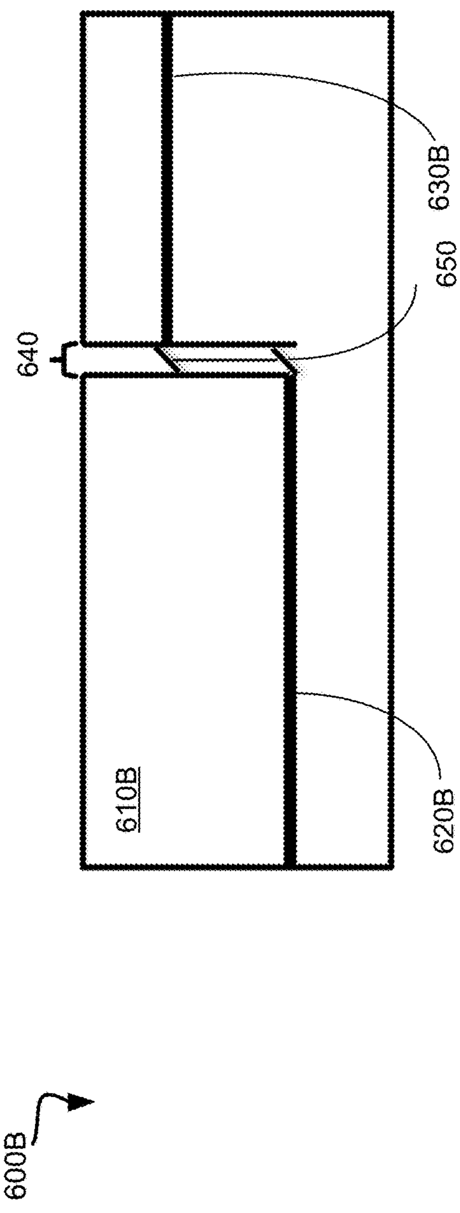


FIG. 6B

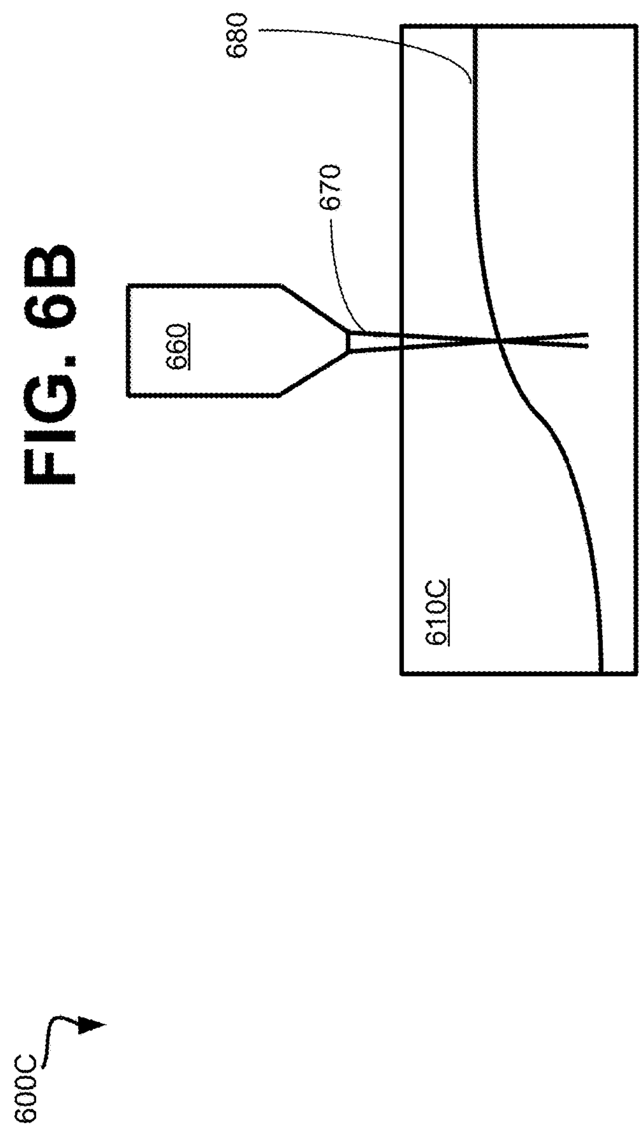


FIG. 6C

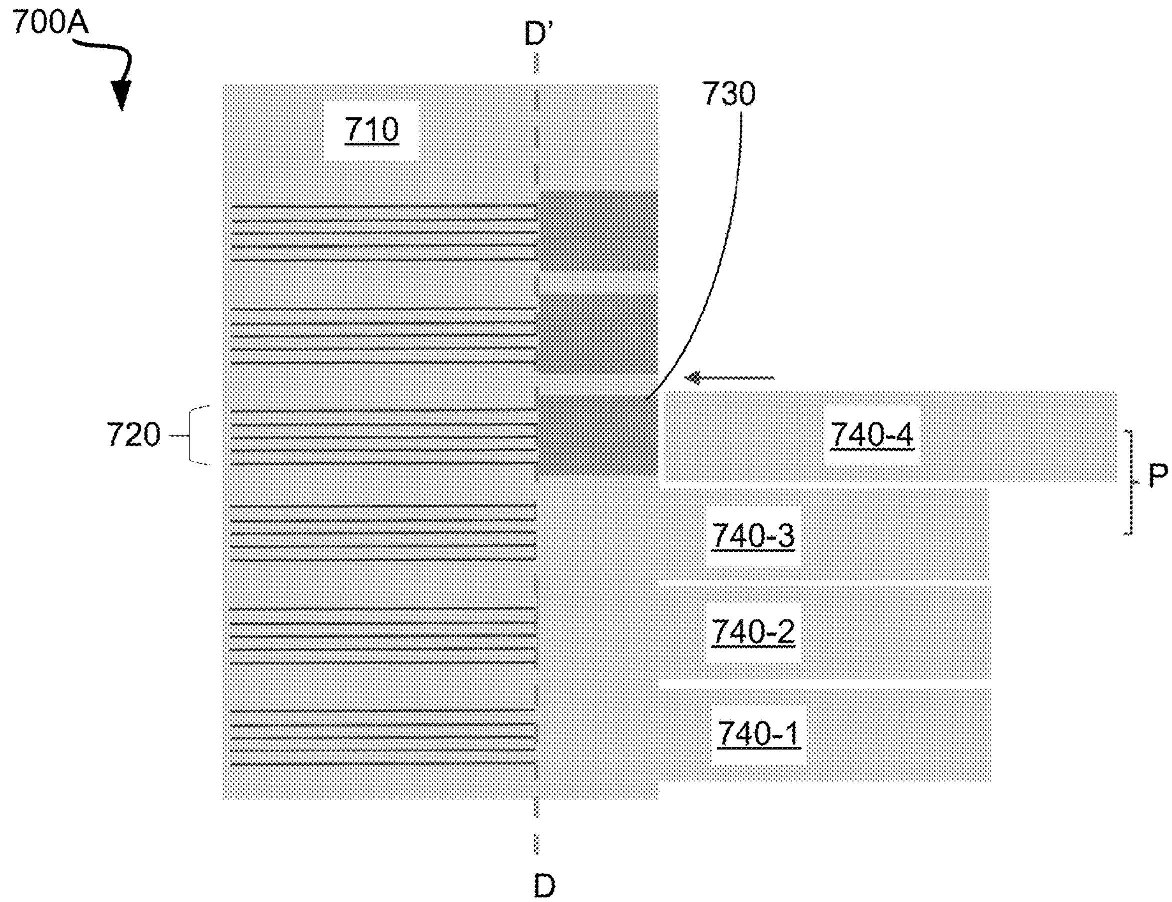

700A
D'
710
730
720
740-4
P
740-3
740-2
740-1
D

FIG. 7A

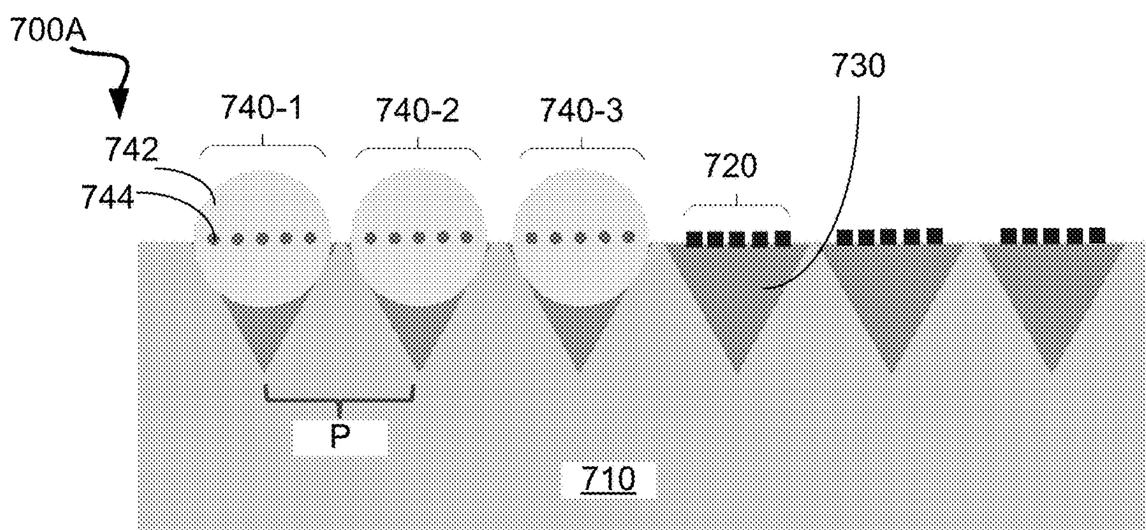

700A
740-1
740-2
740-3
730
742
720
744
P
710

FIG. 7B

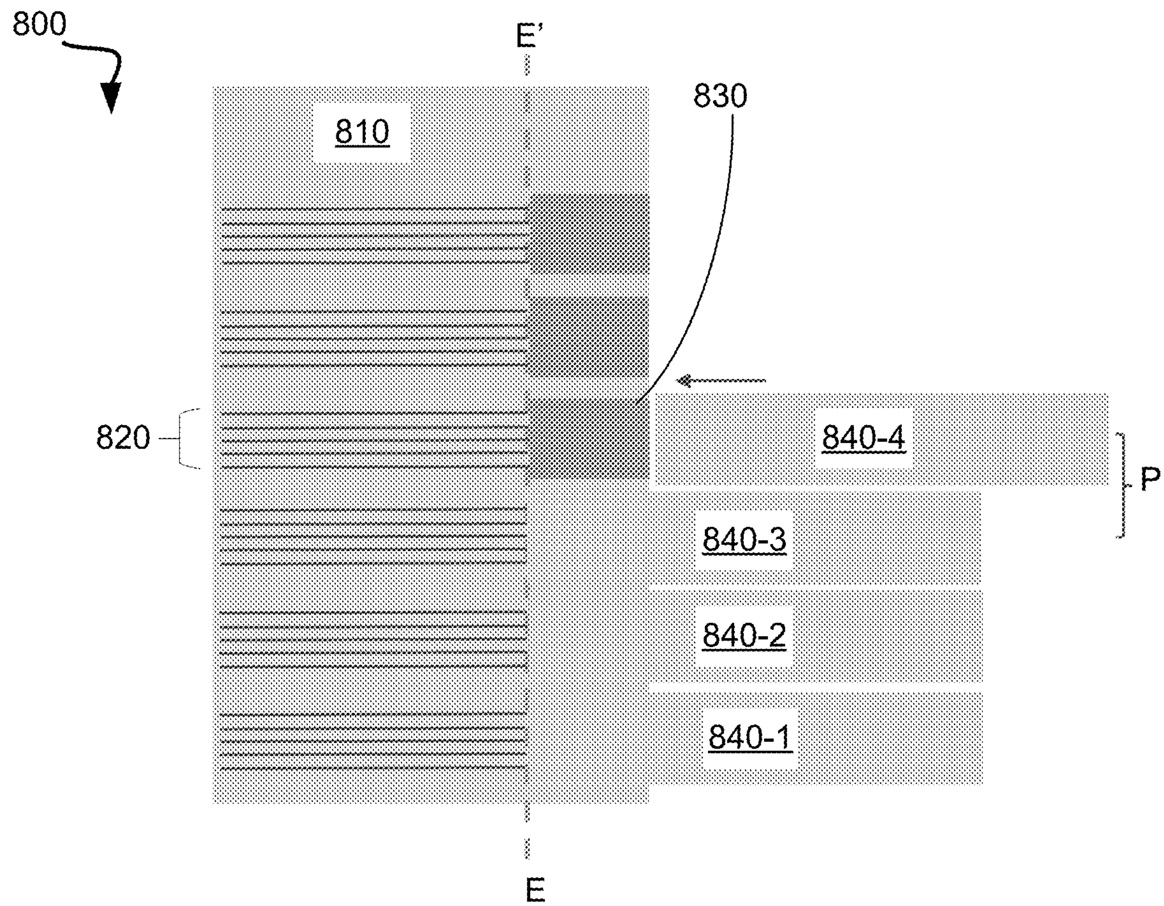

800
E'
810
830
820
840-4
P
840-3
840-2
840-1
E

FIG. 8A

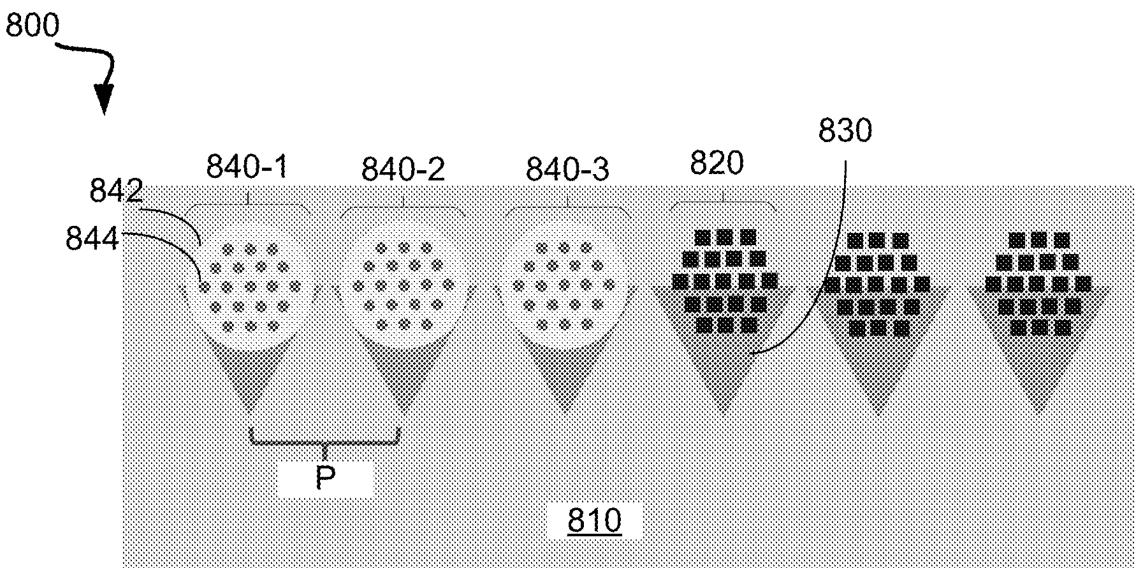

800
842
844
840-1
840-2
840-3
820
830
P
810

FIG. 8B

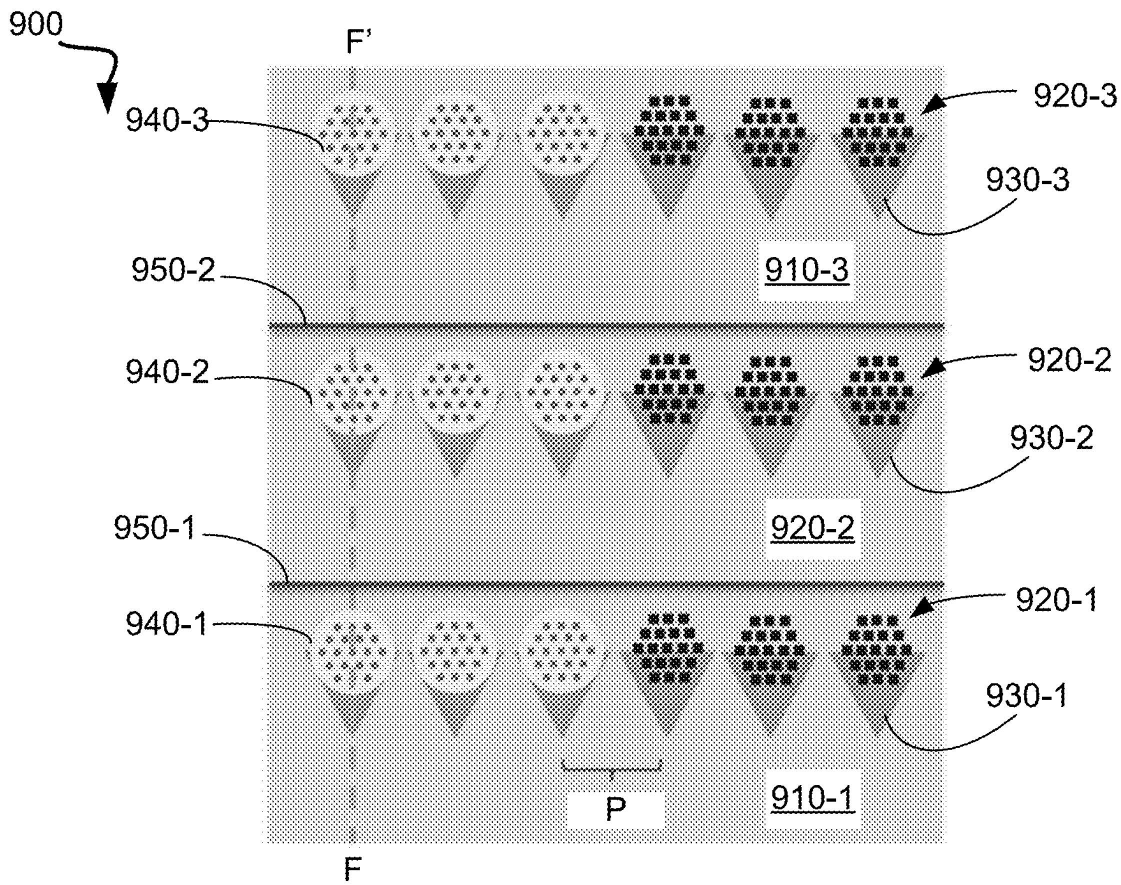

900
F'
940-3
920-3
930-3
910-3
950-2
940-2
920-2
930-2
920-2
950-1
940-1
920-1
930-1
P
910-1
F

FIG. 9A

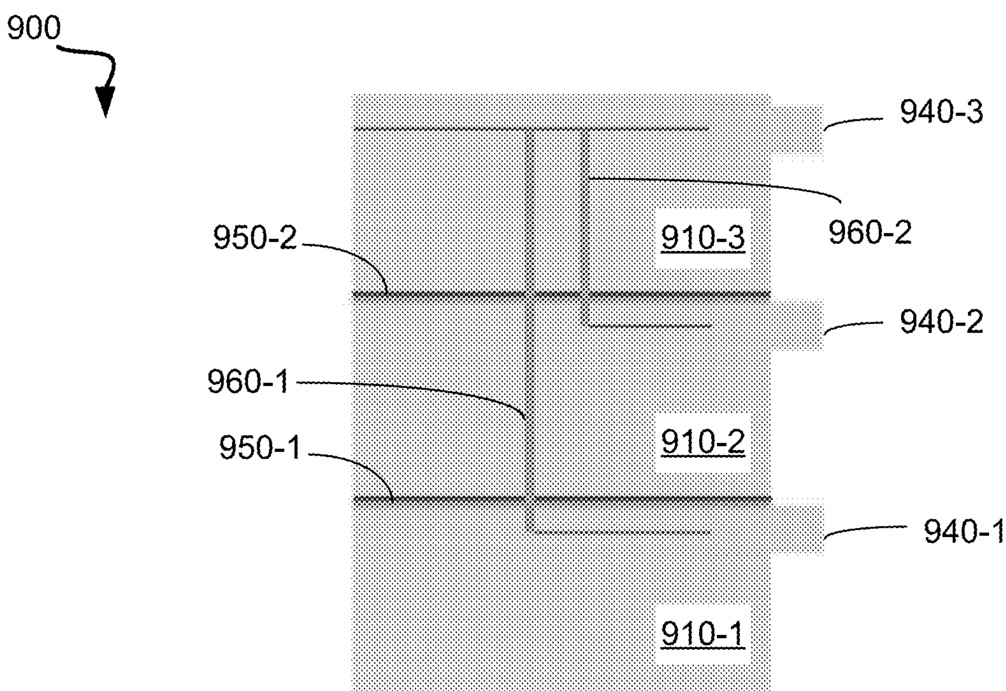

900
940-3
960-2
950-2
910-3
940-2
960-1
910-2
950-1
940-1
910-1

FIG. 9B

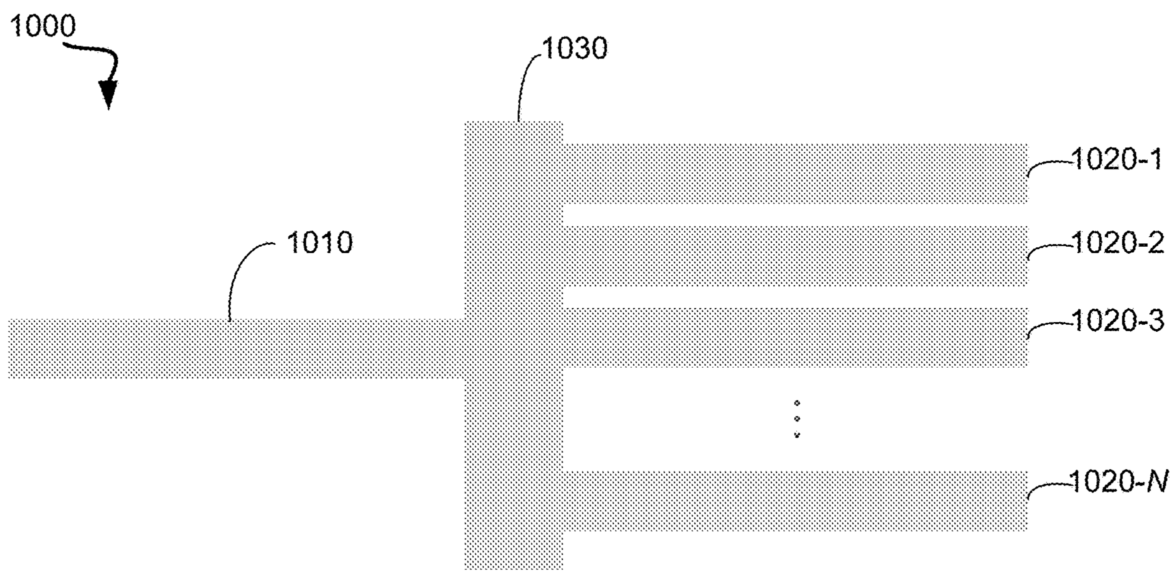


FIG. 10A

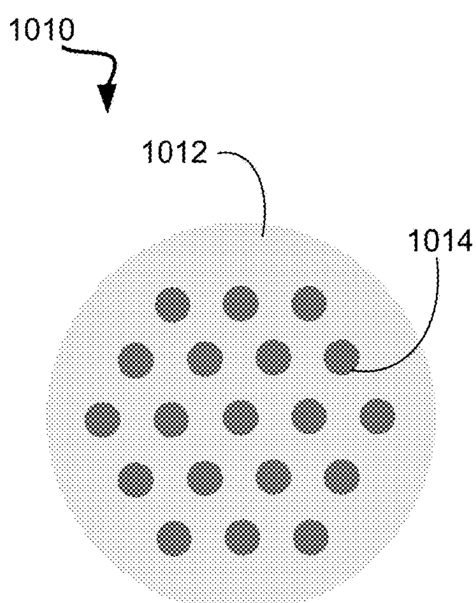


FIG. 10B

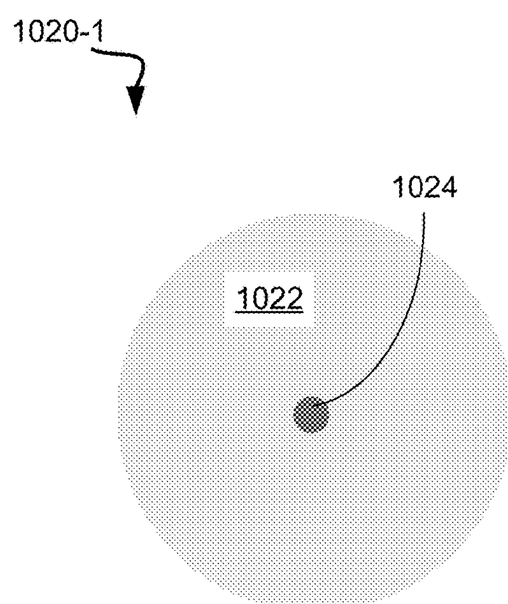


FIG. 10C

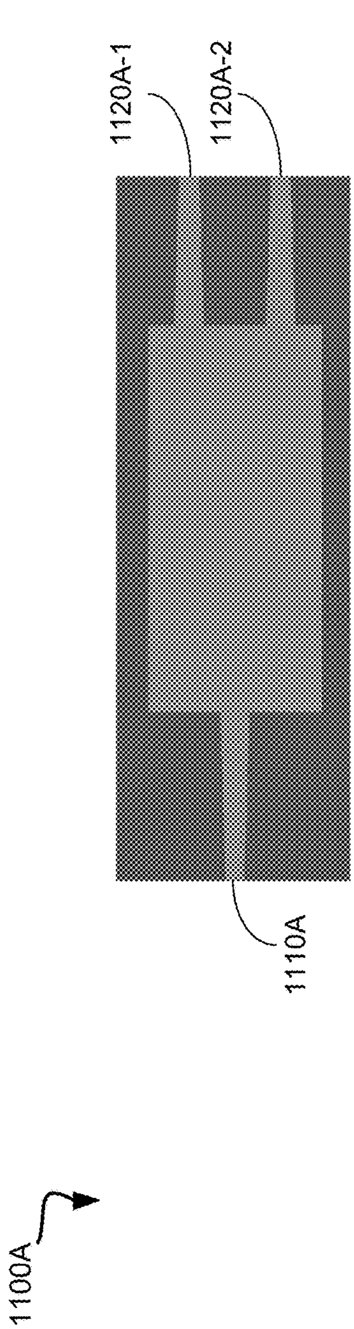


FIG. 11A

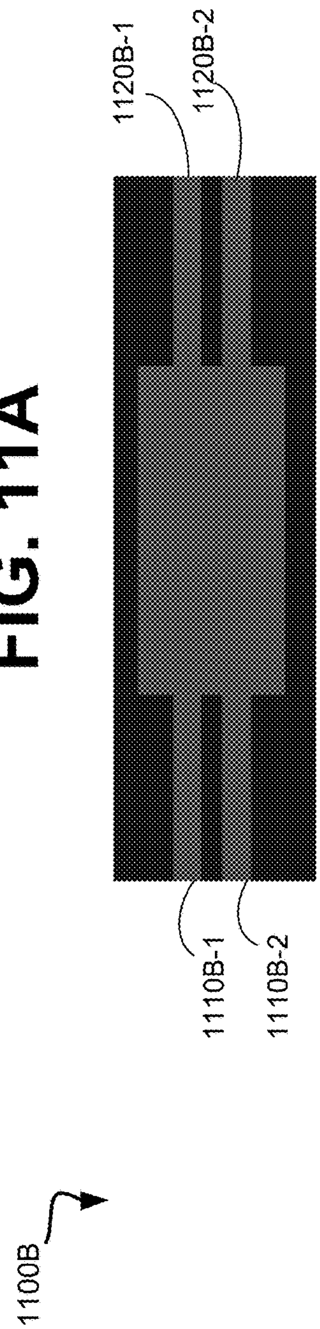


FIG. 11B

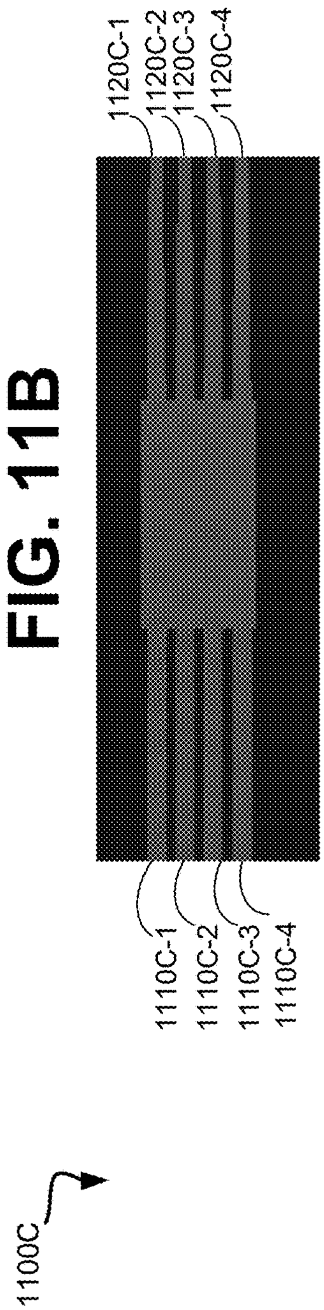


FIG. 11C

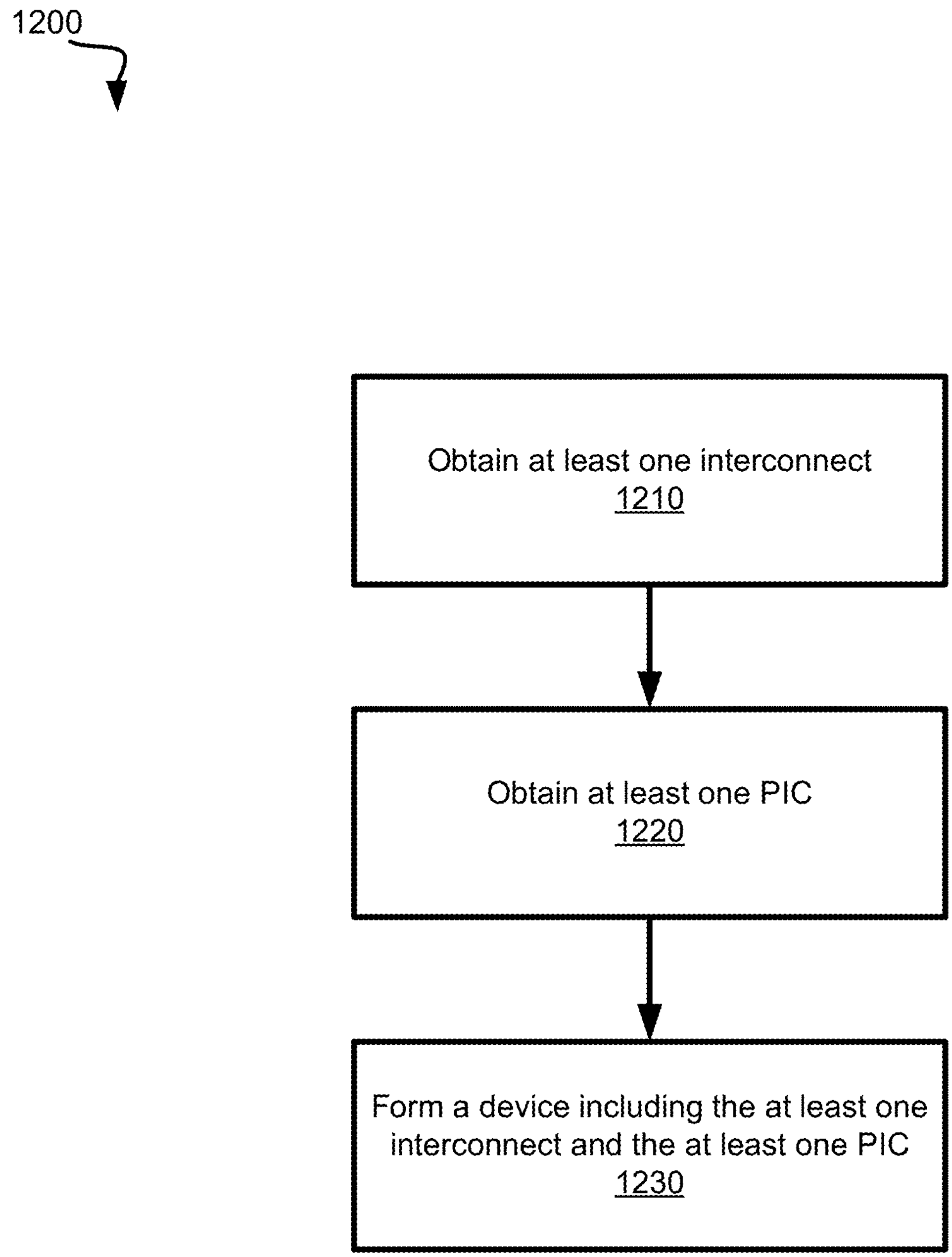

1200
Obtain at least one interconnect
1210
Obtain at least one PIC
1220
Form a device including the at least one interconnect and the at least one PIC
1230

FIG. 12

OFFLOADING PHOTONIC INTEGRATED CIRCUIT FUNCTIONALITY INTO OPTICAL INTERCONNECTS

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] The present application claims priority to U.S. Provisional Patent Application No. 63/556,092, filed on Feb. 21, 2024 and entitled "OFFLOADING PHOTONIC INTEGRATED CIRCUIT FUNCTIONALITY ONTO OPTICAL INTERCONNECTS", the entire contents of which are hereby incorporated by reference herein.

TECHNICAL FIELD

[0002] Embodiments of the present disclosure relate to optical systems, and more particularly to offloading photonic integrated circuit (PIC) functionality into optical interconnects (e.g., interposers).

BACKGROUND

[0003] A co-packaged device (e.g., multi-chip module) can include a package substrate having multiple integrated circuit devices assembled closely together. More specifically, optical components can be integrated on substrates (e.g., silicon (Si) substrate) for fabricating large-scale PICs that co-exist with micro-electronic chips. With the use of an optical transceiver, received optical signal can be converted to an electrical signal capable of being processed by an integrated circuit, or the processed electrical signal can be converted to an optical signal to be transmitted via an optical fiber.

[0004] A co-packaged device can include an interconnect device ("interconnect") disposed between a first component and a second component. For example, an interconnect can be a placed between a package substrate and a ball grid array. In some implementations, an interconnect includes an interposer. An interposer is an electrical interface that routes connections between sockets or connections between the first component and the second component. An interposer can be used to connect components that may not naturally connect to one another.

SUMMARY

[0005] In some embodiments, a system is provided. The system includes an interconnect including at least one power splitter; and a photonic integrated circuit (PIC) disposed on the interconnect, the PIC including at least one set of modulators.

[0006] In some embodiments, a method is provided. The method includes obtaining at least one interconnect including at least one power splitter, obtaining at least one photonic integrated circuit (PIC) including at least one set of modulators, and forming a device including the at least one interconnect and the at least one PIC.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The present disclosure is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings in which like references indicate similar elements. It should be noted that different references to "an" or "one" embodiment in this disclosure are not necessarily to the same embodiment, and such references mean at least one.

[0008] FIGS. **1**A-**1**B are diagrams of views of an example system that can enable offloading of photonic integrated circuit (PIC) functionality into an optical interconnect, according to some embodiments.

[0009] FIGS. **2**A-**3** are diagram of example implementations of systems that offload photonic integrated circuit (PIC) functionality into an optical interconnect, according to some embodiments.

[0010] FIGS. **4**A-**4**B are diagrams of example implementations of arrayed channel waveguides that can be implemented within an optical interconnect, according to some embodiments.

[0011] FIGS. **5**-**6**C are diagrams of example implementations of waveguide routing solutions within an optical interconnect, according to some embodiments.

[0012] FIGS. **7**A-**10**C are diagrams of views of a system including a device that can enable dense photonic waveguide ("waveguide") to optical fiber edge coupling, according to some embodiments.

[0013] FIGS. **11**A-**11**C are diagrams of example multimode interferometers (MMIs) that can be used to implement power splitting and combining, according to some embodiments.

[0014] FIG. **12** is a flowchart of a method to enable offloading of photonic integrated circuit (PIC) functionality into an optical interconnect, according to some embodiments.

DETAILED DESCRIPTION

[0015] Embodiments of the present disclosure relate to offloading of photonic integrated circuit (PIC) functionality into an optical interconnect. Coupling of optical fibers to waveguides on a PIC can be implemented using an optical fiber connector ("connector"). A connector can be a single-fiber (or simplex-fiber) connector, a duplex-fiber connector, or a multi-fiber connector. Examples of types of connectors include SC (square connector) connectors, FC (ferrule connector) connectors, little or local LC (little connector or local connector) connectors, ST (straight tip) connectors, and MPO (multi-fiber push-on) connectors. One example of an MTO connector is an MTP® (multi-fiber termination push-on) connector.

[0016] A connector can include a connection substrate having multiple grooves formed therein, into which multiple respective optical fibers can be inserted and secured. Each optical fiber can be optically coupled to a respective waveguide. A connection substrate can be formed with a geometry that can provide the proper spacing to achieve optical coupling (e.g., evanescent wave coupling). For example, a large number of optical fiber-to-waveguide couplings may be needed for a multichannel wavelength division multiplexing (WDM) optical system.

[0017] One type of a connection substrate is a V-groove connection substrate, which is a substrate having multiple V-grooves formed therein. A V-groove is an opening that has a tapered shape in which the sides of the groove converged to a point (e.g., triangular shape). For each V-groove, an optical fiber can be inserted into the V-groove and secured in the V-groove using an adhesive (e.g., glue).

[0018] Some edge coupling solutions utilize single-mode fiber (SMF) to waveguide edge coupling through V-grooves.

More specifically, a cladding layer can have a single-mode inner core disposed therein to form a waveguide, which can be placed in a V-groove. Such implementations cannot be densely scaled up due to limitations in cladding layer diameters. Additionally, high-speed interconnects can utilize hundreds of SMFs connected to a PIC. Individually attaching SMFs can consume a large number of spatiotemporal resources.

[0019] Typically, a PIC implementing a multichannel wavelength division multiplexing (WDM) system includes active components such as modulators, multiplexers, etc. For example, a given modulator can receive an optical wave from an optical wave source, and generate a modulated wave. A set of modulated waves generated from a set of optical waves can be combined using a respective multiplexer to generate a multiplexed wave for a given channel. Such one-to-one optical fiber-to-waveguide connections can implement many optical fiber-to-waveguide couplings for a multichannel WDM system. For example, the number of couplings can be N*M, where N is the number of optical wave sources (e.g., external light sources) and M is the number of channels of the multichannel WDM system. Accordingly, it can be difficult to scale up the number of channels in an optical system.

[0020] Aspects and implementations described herein can address these and other drawbacks by enabling offloading of PIC functionality into an optical interconnect. For example, embodiments described herein can be used to enable on-chip WDM and power splitting to reduce the number of channels (and optical fibers) designated for optical wave sources (e.g., external light sources). In some embodiments, an optical wave source is a continuous optical wave source. Reducing the number of channels designed for optical wave sources can increase bandwidth density (e.g., data flow) enabled by an optical interconnect. For example, bandwidth density can be measured in terabits per second per millimeter (Tbps/mm).

[0021] Fiber function description for N fiber coupling ports n×External laser source (ELS) backup channels (n equals the number of wavelengths in wavelength division multiplexing (WDM) or larger if the power of one individual ELS is not enough) (N-n)/2 for Rx, (N-n)/2 for Tx.

[0022] More specifically, embodiments described herein provide for various system configurations that can enable M channels of a multichannel WDM system with N wavelengths per channel.

[0023] In some embodiments, a system enables M channels of a multichannel WDM system with N wavelengths per channel by implementing 1-to-M power splitting and combining. For example, the system can include N optical wave sources (e.g., external light sources) that each generate a respective wavelength of an optical wave, N 1-to-M power splitters, N sets of modulators each including M modulators, and M multiplexers. In these embodiments, each of the 1-to-M power splitters can receive a respective wavelength of an optical wave generated by the respective optical wave source, and generate M outputs (e.g., splits waves). Each of the outputs of a 1-to-M power splitter can be received by a respective modulator of a respective one of the N sets of modulators. Each modulator of a set of modulators can generate an output that is received by a respective multiplexer of the M multiplexers. This is contrast to other implementations in which a single multiplexer receives an output from each modulator of the set of modulators. An illustrative example of these embodiments will be described below with reference to FIG. **2**A.

[0024] In some embodiments, a system enables M channels of a multichannel WDM system with N wavelengths per channel by implementing power splitting and combining with an N-to-M power splitter. For example, a system can include N optical wave sources (e.g., external light sources) that each generate a respective wavelength of an optical wave, an N-to-M power splitter, and N sets of modulators, where each set of modulators includes M modulators, and each set of modulators corresponds to a respective wavelength of the N wavelengths of optical waves. In these embodiments, the N-to-M power splitter can receive the N wavelengths of optical waves from the N optical wave sources, and generate M outs. Each output generated by the N-to-M power splitter can be received by a respective modulator of a set of modulators, and the respective modulator can generate an output from the split wave. An illustrative example of these embodiments will be described below with reference to FIG. **2**B.

[0025] In some embodiments, a system enables M channels of a multichannel WDM system with N wavelengths per channel by implementing power splitting and combining with an N-to-N power splitter and N additional 1-to-M/N power splitters. For example, a system can include N optical wave sources (e.g., external light sources) that each generate a respective wavelength of an optical wave, an N-to-N power splitter, N additional 1-to-M/N power splitters, and N sets of modulators, where each set of modulators includes M modulators, and each set of modulators corresponds to a respective wavelength of the N wavelengths of optical waves. In these embodiments, the N-to-N power splitter can receive the N wavelengths of optical waves from the N optical wave sources, and generate N outputs. Each output generated by the N-to-N power splitter can be received by a respective one of the 1-to-M/Npower splitters. Each set of modulators can be divided into N subsets of modulators, where each subset of modulators includes N/M modulators. Each output of a 1-to-M/Npower splitter can be received by a respective modulator of a respective subset of modulators corresponding to the 1-to-M/N power splitter. An illustrative example of these embodiments will be described below with reference to FIG. **2**C.

[0026] Embodiments described herein can further provide for waveguide routing solutions that can enable dense waveguide routing in a substrate in a manner that reduces (e.g., eliminates) interference. In some embodiments, a waveguide routing solution is a two-dimensional (2D) waveguide routing solution.

[0027] In some embodiments, a waveguide routing solution is a three-dimensional (3D) waveguide routing solution. A 3D waveguide routing solution can route an optical wave from a first waveguide in a first layer to a second waveguide in a second layer (e.g., above the first layer). For example, a 3D waveguide routing solution can be an evanescent coupling 3D waveguide routing solution. In this example, an optical wave from the first waveguide can be routed to the second waveguide using evanescent coupling.

[0028] As another example, a 3D waveguide routing solution can be a through via 3D waveguide routing solution. In this example, an optical wave from the first waveguide can be routed from the first waveguide to the second waveguide using a through via (e.g., through glass via (TGV) or a through silicon vias (TSV)). More specifically, a set of routing elements within the through via can be used to route the optical wave from the first waveguide to the second waveguide. For example, the set of routing elements can include a vertical waveguide, a set of optical elements (e.g., microlens, mirrors, meta-surfaces), etc.

[0029] As yet another example, a 3D waveguide routing solution can be a direct waveguide writing 3D waveguide routing solution. In this example, an optical wave generator (e.g., laser) can generate optical waves that can directly write waveguides inside of a substrate.

[0030] Embodiments described herein can implement multicore single-mode fiber (MC-SMF) to waveguide array edge coupling. An MC-SMF described herein can be connected to multiple standard SMFs with appropriate connector for standard product connection.

[0031] For example, a device described herein can include a substrate having multiple grooves (e.g., V-grooves) formed therein. The substrate can further include multiple sets of waveguides. Each set of waveguides can correspond to a respective groove of the substrate. In some embodiments, a pitch corresponding to the distance between adjacent grooves (e.g., distance between points of adjacent V-grooves) ranges between about 100 micrometers (μm) to about 150 μm. In some embodiments, the pitch is about 127 μm. Each groove can receive a respective MC-SMF optical fiber, which can be secured with an adhesive (e.g., glue). An MC-SMF optical fiber can include a cladding layer and multiple inner cores disposed within the cladding layer. Each inner core of an MC-SMF optical fiber disposed in a groove can be optically coupled to a respective waveguide of the corresponding set of waveguides formed within the substrate.

[0032] Inner cores can be arranged within a cladding layer using any suitable configuration or geometry. In some embodiments, a cladding layer has a diameter that ranges between about 100 μm to about 150 μm. In some embodiments, a cladding layer has a diameter of about 125 μm.

[0033] In some embodiments, inner cores are arranged within a cladding layer in an approximately linear configuration. In some embodiments, an inner core has a diameter that ranges between about 6 μm to about 10 μm. In some embodiments, an inner core has a diameter of about 8 μm. In some embodiments, a distance between each inner core ranges between about 15 μm to about 25 μm. In some embodiments, a distance between each inner core is about 20 μm.

[0034] In some embodiments, inner cores are arranged within a cladding layer in a non-linear configuration. For example, the non-linear configuration can have a hexagonal cross-sectional shape. The number of inner cores that can be included in a cladding layer can depend at least in part on the diameter of the cladding layer. In some embodiments, an inner core has a diameter that ranges between about 6 μm to about 10 μm. In some embodiments, an inner core has a diameter of about 8 μm.

[0035] In some embodiments, a device includes multiple substrates bonded together (e.g., vertically). More specifically, each substrate can include MC-SMF optical fibers formed in respective grooves, where each MC-SMF optical fiber includes multiple inner cores optically coupled to respective waveguides of a set of waveguides corresponding to the respective groove, similar to the substrate described above. In some embodiments, inner cores are arranged within a cladding layer in a linear configuration. In some embodiments, inner cores are arranged within a cladding layer in a non-linear configuration. For example, the non-linear configuration can have a hexagonal cross-sectional shape. Waveguides from one substrate can be routed to waveguides of another substrate using vias (e.g., through-glass vias (TGVs)), using techniques such as photonic wire bounding, meta-lens, etc.

[0036] Embodiments described herein can provide for numerous other technical advantages. For example, embodiments described herein can reduce evanescent wave decay within devices (e.g., interconnects), which can improve the ability of waveguides of these devices to transmit optical signals. Embodiments described herein can reduce the size of a PIC, which can reduce costs, and enable more PICs to be used per area on the interconnect to increase the area bandwidth density.

[0037] FIGS. **1A**-**1**B are block diagrams of views of an apparatus or system **100**, according to some embodiments. More specifically, FIG. **1**A is a top-down view of the system **700**, and FIG. **1**B is a side view of the system **100**.

[0038] As shown in FIG. **1**A, system **100** can include printed circuit board (PCB) **102**, base interconnect (e.g., interposer) **105**, at least one processing unit and/or switch (PU/switch) **110** disposed on base interconnect **105**, at least one network interface card (NIC) **120** disposed on base interconnect **105**, serializer-deserializer (SERDES) **130** disposed on base interconnect **105**, multiple supplemental interconnects **140-1** through **140-3** disposed on base interconnect **105**, multiple photonic integrated circuits (PICs) **150** disposed on each of supplemental interconnects **140-1** through **140-3**, and multiple waveguides **160-1** through **160-3** each coupled to a respective one of supplemental interconnects **140-1** through **140-3**. In some embodiments, and as shown, the number of supplemental interconnects is three. However, the number of supplemental interconnects should not be considered limiting. In some embodiments, and as shown, each set of PICs **750***s* includes four PICs. However, the number of PICs should not be considered limiting.

[0039] More specifically, each of supplemental interconnects **140-1** through **140-3** can be disposed between respective sets of PICs **150** and base interconnect **105**. For example, as further shown in FIG. **1**B, bumps **170** are disposed between PU/Switch **110** and base interconnect **105**, and between PICs **150** and supplemental interconnects **140-1** through **140-3**. Conductive wires **180** can be formed through the base interconnect **705** and the supplemental interconnects **140-1** through **140-3** to enable electrical connections between components of the system **100** (e.g., PU/switch **110** and PICs **150**). Additionally, through each of supplemental interconnects **140-1** through **140-3**, a respective waveguide system **180** can be formed to provide optical signals to the PICs **150**.

[0040] FIG. **2**A is a diagram of an example system **200**A, according to some embodiments. As shown, system **200**A includes supplemental interconnect **140-1** and PIC **150** of FIGS. **1A**-**1**B.

[0041] System **200**A can further include multiple optical wave sources including optical wave sources **210**A-**1** and **210**A-**2**. More specifically, the optical wave sources can be external optical wave sources. In some embodiments, an optical wave source is an external laser source. Each of the optical wave sources can generate a respective wavelength of an optical wave.

[0042] As further shown, system **200**A can further include multiple power splitters including power splitters **220**A-**1** and **220**A-**2**, multiple sets of modulators including a first set of modulators (e.g., modulators **230**A-**1** and **230**A-**2**) and a second set of modulators (e.g., modulators **240**A-**1** and **240**A-**2**), and multiple multiplexers including multiplexers **250**A-**1** and **250**A-**2**. More specifically, the power splitters and the multiplexers can be integrated within supplemental interconnect **140**-**1**, and the modulators are integrated within PIC **150**.

[0043] Each optical wave source can be coupled to a respective power splitter. For example, optical wave source **210**A-**1** can be coupled to power splitter **220**A-**1** and optical wave source **210**A-**2** can be coupled to power splitter **220**A-**2**. More specifically, each optical wave source can be connected to an optical fiber that can be coupled to a waveguide that can be connected to the respective power splitter. For example, optical fiber **260**A, connected to optical wave source **210**A-**1**, can be coupled to waveguide **270**A, and waveguide **270**A can be connected to power splitter **220**A-**1**.

[0044] Each power splitter can generate multiple split waves from the respective optical wave, and each split wave can be received by a respective modulator of a respective set of modulators. For example, power splitter **220**A-**1** can generate multiple split waves from an optical wave generated by optical wave source **210**A-**1**, and each split wave generated by power splitter **220**A-**1** can be received by a respective modulator of the first set of modulators. As another example, power splitter **220**A-**2** can generate multiple split waves from an optical wave generated by optical wave source **210**A-**2**, and each split wave generated by power splitter **220**A-**2** can be received by a respective modulator of the second set of modulators.

[0045] Each modulated wave generated by a modulator can be received by a respective multiplexer of the multiple multiplexers to generate a respective multiplexed wave. For example, multiplexer **250**A-**1** can receive the modulated wave generated by modulator **230**A-**1** of the first set of modulators, the modulated wave generated by modulator **240**A-**1** of the second set of modulators, etc. As another example, multiplexer **250**A-**2** can receive the modulated wave generated by modulator **230**A-**2** of the first set of modulators, the modulated wave generated by modulator **240**A-**2** of the second set of modulators, etc.

[0046] Each multiplexed wave can correspond to a respective channel of a multichannel WDM system. For example, the multiplexed wave generated by multiplexer **250**A-**1** can correspond to channel **280**A-**1**, and the multiplexed wave generated by multiplexer **250**A-**2** can correspond to channel **280**A-**2**.

[0047] FIG. **2**B is a diagram of an example system **200**B, according to some embodiments. As shown, system **200**B can include supplemental interconnect **140**-**1**.

[0048] System **200**B can further include multiple optical wave sources including optical wave sources **210**B-**1** and **210**B-**2**. More specifically, the optical wave sources can be external optical wave sources. In some embodiments, an optical wave source is an external laser source. The number of optical wave sources can be equal to N. Each of the optical wave sources can generate a respective wavelength of an optical wave.

[0049] System **200**B can further include power splitter **220**B, and multiple sets of modulators including a first set of modulators **230**B-**1** through **230**B-M and an N-th set of modulators **240**B-**1** through **240**B-M. The set of modulators **230**B-**1** through **230**B-M can correspond to a first wavelength of an optical wave (λ_1). The set of modulators **240**B-**1** through **240**B-M can correspond to an N-th wavelength of an optical wave (λ_N). In some embodiments, power splitter **220**B is integrated within supplemental interconnect **140**-**1**, and the modulators are integrated within a PIC (e.g., the PIC **150** of FIGS. **1**A-**1**B).

[0050] Each optical wave source can be coupled to power splitter **220**B. More specifically, each optical wave source can be connected to an optical fiber that is coupled to a waveguide that is connected to power splitter **220**B. For example, optical fiber **260**B, connected to optical wave source **210**B-**1**, can be coupled to waveguide **270**B, and waveguide **270**B can be connected to power splitter **220**B. Power splitter **220**B can be an N-to-M splitter that generates M split waves from N optical waves received from the N optical wave sources including optical wave source **210**B-**1** and optical wave source **210**B-**2**.

[0051] Each of the M split waves can be received by a respective modulator of the set of modulators **230**B-**1** through **230**B-M. Each output of a modulator of the set of modulators **230**B-**1** through **230**B-M can be received by a respective modulator of the set of modulators **240**B-**1** through **240**B-M. Each modulator can correspond to a respective channel **280**B of a of a multichannel WDM system.

[0052] FIG. **2**C is a diagram of an example system **200**C, according to some embodiments. As shown, system **200**C includes supplemental interconnect **140**-**1** of FIGS. **1**A-**1**B.

[0053] System **200**C can further include multiple optical wave sources including optical wave sources **210**C-**1** and **210**C-**2**. More specifically, the optical wave sources can be external optical wave sources. In some embodiments, an optical wave source is an external laser source. The number of optical wave sources can be equal to N. Each of the optical wave sources can generate a respective wavelength of an optical wave.

[0054] System **200**C includes power splitter **220**C, and an additional set of power splitters including power splitter **225**C-**1** and power splitter **225**C-**2**. The number of power splitters of the additional set of power splitters can be equal to N. System **200**C further includes multiple sets of modulators including a first set of modulators **230**C-**1** through **230**C-M and a final (N-th) set of modulators **240**C-**1** through **240**C-M. The set of modulators **230**B-**1** through **230**-M can correspond to a first wavelength of an optical wave (λ_1). The set of modulators **240**B-**1** through **240**B-M can correspond to an N-th wavelength of an optical wave (λ_N). In some embodiments, power splitter **220**B is integrated within supplemental interconnect **140**-**1**, and the modulators are integrated within PIC **150**.

[0055] Each optical wave source can be coupled to power splitter **220**C. More specifically, each optical wave source can be connected to an optical fiber that is coupled to a waveguide that is connected to power splitter **220**C. For example, optical fiber **260**C, connected to optical wave source **210**C-**1**, can be coupled to waveguide **270**C, and waveguide **270**C can be connected to power splitter **220**C. Power splitter **220**B can be an N-to-N splitter that generates N split waves from N optical waves received from the N optical wave sources including optical wave source **210**B-**1** and optical wave source **210**B-**2**.

[0056] Each power splitter of the set of additional power splitters can receive a respective split wave of the N split waves from the power splitter **220**C. For example, a first split wave can be received by power splitter **225**C-**1** and a second split wave can be received by power splitter **225**C-**2**. Each power splitter of the set of additional power splitters can be a 1-to-M/N splitter that generates M/N split waves from the respective split wave received from power splitter **220**C.

[0057] Each of the M/N split waves generated by a respective power splitter of the set of additional power splitters can be received by a respective modulator. More specifically, each set of modulators **230**C-**1** through **230**C-M and **240**C-**1** through **240**C-M can be divided into N subsets, where each subset includes M/N modulators. For example, as shown in FIG. **2**C, a first subset of modulators of the set of modulators **230**C-**1** through **230**C-M can include modulators **230**C-**1** through **230**C-(M/N), a second subset of the set of modulators **230**C-**1** through **230**C-M can include modulators **230**C-(M/N+1) through **230**C-(2M/N), etc. Moreover, a first subset of modulators of the set of modulators **240**C-**1** through **240**C-M can include modulators **240**C-**1** through **240**C-(M/N), a second subset of the set of modulators **240**C-**1** through **240**C-M can include modulators **240**C-(M/N+1) through **240**C-(2M/N), etc. Each of the M/N split waves generated by power splitter **225**C-**1** can be received by a respective modulator of a subset of modulators. Each modulator can correspond to a respective channel **280**C of a of a multichannel WDM system.

[0058] In some embodiments, power splitting and combining can be implemented by a single multimode interferometer (MMI). In some embodiments, power splitting and combining can be implemented by cascaded MMIs. Illustrative examples of MMIs are described below with reference to FIGS. **11**A-**11**C.

[0059] FIG. **3** is a diagram of an example system **300**, according to some embodiments. As shown, system **300** includes supplemental interconnect **140**-**1** and PIC **150** of FIGS. **1**A-**2**C. The system **300** can further include power splitter **305** (e.g., power splitter **210**A-**1** of FIG. **2**A) that can receive input optical wave **310** (e.g., from optical wave generator **210**A-**1** of FIG. **2**A). Power spitter **305** can generate, from input optical wave **310**, N split waves **320**, represented by λ_1 through λ_N, that are received by PIC **150**. PIC **150** can generate N modulated waves **330**, represented by λ_1 through λ_N, that are received by multiplexer **335** (e.g., multiplexer **250**A-**1** of FIG. **2**A). Multiplexer **335** can generate modulated wave **340** from N modulated waves **330**. Modulated wave **340** can correspond to a channel of a multichannel WDM system (e.g., channel **280**A-**1** of FIG. **2**A).

[0060] FIGS. **4**A-**4**B are diagram of an example device **400**, according to some embodiments. In some embodiments, device **400** is an interconnect (e.g., supplemental interconnect **140**-**1** of FIGS. **1**-**3**). Device **400** can include input slab guide **410**, output slab guide **420**, and a set of arrayed channel waveguides **430**. Device **400** can include input channel **415** to receive input optical waves within a single optical fiber. Device **400** can include output channels **425**. Each channel **425** corresponds to a respective output optical wave. In some embodiments, as shown in FIG. **4**B, device **400** includes multiple through vias **440**, and the arrayed channel waveguides **430** are routed around through vias **440**.

[0061] FIG. **5** is a diagram of a system **500** including a device implementing a 2D waveguide routing solution. More specifically, the device can include substrate **510** including waveguides **520** and **530** formed therein. Waveguides **520** and **530** can be formed on the same level and can cross at intersection **540**. Insertion loss and cross-talk can be reduced to a sufficiently low amount by fine tuning the crossing dimensions.

[0062] FIG. **6**A is a diagram of a system **600**A including a device implementing evanescent coupling 3D waveguide routing. More specifically, the device can include substrate **610**A including waveguides **620**A and **630**A formed therein. Waveguide **620**A corresponds to a first level and waveguide **630**A corresponds to a second level above the first level. Evanescent coupling can be used to transmit an optical wave from waveguide **620**A to waveguide **630**A (or vice versa).

[0063] FIG. **6**B is a diagram of a system **600**B including a device implementing through via 3D waveguide routing. More specifically, the device can include substrate **610**B including waveguides **620**B and **630**B formed therein. Waveguide **620**B corresponds to a first level and waveguide **630**B corresponds to a second level above the first level. The device can further include through via **640** formed within substrate **610**B, and a set of routing elements **650** disposed within through via **640**. An optical wave can be routed from waveguide **620**B to waveguide **630**B (or vice versa) using set of routing elements **650**. For example, set of routing elements **650** can include a vertical waveguide, a set of optical elements (e.g., microlens, mirrors, meta-surfaces), etc.

[0064] FIG. **6**C is a diagram of a system **600**C including a device implementing direct waveguide writing 3D waveguide routing. More specifically, the device can include substrate **610**C. System **600**C can include optical wave generator (e.g., laser) **660** that can generate optical wave (e.g., laser beam) **670** that can directly write waveguide **680** inside of substrate **610**C. Waveguide **680** can traverse a first level and a second level (e.g., similar to the first and second levels of FIGS. **6**A-**6**B) to enable 3D waveguide routing.

[0065] FIGS. **7**A-**7**B are diagrams of views of an apparatus or system **700**, according to some embodiments. More specifically, FIG. **7**A is a top-down view of the system **700**, and FIG. **7**B is a cross-sectional view of the system **700** through line D-D'.

[0066] As shown in FIGS. **7**A-**7**B, system **700** can include substrate **710** (e.g., corresponding to supplemental interconnect **140**-**1** of FIGS. **1**-**3**), multiple sets of waveguides including set of waveguides **720** formed within substrate **710**, and multiple grooves including groove **730** formed within substrate **710**. In some embodiments, and as shown, groove **730** is a V-groove. Each set of waveguides can correspond to a respective groove (e.g., set of waveguides **720** corresponds to groove **730**).

[0067] As further shown in FIGS. **7**A-**7**B, system **700** can include multiple MC-SMF optical fibers including optical fibers **740**-**1** through **740**-**4**. Each groove can receive a respective optical fiber, which can be secured with an adhesive (e.g., glue). For example, groove **730** can receive optical fiber **740**-**4**. Each optical fiber can include a cladding layer and multiple inner cores disposed within the cladding layer. More specifically, each inner core can be a single-mode core. For example, optical fiber **740**-**1** includes cladding layer **742** and inner cores **744**. Inner cores **744** can be arranged within cladding layer **742** using any suitable configuration or geometry. In these illustrative embodiments, inner cores **744** are arranged within cladding layer **742** in an approximately linear configuration. Each inner core **744** can be optically coupled to a respective waveguide of the corresponding set of waveguides.

[0068] The number of inner cores **744** that can be included in cladding layer **742** can depend at least in part on the diameter of the cladding layer **742** and the diameter of each inner core **744**. In some embodiments, cladding layer **742** has a diameter that ranges between about 100 μm to about 150 μm. In some embodiments, cladding layer **742** has a diameter of about 125 μm. In these illustrative embodiments, each set of waveguides includes five waveguides and each optical fiber includes five inner cores. However, such an example should not be considered limiting. In some embodiments, up to seven inner cores can be linearly arranged within a cladding layer of an MC-SMF optical fiber.

[0069] In some embodiments, each inner core **744** has a diameter that ranges between about 6 μm to about 10 μm. In some embodiments, each inner core **744** has a diameter of about 8 μm. In some embodiments, a distance between each inner core **744** ranges between about 15 μm to about 25 μm. In some embodiments, a distance between each inner core **744** is about 20 μm.

[0070] In some embodiments, a pitch "P" corresponding to the distance between adjacent grooves (e.g., distance between points of adjacent V-grooves) ranges between about 100 μm to about 150 μm. In some embodiments, the pitch is about 127 μm. An effective pitch is defined as a ratio between the pitch and the number of inner cores within the pitch. For example, if the pitch is about 127 μm and the number of inner cores is five, then the effective pitch is about 25.4 μm.

[0071] FIGS. **8**A-**8**B are diagrams of views of an apparatus or system **800**, according to some embodiments. More specifically, FIG. **8**A is a top-down view of the system **800**, and FIG. **8**B is a cross-sectional view of the system **800** through line E-E'.

[0072] As shown in FIGS. **8**A-**8**B, system **800** can include substrate **810** (e.g., corresponding to supplemental interconnect **140-1** of FIGS. **1-3**), multiple sets of waveguides including set of waveguides **820** formed within substrate **810**, and multiple grooves including groove **830** formed within substrate **810**. In some embodiments, and as shown, groove **830** is a V-groove. Each set of waveguides can correspond to a respective groove (e.g., set of waveguides **820** corresponds to groove **830**).

[0073] As further shown in FIGS. **8**A-**8**B, system **800** can include multiple MC-SMF optical fibers including optical fibers **840-1** through **840-4**. Each groove can receive a respective optical fiber, which can be secured with an adhesive (e.g., glue). For example, groove **830** can receive optical fiber **840-4**. Each optical fiber can include a cladding layer and multiple inner cores disposed within the cladding layer. More specifically, each inner core can be a single-mode core. For example, optical fiber **840-1** includes cladding layer **842** and inner cores **844**. Inner cores **844** can be arranged within cladding layer **842** using any suitable configuration or geometry. In these illustrative embodiments, inner cores **844** are arranged within cladding layer **842** in a non-linear configuration. For example, the non-linear configuration can have a hexagonal cross-sectional shape. Each inner core **844** can be optically coupled to a respective waveguide of the corresponding set of waveguides.

[0074] The number of inner cores **844** that can be included in cladding layer **842** can depend at least in part on the diameter of the cladding layer **842**. In some embodiments, cladding layer **842** has a diameter that ranges between about 100 μm to about 150 μm. In some embodiments, cladding layer **842** has a diameter of about 125 μm. In these illustrative embodiments, each set of waveguides includes 19 waveguides and each optical fiber includes 19 inner cores. However, such an example should not be considered limiting. In some embodiments, up to 32 inner cores can be non-linearly arranged within a cladding layer of an MC-SMF optical fiber. In some embodiments, each inner core **844** has a diameter that ranges between about 6 μm to about 10 μm. In some embodiments, each inner core **844** has a diameter of about 8 μm.

[0075] In some embodiments, a pitch "P" corresponding to the distance between adjacent grooves (e.g., distance between points of adjacent V-grooves) ranges between about 100 μm to about 150 μm. In some embodiments, the pitch is about 127 μm. As previously mentioned above with reference to FIGS. **7**A-**7**B, an effective pitch is defined as a ratio between the pitch and the number of inner cores within the pitch. For example, if the pitch is about 127 μm and the number of inner cores is 19, then the effective pitch is about 6.7 μm. Accordingly, arranging multiple inner cores in a non-linear configuration can increase the number of inner cores within the optical fiber, which enable a smaller effective pitch as compared to the linear configuration example shown in FIGS. **7**A-**7**B.

[0076] FIGS. **9**A-**9**B are diagrams of views of an apparatus or system **900**, according to some embodiments. More specifically, FIG. **9**A is a cross-section view of the system **900**, and FIG. **9**B is a side view of the system **800** through line F-F'.

[0077] As shown in FIG. **9**A, system **900** can include multiple substrates including substrates **910-1** through **910-3**. Substrate **910-1** (e.g., corresponding to supplemental interconnect **140-1** of FIGS. **1-3**) can include multiple sets of waveguides including set of waveguides **920-1** formed therein, and multiple grooves including groove **930-1** formed therein. Each groove of substrate **910-1** can receive a respective MC-SMF optical fiber (e.g., optical fiber **940-1**), which can be secured with an adhesive (e.g., glue). Substrate **910-2** can include multiple sets of waveguides including set of waveguides **920-2** formed therein, and multiple grooves including groove **930-2** formed therein. Substrate **910-3** can include multiple sets of waveguides including set of waveguides **920-3** formed therein, and multiple grooves including groove **930-3** formed therein. Each groove of substrate **910-2** can receive a respective optical fiber (e.g., optical fiber **940-2**), which can be secured with an adhesive (e.g., glue). Each groove of substrate **910-3** can receive a respective optical fiber (e.g., optical fiber **940-3**), which can be secured with an adhesive (e.g., glue). Substrate **910-1** can be bonded to substrate **910-2** via bonding layer **950-1** and substrate **910-2** can be bonded to substrate **910-3** via bonding layer **950-2**. In some embodiments, each groove is a V-groove. Each set of waveguides can correspond to a respective groove (e.g., set of waveguides **820** corresponds to groove **830**). Each optical fiber can include a cladding layer and multiple inner cores disposed within the cladding layer. More specifically, each inner core can be a single-mode core. As shown in these illustrative embodiments, optical fiber **940-1** through **940-3**

are similar to optical fibers **840-1** through **840-3** described above with reference to FIGS. **8A-8B** (e.g., inner cores arranged within cladding layers in a non-linear configuration). However, such embodiments should not be considered limiting. In some embodiments, a pitch "P" corresponding to the distance between adjacent grooves (e.g., distance between points of adjacent V-grooves) ranges between about 100 μm to about 150 μm. In some embodiments, the pitch is about 127 μm (e.g., between about 2-3 μm effective, as compared to about 25 μm effective). Accordingly, bonding multiple substrates together can enable a smaller effective pitch as compared to the single substrate examples shown in FIGS. **7A-7B** and FIGS. **8A-8B**.

[0078] As further shown in FIG. **9B**, multiple vias including vias **960-1** and **960-2** can be formed to route waveguides from one of substrates **910-1** through **910-3** to another one of substrate **910-1** through **910-3** with techniques such as photonic wire bonding, meta-lens, etc. In some embodiments, a via is a TGV.

[0079] An effective pitch for a system described herein can be determined based on a ratio between the pitch between grooves and the number of inner cores in an optical fiber. For example, in FIGS. **7A-7B**, the effective pitch can be determined as the ratio of the pitch P and the number of inner cores in an optical fiber. Illustratively, if the pitch is 127 μm and the number of inner cores in optical fiber **740-1** is five, then the effective pitch is a about 25.4 μm. As another example, in FIGS. **8A-8B**, the effective pitch can be determined as the ratio of the pitch P and the number of inner cores in an optical fiber. Illustratively, if the pitch is 127 μm and the number of inner cores in optical fiber **840-1** is 19, then the effective pitch is a about 6.7 μm. As yet another example, in FIGS. **9A-9B**, the effective pitch can be determined as the ratio of the pitch P and the number of inner cores in an optical fiber, divided by the number of substrates. Illustratively, if the pitch is 127 μm and the number of inner cores in optical fiber **940-1** is 19, then the effective pitch is about 2.2 μm.

[0080] FIG. **10A** is a diagram of a system **1000** enabling an MC-SMF to SMF connection, according to some embodiments. As shown, system **1000** can include MC-SMF optical fiber **1010** and multiple SMF optical fibers **1020-1** through **1020-N**. MC-SMF optical fiber **1010** is attached (e.g., coupled) to a first end of MC-SMF to SMF connector ("connector") **1030** and SMF optical fibers **1020-1** through **1020-N** are attached (e.g., coupled) to a second end of connector **1030**. MC-SMF optical fiber **1010** can be connected to multiple standard SMF optical fibers **1020-1** through **1020-N** using any suitable connector **1030** for standard connection. An example of MC-SMF optical fiber **1010** including cladding layer **1012** and multiple inner cores **1014** is shown with reference to FIG. **10B** (e.g., similar to MC-SMF optical fiber **840-1** of FIGS. **8A-8B**). An example of SMF optical fiber **1020-1** including cladding layer **1022** and inner core **1024** is shown with reference to FIG. **10C**.

[0081] FIG. **11A** is a diagram of an example MMI **1100A**, according to some embodiments. More specifically, the MMI **1100A** is a 1×2 MMI. For example, as shown, the MMI **1100A** can include a single input port **1110A** and two output ports **1120A-1** and **1120A-2**. Power of an optical wave received via the input port **1110A** can be evenly split between the two output ports **1120A-1** and **1120A-2**. Accordingly, cascading N MMIs **1100A** can enable 2^N power splitting.

[0082] FIG. **11B** is a diagram of an example MMI **1100B**, according to some embodiments. More specifically, the MMI **1100B** is a 2×2 MMI. For example, as shown, the MMI **1100B** can include two input ports **1110B-1** and **1110B-2**, and two output ports **1120B-1** and **1120B-2**. Each of the input ports **1110B-1** and **1110B-2** can receive a respective wavelength of an optical wave, which can be combined into a combined wave. The combined power of the combined wave can be evenly split between the two output ports **1120B-1** and **1120B-2**. Accordingly, cascading N MMIs **1100B** can enable 2^N power splitting and WDM.

[0083] FIG. **11C** is a diagram of an example MMI **1100C**, according to some embodiments. More specifically, the MMI **1100C** is a 2×2 MMI. For example, as shown, the MMI **1100B** can include four input ports **1110C-1** through **1110C-4**, and four output ports **1120B-1** through **1120B-4**. Each of the input ports **1110C-1** and **1110C-4** can receive a respective wavelength of an optical wave, which can be combined into a combined wave. The combined power of the combined wave can be evenly split between the four output ports **1120B-1** through **1120B-4**. Accordingly, MMI **1110C** can achieve similar functionality as a 2×2 MMI (e.g., the MMI **1100B** of FIG. **2B**), with a more compact footprint.

[0084] FIG. **12** is a flowchart of a method to enable offloading of photonic integrated circuit (PIC) functionality into an optical interconnect, according to some embodiments. At block **1210**, at least one interconnect is obtained. The at least one interconnect can include a set of power splitters and a set of multiplexers. For example, the at least one interconnect can be similar to supplemental interconnect **140-1** of FIGS. **1A-3**.

[0085] At block **1220**, at least one PIC is obtained. The at least one PIC can include a set of modulators. For example, the at least one PIC can be similar to PIC **150** of FIGS. **1A-3**.

[0086] At block **1230**, a device including the at least one interconnect and the at least one PIC is formed. For example, the device can include a PCB (e.g., PCB **102** of FIGS. **1A-1B**), a base interconnect formed on the PCB (e.g., base interconnect **105** of FIGS. **1A-1B**), the at least one interconnect (as at least one supplemental interconnect) formed on the base interconnect, and the at least one PIC formed on the at least one interconnect. For example, a ball grid array can be disposed between the at least one interconnect and the at least one PIC. Further details regarding blocks **1210-1230** are described above with reference to FIGS. **1A-11C**.

[0087] The preceding description sets forth numerous specific details such as examples of specific systems, components, methods, and so forth, in order to provide a good understanding of several embodiments of the present disclosure. It will be apparent to one skilled in the art, however, that at least some embodiments of the present disclosure may be practiced without these specific details. In other instances, well-known components or methods are not described in detail or are presented in simple block diagram format in order to avoid unnecessarily obscuring the present disclosure. Thus, the specific details set forth are merely exemplary. Particular implementations may vary from these exemplary details and still be contemplated to be within the scope of the present disclosure.

[0088] As used herein, the singular forms "a," "an," and "the" include plural references unless the context clearly indicates otherwise. Thus, for example, reference to "a precursor" includes a single precursor as well as a mixture of two or more precursors; and reference to a "reactant" includes a single reactant as well as a mixture of two or more reactants, and the like.

[0089] Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearances of the phrase "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. In addition, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or." When the term "about" or "approximately" is used herein, this is intended to mean that the nominal value presented is precise within ±10%, such that "about 10" would include from 9 to 11.

[0090] The term "at least about" in connection with a measured quantity refers to the normal variations in the measured quantity, as expected by one of ordinary skill in the art in making the measurement and exercising a level of care commensurate with the objective of measurement and precisions of the measuring equipment and any quantities higher than that. In certain embodiments, the term "at least about" includes the recited number minus 10% and any quantity that is higher such that "at least about 10" would include 9 and anything greater than 9. This term can also be expressed as "about 10 or more." Similarly, the term "less than about" typically includes the recited number plus 10% and any quantity that is lower such that "less than about 10" would include 11 and anything less than 11. This term can also be expressed as "about 10 or less."

[0091] Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to illuminate certain materials and methods and does not pose a limitation on scope. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the disclosed materials and methods.

[0092] Although the operations of the methods herein are shown and described in a particular order, the order of the operations of each method may be altered so that certain operations may be performed in an inverse order or so that certain operation may be performed, at least in part, concurrently with other operations. In another embodiment, instructions or sub-operations of distinct operations may be in an intermittent and/or alternating manner.

[0093] It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent to those of skill in the art upon reading and understanding the above description. The scope of the disclosure should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. A system comprising:

an interconnect comprising at least one power splitter; and

a photonic integrated circuit (PIC) disposed on the interconnect, the PIC comprising at least one set of modulators.

2. The system of claim **1**, wherein the at least one power splitter is to receive at least one optical wave from at least one optical wave source.

3. The system of claim **1**, wherein each modulator of the at least one set of modulators is to receive a respective output of the at least one power splitter.

4. The system of claim **1**, wherein the interconnect further comprises a set of multiplexers, and wherein each multiplexer of the set of multiplexers is to receive a respective output of a respective modulator of the at least one set of modulators.

5. The system of claim **4**, wherein each multiplexer of the set of multiplexers corresponds to a respective channel of a multichannel wavelength division multiplexing system.

6. The system of claim **1**, wherein the interconnect comprises a set of arrayed channel waveguides.

7. The system of claim **6**, wherein the set of arrayed channel waveguides is routed around a set of through vias.

8. The system of claim **1**, wherein the interconnect implements two-dimensional (2D) waveguide routing.

9. The system of claim **1**, wherein the interconnect implements three-dimensional (3D) waveguide routing.

10. The system of claim **9**, wherein the 3D waveguide routing is one of:

evanescent coupling 3D waveguide routing;

through via 3D waveguide routing; or

direct waveguide writing 3D waveguide routing.

11. A method comprising:

obtaining at least one interconnect comprising at least one power splitter;

obtaining at least one photonic integrated circuit (PIC) comprising at least one set of modulators; and

forming a device comprising the at least one interconnect and the at least one PIC.

12. The method of claim **11**, wherein the at least one power splitter is to receive at least one optical wave from at least one optical wave source.

13. The method of claim **11**, wherein each modulator of the set of modulators is to receive a respective output of the at least one power splitter.

14. The method of claim **11**, wherein the interconnect further comprises a set of multiplexers, and wherein each multiplexer of the set of multiplexers is to receive a respective output of a respective modulator of the at least one set of modulators.

15. The method of claim **14**, wherein each multiplexer of the set of multiplexers corresponds to a respective channel of a multichannel wavelength division multiplexing system.

16. The method of claim **11**, wherein the interconnect comprises a set of arrayed channel waveguides.

17. The method of claim **16**, wherein the set of arrayed channel waveguides is routed around a set of through vias.

18. The method of claim **11**, wherein the interconnect implements two-dimensional (2D) waveguide routing.

19. The method of claim **11**, wherein the interconnect implements three-dimensional (3D) waveguide routing.

20. The method of claim **19**, wherein the 3D waveguide routing is one of:

evanescent coupling 3D waveguide routing;

through via 3D waveguide routing; or

direct waveguide writing 3D waveguide routing.

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